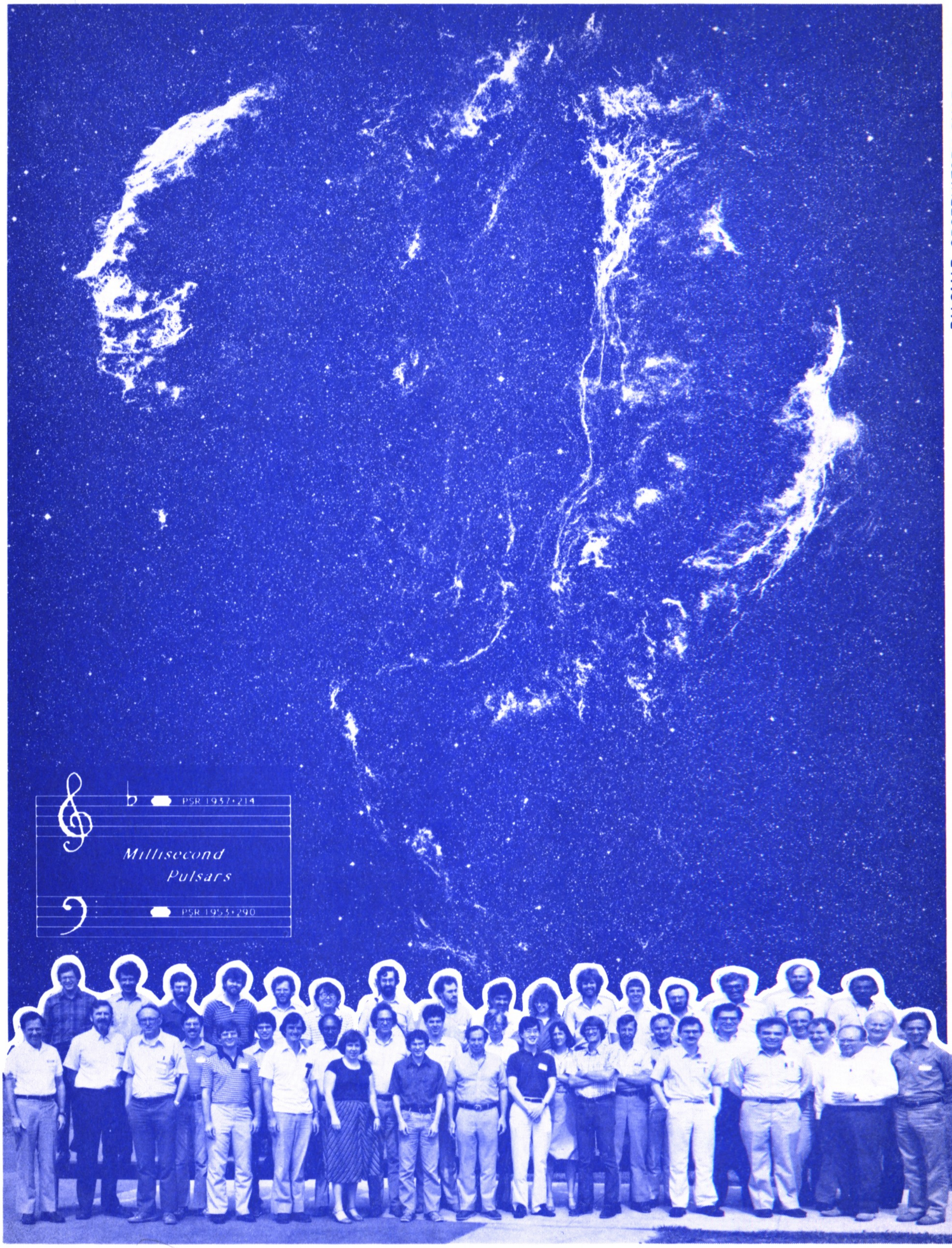
MILLISECOND PULSARS

Proceedings of a Workshop held at the National Radio Astronomy Observatory Green Bank, West Virginia on June 6, 7, 8, 1984



PALOMAR OBSERVATORY PHOTOGRAPH

Edited by S. P. Reynolds and D. R. Stinebring

Birth and Evolution of Neutron Stars: Issues Raised by Millisecond Pulsars

Proceedings of a Workshop held at the National Radio Astronomy Observatory Green Bank, West Virginia on June 6, 7, 8, 1984

Edited by S. P. Reynolds and D. R. Stinebring

Workshop No. 8

Distributed by:
National Radio Astronomy Observatory
P.O. Box 2
Green Bank, WV 24944-0002 USA

The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

1. Mal Ruderman
2. Mike Davis
3. Miller Goss
4. Harry Payne
5. Joel Tohline
6. Tom Loredo
7. Roger Chevalier
8. Ganesh Chanmugam
9. Rachel Dewey
10. Ken Brecher
11. Lloyd Rawley
12. G. Stollman
13. David Pines
14. Ed van den Heuvel
15. Andy Cheng
16. Alice Harding
17. Steve Reynolds
18. Dick Manchester
19. Andrew Lyne
20. Pat McDermott
21. Joe Taylor
22. Jacob Shaham
23. Hugh Van Horn
24. Grant Stokes
25. Val Boriakoff
26. Tor Hagfors
27. Don Backer
28. V. Radhakrishnan
29. Tim Hankins
30. Ramesh Narayan
31. Nicolo D'Amico
32. Blaise Canzian
33. Dan Stinebring
34. Mary Stevens
35. Shri Kulkarni
36. Rino Bandiera
37. Francesco Fauci
38. Jim Imamura
39. Joel Weisberg
40. Jim Cordes
41. Gary Chanan
42. Ali Alpar
43. Jim Applegate

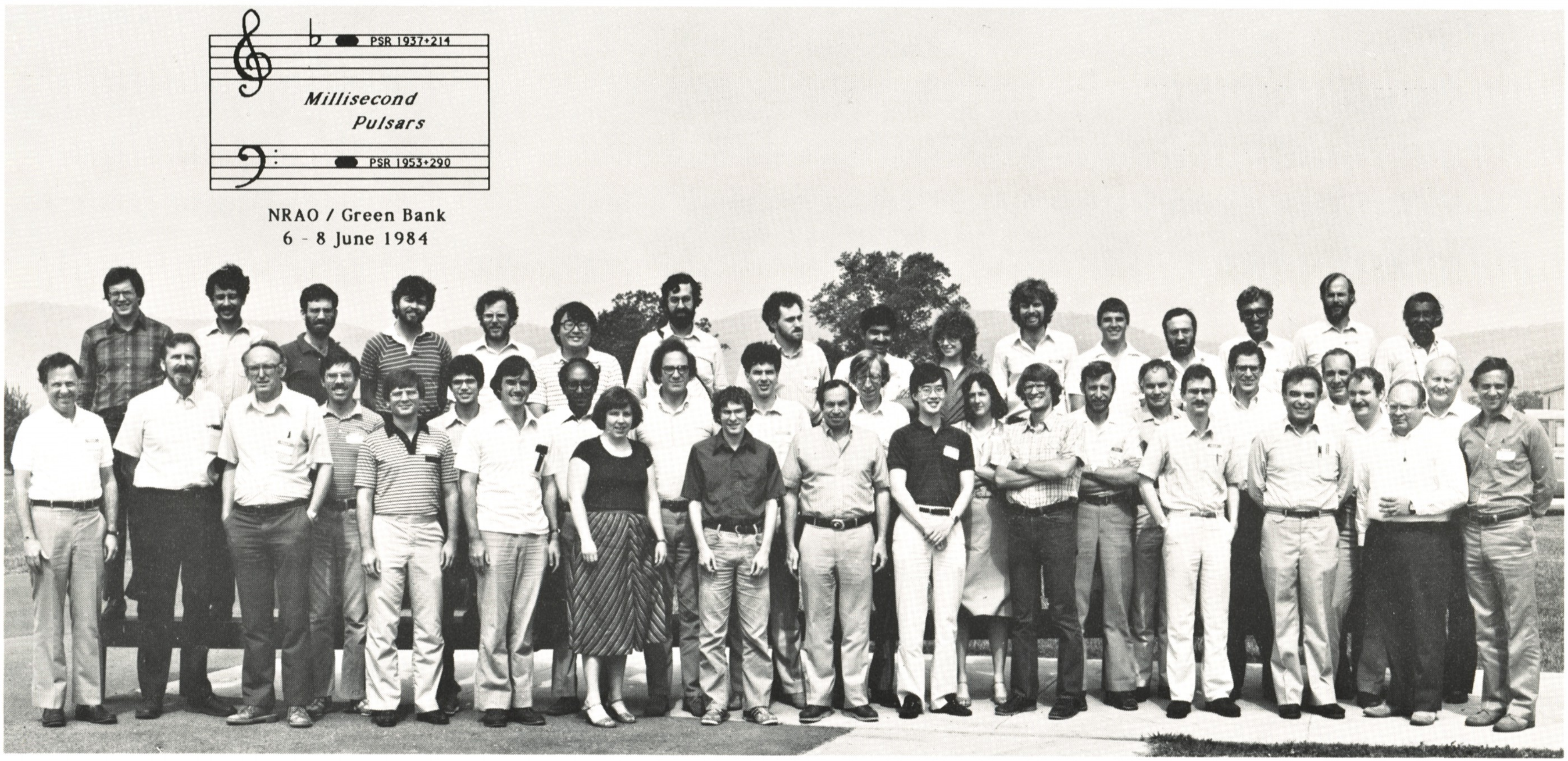

PSR 1937+214
Millisecond
Pulsars
PSR 1953+290
NRAO / Green Bank
6 - 8 June 1984

TABLE OF CONTENTS

Delivering author is underlined.

Preface

It is now two years since the initial reports of the discovery of the 1.6 millisecond pulsar 1937+214 astonished and delighted the astronomical community. In displacing the Crab pulsar from the distinction of fastest pulsar which it had held for fifteen years, this new object produced an explosion of theoretical and observational interest, and led to the reformulation of pulsar search techniques. The discovery of the 6.1 millisecond pulsar 1953+29 in a COS-B error box further fueled the new efforts. As various searches got under way, and as the theoretical dust began to settle, it seemed timely to arrange a meeting on these fascinating objects, on searches for more, and on their theoretical implications. Thus the Green Bank workshop, formally titled, "Birth and Evolution of Neutron Stars: Issues Raised by Millisecond Pulsars."

In a sense, the workshop's most direct result was a negative one: No new ultrafast pulsars have been found, and candidates as strong as that which yielded 1937+214 are not common. The large-scale searches have not been completed, and some are not yet operating; but the sky cannot be full of very fast pulsars. The theoretical counterpart of this finding was a growing consensus (though not unanimous) that ultrafast pulsars are recycled—spun up through a binary phase of mass transfer—rather than born with millisecond periods. Vigorous discussion took place on topics surrounding these. In particular, the seclusion of the Green Bank facility made it impossible for theorists and observers to escape each other, and the informality created a stimulating atmosphere of excitement and productivity which will (we hope) manifest itself in a burst of penetrating and insightful papers a few months hence.

All of the participants who spoke provided written papers, thanks to a rather elastic deadline. The papers and discussions were taped, and the discussions (by great pain and sacrifice) transcribed. We apologize to any speakers whose remarks were unjustly edited or misunderstood from the tapes. However, we feel that these discussions carry much of the flavor of the meeting.

Phyllis Jackson and Saundra Mason were a great help in preparing for the workshop and coordinating travel plans. We thank them for their cordial and professional assistance. We would also like to thank the excellent Green Bank staff for their outstanding job: Wally Oref, Becky Warner, Maxine Foe, and Beaty Sheets led a large cast who attended to our every need, scheduled or unscheduled. We also appreciate the support of the NRAO Recreation Association, which cosponsored the evening of mountain music and tall tales. And, of course, we thank the participants for contributing their thoughts, researches, ideas, reactions, and hard work to make the workshop a success.

— *The Editors*

List of Participants

M. Ali Alpar, University of Illinois at Urbana-Champaign
James H. Applegate, California Institute of Technology
Donald C. Backer, University of California, Berkeley
Rino Bandiera, European Southern Observatory
Valentin Boriakoff, Cornell University
Kenneth Brecher, Boston University
Rosolino Buccheri, Istituto de Fisica Cosmica e Informatica (Palermo)
Blaise Canzian, Arecibo Observatory
Gary Chanan, Columbia University
Ganesar Chanmugam, Louisiana State University
Roger A. Chevalier, University of Virginia
Andrew F. Cheng, Johns Hopkins University
James M. Cordes, Cornell University
Nicolo D'Amico, University of Palermo
Michael M. Davis, Arecibo Observatory
Rachel Dewey, Princeton University
Francesco Fauci, University of Palermo
J. Richard Fisher, National Radio Astronomy Observatory
Janusz Gil, National Radio Astronomy Observatory
W. Miller Goss, National Radio Astronomy Observatory
Tor Hagfors, Cornell University
Timothy Hankins, Dartmouth College
Alice Kust Harding, NASA-Goddard Space Flight Center
Carl E. Heiles, University of California, Berkeley
James N. Imamura, Los Alamos National Laboratory
Shrinivas Kulkarni, University of California, Berkeley
Thomas Loredo, Massachusetts Institute of Technology
Andrew G. Lyne, Nuffield Radio Astronomy Laboratories
Richard N. Manchester, CSIRO
Patrick McDermott, University of Rochester
Ramesh Narayan, California Institute of Technology
L. Nowakowski, Dartmouth College
Ludwig Oster, National Science Foundation
David Pines, University of Illinois
Mike Proszynski, Space Telescope Science Institute
V. Radhakrishnan, Raman Research Institute
Lloyd Rawley, Princeton University
Stephen P. Reynolds, National Radio Astronomy Observatory
Malvin A. Ruderman, Columbia University
Ronald Schorn, Sky and Telescope
David Segelstein, Princeton University
Jacob Shaham, Columbia University
Mary Stevens, University of California, Berkeley
Daniel R. Stinebring, National Radio Astronomy Observatory
Grant Stokes, Princeton University
G. Stollman, University of Amsterdam
Joseph H. Taylor, Jr., Princeton University
Joel E. Tohline, Louisiana State University
Edward P.J. van den Heuvel, University of Amsterdam
Hugh M. Van Horn, University of Rochester
Joel M. Weisberg, Princeton University
Dan Werthimer, University of California, Berkeley
Alex Wolszczan, Arecibo Observatory

I. INTRODUCTION; OBSERVATIONS OF MILLISECOND PULSARS

AN INTRODUCTION TO MILLISECOND PULSARS

D. C. Backer
Radio Astronomy Laboratory and Astronomy Department
University of California, Berkeley

Basic Parameters

In late 1982 we discovered a pulsar, 1937+214, which has the fastest known rotation period, 1.558 milliseconds (3). Pulse arrival-time measurements clearly show that the spindown is 1.1×10^{-19} s/s, the lowest yet observed (4,16). These parameters indicate a surface magnetic dipole field of 5×10^{8} G and a time scale for period evolution of 4×10^{8} yrs. The distance to 1937+214 has been determined to be 5 kpc based on the interstellar electron column density which disperses the pulsar signal, and the neutral hydrogen column density which absorbs the signal (12). Its galactocentric distance is then 8.4 kpc, and it is located 40 pc below the plane. The proper motion is within the reach of pulse timing measurements, but has yet to be determined. There is no convincing evidence for electromagnetic radiation from the pulsar or from its close environs at any wavelength outside the radio window (9,17,18, 29).

How Does One Make a Fast Pulsar with a Weak Magnetic Field ?

The period, the period derivative, the distance and the absence of a supernova remnant or synchrotron nebula for 1937+214 did not create extreme difficulties for existing theories of magnetized neutron stars (2). The rotation is just beyond the limit where neutron stars are unstable to the production of gravitational waves for a wide range of equations of state (11,24). The fast rotation more than makes up for the small magnetic field in creating a potential drop in the open field region that can generate e-/e+ pairs and accelerate them to produce radio emission. The radio luminosity is a small fraction of the spindown luminosity. Any supernova remains from the neutron star formation could have dissipated in a small fraction of the spindown time scale. Estimates of blackbody radiation from the neutron star (29) and of synchrotron nebula emission from the environs (2) are below current detection limits.

The primary question raised by the discovery of 1937+214 concerns the origin of a fast, low-field pulsar (1,2,21). Two avenues have been explored based on acceptance or rejection of the assumption that all neutron stars have a surface dipole field in excess of 10^{12} G at birth, or develop this field strength as a consequence of electrical currents generated in the cooling star (6). Acceptance leads to a binary origin scenario wherein field decay in the primary neutron star is followed first by angular momentum accretion from the evolving secondary, and then by (cool) coalescence of the two stars (22,28). Origin issues will be discussed more fully in the course of this workshop.

How Does a Millisecond Pulsar Pulse?

The radio emission from 1937+214 is concentrated in two 15 degree beams spaced by 174 degrees of rotational longitude (3,8,16,25,26). The angular width of these beams scales with a low power of the radio frequency, 15° $\nu^{-.37}$; ν is the radio frequency in GHz (8). The spectrum of the radio emission is approximately 10 mJy ν^{-2} between 30 MHz and 2.4 GHz (3,10). Observations in 1982 and 1983 with broad band interferometry show a 50 % decrease in the intensity at 1400 MHz; this could be the result of slow scintillation recently discussed by Rickett and Coles (30). These parameters of the radio emission are surprisingly similar to those of the slower pulsars. The similarity is not expected in models where the beaming is defined by the open field zone of oblique dipole field (5,8). The open field zone has a minimum width of 21 (65) degrees for a perpendicular (aligned) rotator with period of 1.6 ms and at a radius of 10 km. These widths increase both for closure of the magnetosphere inside the light cylinder and for emission at radii greater than 10 km. The pulse width for 1937+214 is less than the minimum width, in sharp contrast to the typical radio pulsar whose width is greater than the minimum.

In pulsars with periods P near 1 s the beam widths are 15 ° for the objects that display 2-(or 3-) component profiles. This pulse morphology indicates that we view the full width of the emission zone in the hollow-cone model for pulsar emission. This value is an order of magnitude larger than the minimum width of the open field zone. The easy explanation is some combination of emission at altitudes above 10 km, and a magnetosphere which closes inside the light cylinder. Pulsars with the multicomponent morphology display a period dependence to their widths of 15 ° $P^{-0.35}$ (5). This differs from the $P^{-0.5}$ dependence that would result from the decreasing size of the light cylinder. The difference could result from a period dependence of the altitude of emission; viz., 1500 km $P^{0.3}$. The relationship for millisecond periods is somewhat more complicated since the predicted angles are no longer small. The widths for aligned and perpendicular rotators θ_a and θ_p, respectively, are defined in equations (1) and (2) below.

$$\tan(\theta_a/2) = 1.5 \frac{(k\ r)^{0.5}(1 - k\ r)^{0.5}}{(1 - 1.5\ k\ r)} \qquad (1)$$

$$\sin(\theta p/2) = 0.494\ (k\ r)^{0.5} \qquad (2)$$

where $k = 2\ \pi /\ P\ v$
v = highest rotational velocity of closed magnetosphere
r = radius at which radio emission arises

My conclusion from these remarks is that the sharp pulses from 1937+214 result from an emission process that is distinct from the dipole-axis beaming that works so well in explaining the slow pulsar pulse morphology. This conclusion is strengthened by the analagous sharp pulses in the Crab radio pulsar, the main pulse and interpulse. These pulses are unique in having high energy counterparts. The sharp increase of the pulse width below 430 MHz seen by Cordes and Stinebring suggests that further low frequency investigations could lead to important clues concerning the emission mechanism in 1937+214 (8).

What Is the Galactic Population of Millisecond Pulsars ?

General surveys of the Galaxy for pulsars have had a period cutoff around 60 ms. This limit resulted from the data handling difficulties associated with faster sampling and analysis, and the 'known' period distribution. New surveys have been started and will be reported on during this meeting. What can we learn from the discovery of the 1.6 and 6.1 ms pulsars ?

The discovery of 1937+214 was triggered by the curious combination of strong interplanetary scintillation (IPS), low galactic latitude and steep intensity spectrum for the catalog object 4C21.53 (3,10,20). The 4C instrument would have bypassed 1937+214 had it not been for the coincidental arrangement of 3 unrelated objects of comparable strength in two of the 4C interferometer lobes. Any one of the sources would not have been above the 4C intensity threshold. If 1937+214 had been isolated on the sky, we might not be here today ! On the other hand, if we had come across 1937+214 as an isolated IPS object, we might have been here three years ago ! The first observations which isolated 1937+214 from the confusion in 4C21.53 showed that it displayed IPS, had a steep spectrum, was highly polarized, and displayed interstellar scintillation. These observations then suggest several continuum source paths to the discovery of further millisecond pulsar candidates. A number of authors will discuss these approaches this week.

The firmest limit on the galactic population of millisecond pulsars comes from the discovery of the 6.1-ms binary pulsar (7). Several authors have proposed that the companion is a low mass white dwarf (14,19,23). The observations leading to this discovery covered approximately 5 square degrees in the direction of COS-B gamma ray sources with 430-MHz, milliJansky sensitivity out to periods of 4 ms. If the pulsar and gamma ray object are unrelated, then the 6.1-ms pulsar is the first millisecond pulsar to be discovered in a general search. We will hear more about this search from Boriakoff.

What Time Is It?

The rotation of 1937+214 is extremely stable, and, in fact, may be the most stable long-term oscillator known. The source of this stability is rapid, and near frictionless rotation of a stellar mass. The rotational Q of this oscillator, $2\pi/$ Pdot, is 6.6×10^{19}. The rotational energy, 8×10^{51} erg/s, is comparable to the entire mechanical energy output of a supernova. However we observe the object through microwave beams that remove only 10^{31} ergs/s. An additional 10^{36} ergs/s is being removed by particle acceleration and low frequency radiation; this is comparable to the energy loss rate of the Vela pulsar. The electromagnetic torque associated with the latter energy loss produces the slow decay of the period.

A Maclaurin spheroid with rotation period of 1.6 ms and uniform density of 10^{15} gm cm^{-3} has an ellipticity of 0.38, and an equatorial to polar radius ratio, y, of 0.92. The period decay then leads to a equilibrium figure adjustment of

$$\Delta r/r = 2\,(1 - y^2)\,\delta P/P, \qquad (4)$$

$$= 6.5 \times 10^{-10}\ yr^{-1}.$$

This amounts to 3 microns per year in the middle of the neutron star. For comparison the typical neutron spacing is 10^{-9} microns. The 1.6-ms pulsar may adjust its figure to new equilibrium values either by slow creep or by rare starquakes that occur when sufficient strain has built up. The stress buildup rate is proportional to ΩΩdot which is not small for 1937+214 in comparison to other pulsars:

Pulsar	ΩΩdot(s^{-3})	Timing noise
Crab	1.2×10^{-08}	Yes !!
Vela	1.8×10^{-10}	Yes !!
1237+25	3.6×10^{-16}	The quietest measured
1937+214	2.8×10^{-11}	None observed
1913+16	4.3×10^{-14}	None observed

Although the first 18 months of timing data from 1937+214 are 'quiet', we will not be surprised if a 'glitch' occurs in the coming years.

Accurate arrival-time measurements have been made at the Arecibo Observatory since late 1982 (4,5). The passage of a pulse peak through the center of curvature of the Arecibo reflector is the 'event' whose time we can determine on the observatory atomic standard. The poorly calibrated (relatively !!) observatory standard is calibrated against a more precise atomic time standard kept by the US Naval Observatory, or other standards lab. Determination of the stability of the neutron star rotation requires correction of the atomic-time-scale, pulse-arrival events for the effects of the moving Earth. Atomic time is a proper time for Earthlings, and must be corrected with great precision to the coordinate time of a fictitious observer in uniform motion with respect to the pulsar and in a constant gravitational field. This correction results from the integrated effects of gravitational redshift and transverse Doppler; verification of these corrections provides an independent test of the strong equivalence principle and special relativity, respectively. Propagation delays through the interstellar ionized plasma and through the solar gravitational field must be removed; the verification of the latter term provides new data to test the weak effects of general relativity in our solar system. Finally the arrival time at the observatory fiducial point must be corrected to that at the solar system barycenter with an accurate ephemeris of the Earth's motion. After 18 months of observation the accuracies of the individual two-minute measurements, the observatory atomic time calibration, the USNO atomic time scale, the Earth ephemeris predictions, and, possibly, the interstellar path correction are all comparable and equal to 1 μs, or 300 m.

There is no evidence for a binary companion to the 1.6 millisecond pulsar --no rock around the clock. Origin scenarios involving coalescence have suggested that a 'rock' might be left in orbit at the present moment (22). Our microsecond level of residuals place a limit of 2 x 10^{26} gm on a companion with an orbital period of 1 day; the limit scales with the inverse of the period.

The arrival-time measurements can be used to determine the proper motion and, possibly, the parallax of 1937+214. We will hear further report on this from Davis. The interstellar scintillation parameters indicate a peculiar velocity of about 100 km/s (4,15). Differential galactic rotation will lead to a proper motion of 125 km/s with the following components:

$$\mu_l = Ro \; [\; \omega(R) - \omega(R_o)] \cos(l) - r \; \omega(R) \qquad (3)$$

where l = galactic longitude
R_o = Sun - galactic center distance
R = PSR - galactic center distance
r = Sun - PSR distance
$\omega(R)$ = rotation curve of galaxy.

Conversion of μ_l to μ_α and μ_δ requires the PA of the galactic plane. This can be computed from

$$\cos(PA) = \cos(\delta_{NGP}) \frac{\sin(\alpha - \alpha_{NGP})}{\cos(b)} \qquad (4)$$

where δ_{NGP} = 27.4°
α_{NGP} = 12h49m
α = RA of source
b = galactic latitude of source.

Beware of signs! For 1937+214 the above lead to

$$\mu_\alpha = -2.5 \text{ marcsec/yr} \qquad (5)$$
$$\mu_\delta = -4.3 \text{ marcsec/yr.}$$

One exciting prospect for the future of timing of one, or more, millisecond pulsars is the detection of a cosmological background of gravitational waves. Detection would parallel the discovery of the 3K microwave background. Recent estimates of gravitational wave production by 'strings' which formed during the inflationary phase of the Universe are within the reach of accurate timing of 1937+214 over the next few years (13).

Bibliography (selected)

1 Alpar, M. A. et al. 1982, Nature, 300, 728.
2 Arons, J. 1983, Nature, 302, 301.
3 Backer, D. C., et al. 1982, Nature, 300, 615 [1.6 ms pulsar].
4 Backer, D. C., et al. 1983, Nature, 301, 314.
5 Backer, D. C. 1984, J. Astron. Astrophys., in press.
6 Blandford, R. D., et al. 1983, MNRAS, 204, 1025.
7 Boriakoff, V., et al. 1983, Nature, 304, 417 [6.1 ms pulsar].
8 Cordes, J. M., and Stinebring, D. 1984, Ap. J. (Lett.), 277, L53.
9 Djorgovski, G. 1982, Nature, 300, 618.
10 Erickson, W. E. 1983, Ap. J. (Lett.), 264, 5.
11 Freidman, J. L. 1983, Phys. Rev. Lett., 51, 11.
12 Heiles, C., et al. 1983, Ap. J. (Lett.), 273, L75 [HI absorption].
13 Hogan, C., and Rees, M. 1984, preprint.
14 Joss, P. C., and Rappaport, S. A. 1983, Nature, 304, 419.
15 Lyne, A. G., and Smith, F. G. 1982, Nature, 298, 825.
16 Ashworth, M. et al. 1983, Nature, 301, 313.
17 Marshall, F., and Grindlay, J. E. 1983, APS Meeting, Baltimore.
18 Middleditch, J., et al. 1983, Nature, 306, 163.
19 Paczynski, B. 1983, Nature, 304, 421.
20 Purvis, A. 1983, MNRAS, 202, 605.
21 Radhakrishnan, V. 1982, Contemp. Phys., 23, 207.
22 Ruderman, M. A., and Shaham, J. 1983, 304, 425.
23 Savonije, M. V. 1983, Nature, 304, 422.
24 Shapiro, S. L. et al. 1983, Ap. J., 272, 702.
25 Stinebring, D. R. 1983, Nature, 302, 690.
26 Stinebring, D. R., and Cordes, J. M. 1983, Nature, 306, 349.
27 Taylor, J. H., and Weisberg, J. 1982, Ap. J., 253, 908.
28 Van den Heuvel, E. P. J. 1984, J. Astron. Astrophys., in press.
29 Becker, R. H., and Helfand, D. J. 1983, Nature, 302, 688.
30 Rickett, B. J., and Coles, W. A. 1984, preprint.

DISCUSSION OF BACKER'S PAPER

TAYLOR: I was struck as you were speaking, Don, by the casualness with which we've all come to accept the existence of millisecond pulsars; even you as one of the principals involved--it certainly was a discovery that shook us all to our guts, I think.

STINEBRING: I wondered if any of the gravitational effects on the timing have the possibility of doing better than the timing of the binary pulsar 1913+16, over the long haul.

BACKER: With regard to the cosmological background--the noise--we're looking for a coherent gravitational wave--the better timing accuracy will lead to better measurements by many orders of magnitude. But in terms of the gravitational wave system from the binary, that's a confirmed detection of the effects of the gravitational waves that is not something we're going to get from 1937+21.

BUCCHERI: You gave the period value very precisely, up to 10 decimal places. This is perhaps a good possibility to search for gamma-rays from the COS-B satellite, because we need this kind of precision to search for pulsations in gamma-rays. But I would like to ask about the precise epoch.

BACKER: The timing will be talked about in the next talk.

TAYLOR: One potential problem is that the epoch of gamma-ray observations is substantially before any of the radio data; we'd have to sit down and do some sums. I'm not certain whether the extrapolation over two or three years or more of missing data is going to be good enough. It may well be.

BUCCHERI: In general it is impossible, but with this precision it may be possible.

BACKER: We certainly have worked harder on timing this pulsar than many others so the precision is very much higher.

CHENG: I'm not sure this is the right place to ask this question -

TAYLOR: It's the wrong place to cut off discussion.

CHENG: About your discussion of the average pulse profile: How do you fit in pulsars which apparently have more than three components?

BACKER: This is a little detailed. The pairs of the outer components in 1237+25 are in this model some bifurcation of the hollow cone. Because the properties of the radiation from the pairs of outer components in 1237+25 are so similar...

CHENG: You're going to have to do the mode changes--even the abnormal modes [...] they all kind of change.

BACKER: Well, abnormal modes I don't understand. That's not my department. Seriously, in the abnormal modes something entirely different is going on, in the structure of the zone at the star--It doesn't fit in. That's where the real structure of the particle flow in the open field zones is required.

TAYLOR: Perhaps one of the biggest embarrassments to those of us who have been thinking about and working on pulsars since 1968 is that we still don't understand what's going on in the emission region. That's the simple truth--as you well know.--In some ways, when you look at the pulse profile, polarization, and other things, 1937+21 is just a garden-variety pulsar; if you didn't know that the time scale differed by two orders of magnitude, you would not think anything is especially out of the ordinary when looking at its wave shape. But as a clock it is especially different, and astonishing in its regularity. Mike Davis is going to tell us about the timing behavior of this object.

Since this page was unintentionally left blank, the editors will use the opportunity to thank:

Don Backer

Shri Kulkarni

Carl Heiles

Mike Davis

Miller Goss

for bringing millisecond pulsars to light.

Arrival Time Observations of the Millisecond Pulsar 1937+21

Michael M. Davis
Arecibo Observatory*

Joseph H. Taylor, Joel M. Weisberg
Princeton University

Donald C. Backer
University of California at Berkeley

ABSTRACT

The period, period derivative and celestial coordinates of the 1.6 millisecond pulsar have been derived from eighteen months of Arecibo timing observations. The pulsar has proven to be an extremely accurate and stable clock. Residuals are presently about one microsecond, but improvements in the timing technique may provide an order of magnitude improvement. Even at the present level of accuracy, continued timing of the pulsar can contribute significantly to improved solar system ephemerides, and will provide cosmologically important data on the energy density of long wavelength gravitational radiation from the early universe.

INTRODUCTION

The 1.6 millisecond pulsar 1937+214 proved very early on to be an extremely accurate, highly predictable clock (Backer, Kulkarni and Taylor 1983). Pulse counting was established within the first few days of observations, so that we have, for the last eighteen months, been able to number each consecutive pulse unambiguously as it comes by. Each pulse you heard on the tape recording played by Don Backer had a pulse number associated with it, beginning at zero in November, 1982 and running consecutively up to the present time.

* Arecibo Observatory is part of the National Astronomy and Ionosphere Center operated by Cornell University under contract with the National Science Foundation.

OBSERVING PROCEDURE

Right after the discovery Joe Taylor shipped the binary pulsar timing equipment (Taylor and Weisberg 1982) to Arecibo. Figure 1 shows a simplified block diagram of that equipment. We were able to benefit immediately from the many years of development work that went into the binary pulsar timing procedure.

We observe for about two and a half hours every two to three weeks, using a 1408 MHz center frequency with a bandpass of 8 MHz. Dedispersion is done using a 2X32 channel filter bank having 250 KHz filter widths and spacings, together with Val Boriakoff's digital dedisperser. The output is fed to a signal averager, which accumulates an average profile for two minutes and then writes it on tape. The two minute averages typically have a signal to noise ratio in excess of 100 to 1. A very nice feature of this self-contained timing system is that you can have the new solution for period, period derivative and celestial coordinates within an hour of the last observation of the day, together with a tabulation and plot of the residuals.

A typical day's run, from last April 27th, is shown in figure 2. One problem that we saw very early on is the correlated, slowly drifting residuals which are obvious in the figure. We are not properly receiver noise limited. We think we know the origin of this. We are approximating the dispersion by a linear delay across the 8 MHz passband. A combination of the neglected quadratic term coupled with variations in the effective frequency of the incoming signal caused by interstellar scintillation can give us errors at this one microsecond level. We are working on removing this source of error. If we are successful, the receiver noise alone should permit a timing accuracy of order 0.1 microsecond for a two-hour run.

DATA ANALYSIS AND RESULTS

The next step in the analysis of arrival times is a correction to the earth-moon barycenter and then to the solar system barycenter. For this we have to have an excellent ephemeris. The total geometric delay across the earth's orbit is a thousand million microseconds, and we need to know it to one microsecond or better. In addition, comparison with terrestrial clocks requires an accurate conversion from proper time to coordinate time.

The results shown below in Table 1 are based on a very recent version of the CfA ephemeris (John Chandler, private communication). This version is not yet final; in particular, the right ascension zero point is not yet set. The errors quoted are five times the formal internal standard deviations.

TABLE 1

TIMING PARAMETERS FOR 1937+214

Right Ascension	$(19^h\ 37^m\ 28.78459^s)^*$ ±4	+ 1.1 mas/yr ±0.9
Declination	$(21°\ 28'\ 01.279'')^*$ ±2	+ 0.7 mas/yr ±2.1
Period	1.557 806 448 873 7 msec ±6	
Period Derivative	1.0508×10^{-19} s/s ±3	
Epoch	JD 2 445 303.273 165 8	
Data	29 NOV 82 - 13 JUL 84	
Pulse Periods Elapsed	32 802 959 235	

* Preliminary ephemeris; coordinate system rotation not final. The present offset is ~0.6" E.

The fit uses half-hour averages of the pulse profile. Post-fit residuals are shown in figure 3. The standard deviation is slightly less than 0.9 microseconds.

APPLICATION OF THE TIMING RESULTS

To put the pulsar timing in perspective, figure 4 is an Allan Variance plot showing the log of the fractional frequency stability for various types of clocks versus the elapsed time of the measurement. The banks of cesium clocks used by the Naval Observatory and other national timekeeping services typically bottom out after a year or so around one microsecond. Therefore at the present time the pulsar timing is competitive in accuracy.

In response to Dan Stinebring's question about what we can do about relativity, cosmology and gravitational radiation, figure 5 is a plot of the upper limits which have been placed on the energy density of gravitational radiation (Romani and Taylor 1983, Hellings and Downs 1983). In this application, the distance to the pulsar is monitored very accurately by the timing observations. Any differential "buffeting" of the pulsar or the earth by long-wavelength gravitational radiation will show up as variations in the time of arrival. If the millisecond pulsar timing fails to show such stochastic variations over the next few years, this will establish very severe constraints on the amount of energy contained in long wavelength gravitational radiation.

We plan to eliminate many of the known sources of error in the timing within the next few months. Lloyd Rawley, working with Joe Taylor, is constructing a bank of signal averagers, one for each filter channel, which will permit proper amplitude-dependent weighting and precise correction for dispersion. In cooperation with the National Bureau of Standards, we will install a GPS satellite receiver at the Observatory in September, to improve time transfer accuracy to about twenty nanoseconds. Variation in the dispersion measure may become evident at the tenth of a microsecond level. For that reason a parallel program of observations is being carried out by Jim Cordes and his colleagues to provide very accurate monitoring of the dispersion measure, using timing measurements at widely spaced frequencies.

In summary, we anticipate about a factor of ten improvement in the timing accuracy within the next few months. However, the results to date already show that the pulsar is an extremely accurate and reliable clock.

REFERENCES

Backer, D.C., Kulkarni, S.R., and Taylor, J.H. 1983, Nature, 301, 314.

Hellings, R.W., and Downs, G.S. 1983, Astrophys. J. (Letters), 265, L39.

Romani, R.W., and Taylor, J.H. 1983, Astrophys. J. (letters), 265,L35.

Taylor, J.H., and Weisberg, J.M. 1982, Astrophys. J., 253, 908.

Editorial Note: The results presented at the workshop were based on the old Lincoln Lab PEP 311 ephemeris, whereas those presented above use a recent, preliminary CfA version. In addition, an accurate numerical integration replaces an analytic approximation to the difference between atomic time and coordinate time. The systematic sinusoidal variation in the residuals apparent in the earlier fit have now disappeared.

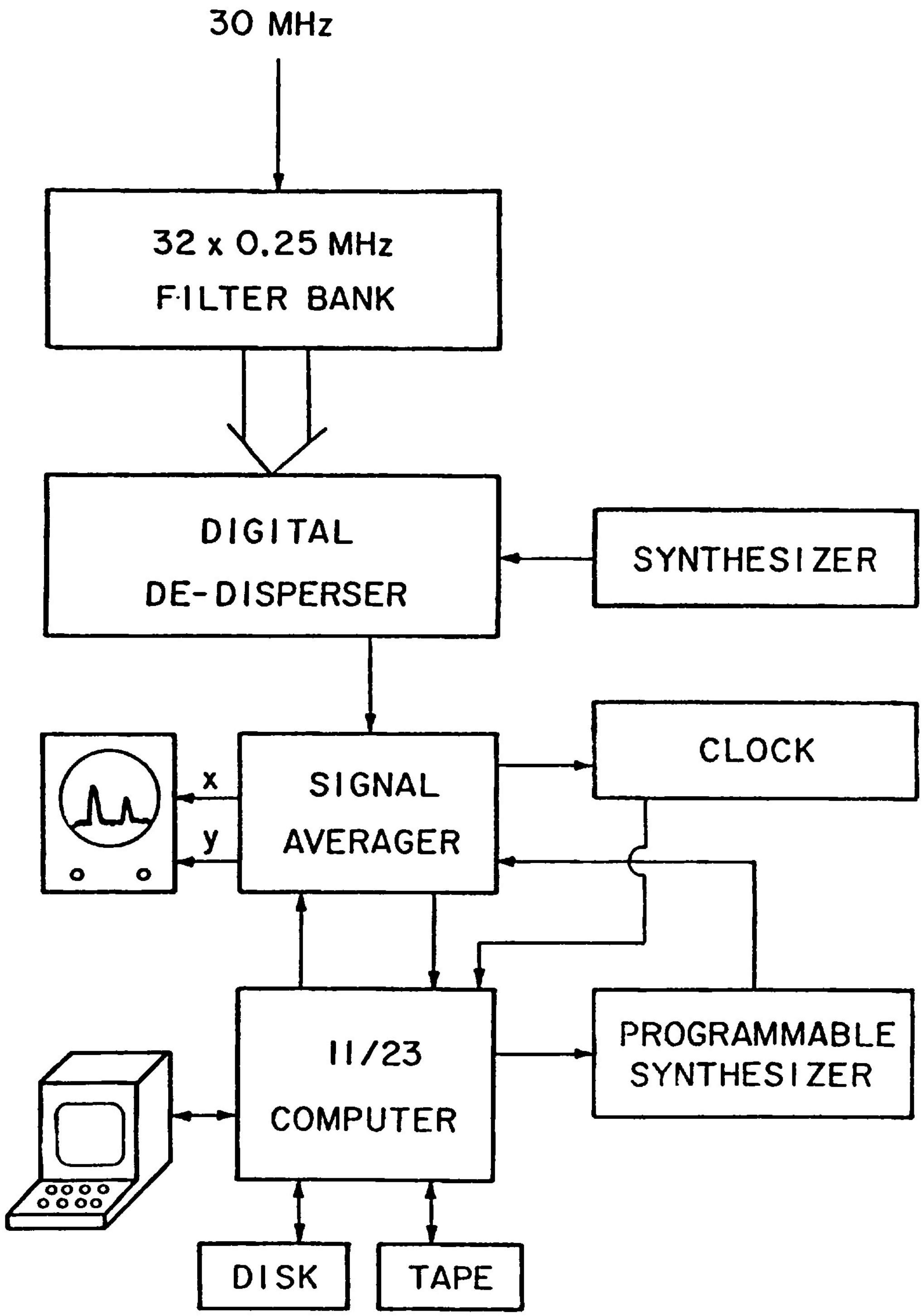


Figure 1. Block diagram of the pulsar timing equipment. This is the same equipment used in timing the binary pulsar 1913+16.

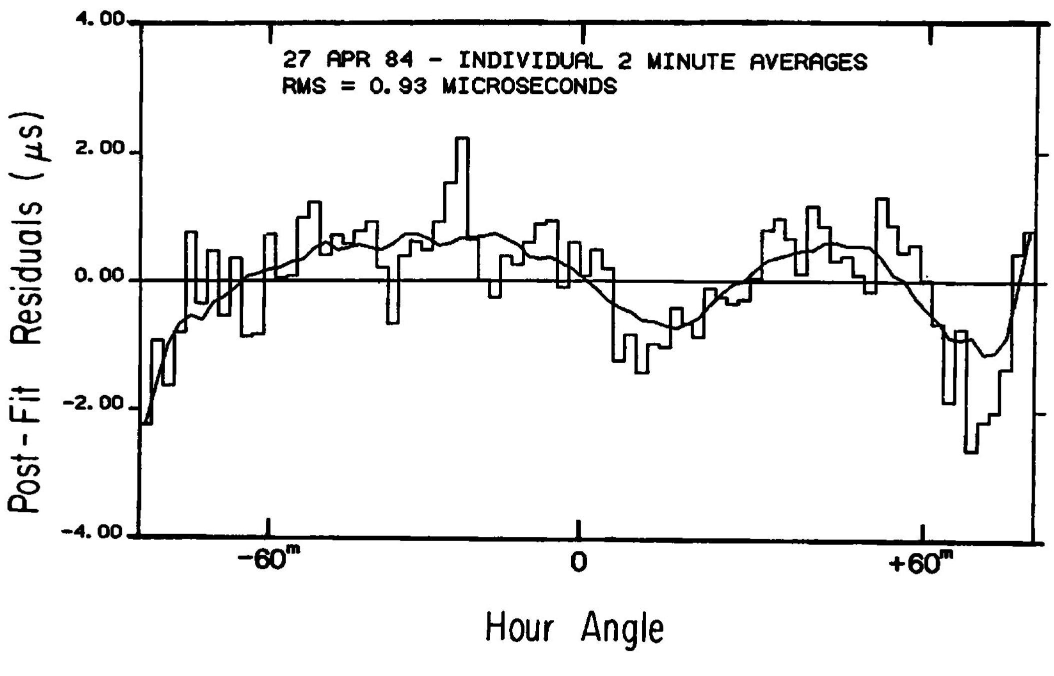


Figure 2. Residuals for the timing run of 27 April 1984. The independent two-minute averages are shown together with a smooth line representing a twenty-minute running average.

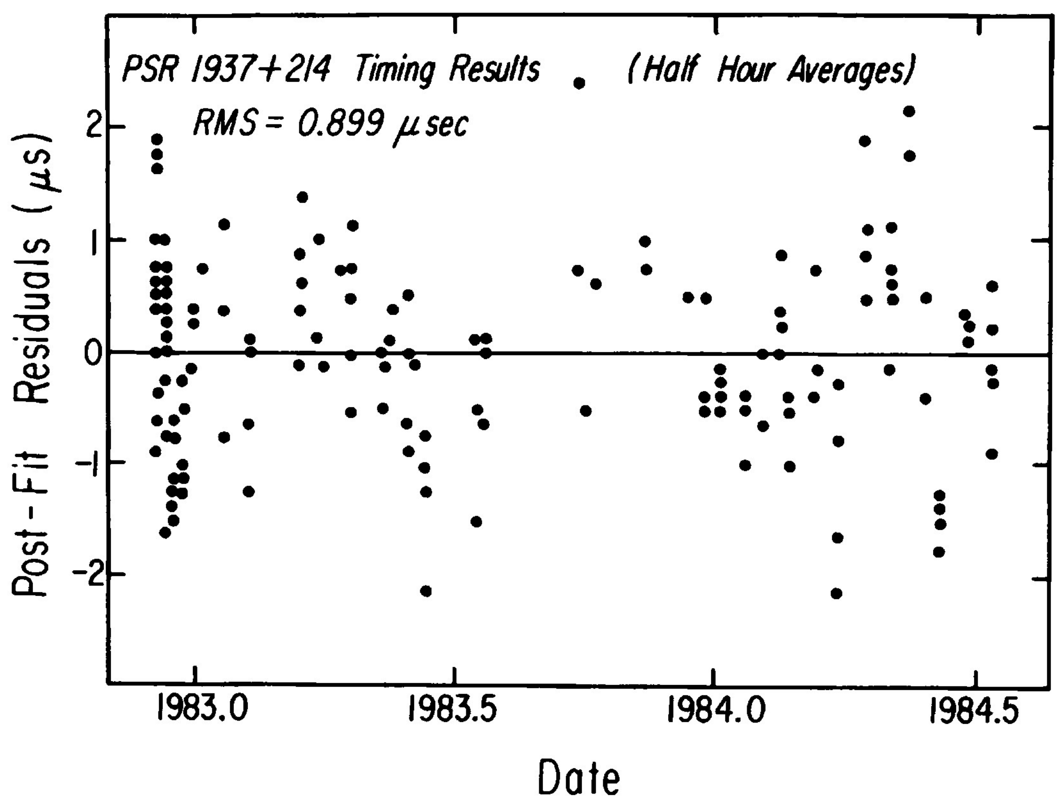


Figure 3. Post-fit residuals for the entire 18-month data set, using a new ephemeris from CfA. Each data point represents 30 minutes of observing time. The last twelve points on the right do not yet include final Loran-C corrections.

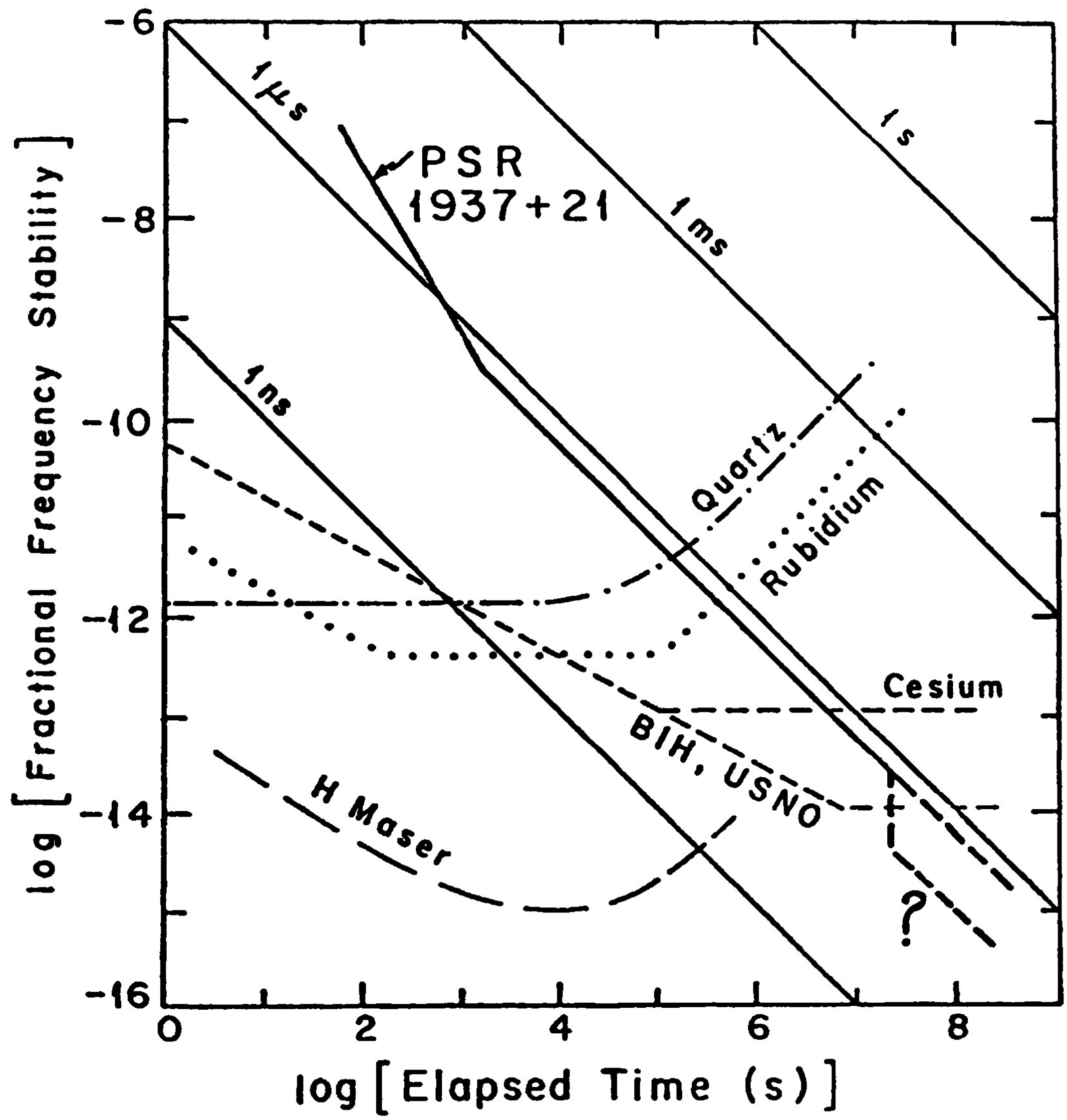


Figure 4. Comparison of the fractional frequency stabilities of various types of clocks, as a function of elapsed time. Performance that should be attainable with the proposed improvements is indicated by the broken-line extrapolation.

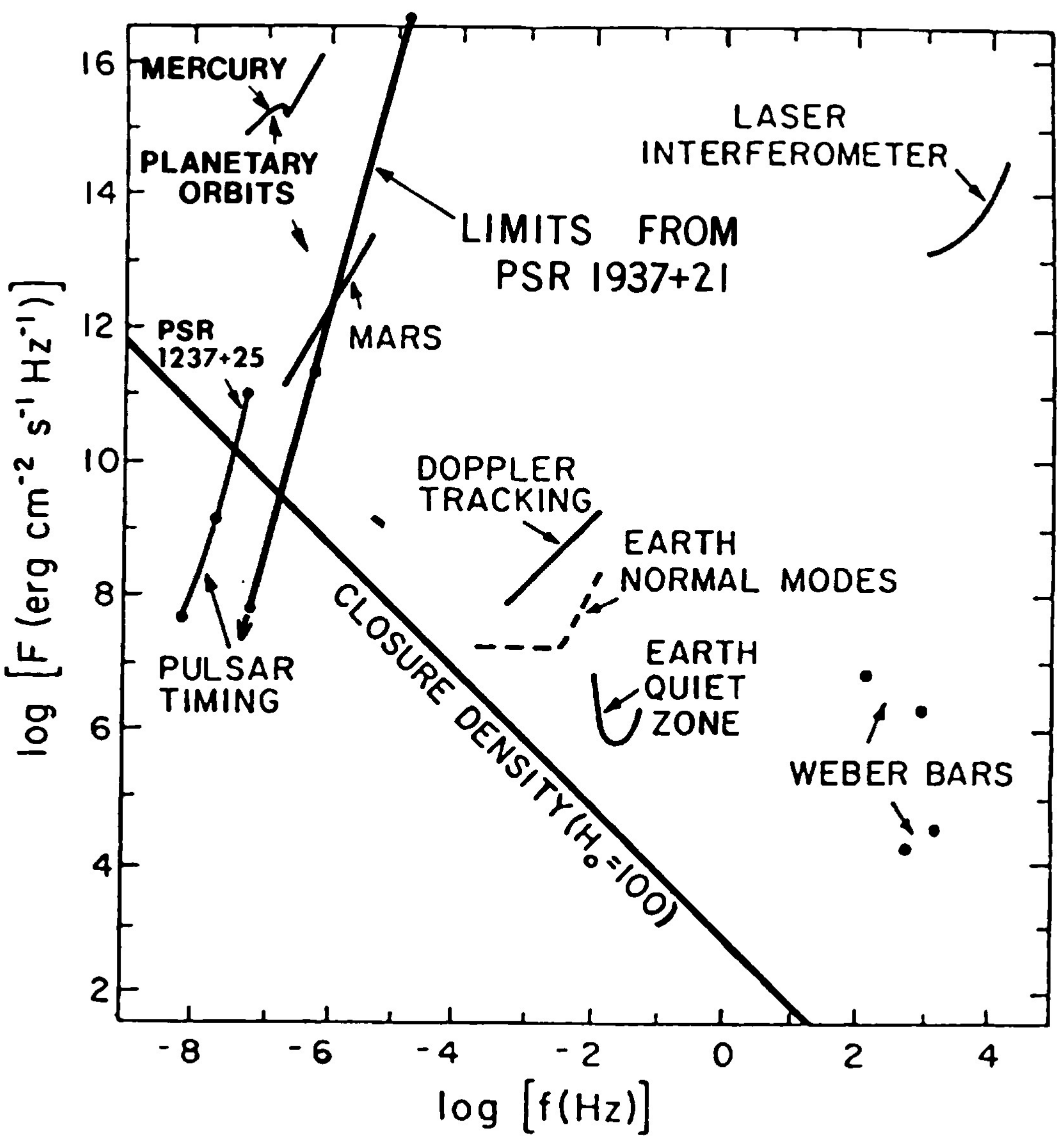


Figure 5. Experimental limits on the isotropic flux density of stochastic gravitational radiation in the universe (from Romani and Taylor 1983).

DISCUSSION OF DAVIS'S PAPER

[unidentified]: Do you have a plot of the spectrum of timing noise?

DAVIS: I guess that plot that showed the seven or eight tenths of a microsecond rms is the best indicator. If it turns out that the filter bank--the bank of signal averagers--does not make that coordinated noise go away, I don't know what we'd do then; but I think that's probably the best number to use right now.

TAYLOR: On that Allen--variance plot that you put other pulsars for which there are all kinds of data--they are typically a few orders of magnitude above us in there. First it starts to come down, then it eventually turns up, and that's the timing noise. All we can say is that present observations haven't identified that turning point, that presumably exists at some level.

GOSS: Mike, how does your position compare with the VLA position, which is known with such precision?

DAVIS: The last I looked, I thought they agreed within the errors. The VLA position of course is an equatorial position, and the timing position is an ecliptic position. There are uncertainties in the transformation from one system to the other. But my feeling at the moment is, if I recall correctly, that it's relatively close to agreement.

STINEBRING: Until someone else finds some more millisecond pulsars, or some other pulsars that are such good timers, how do you expect to get below the 1 microsecond clock-bank variance that seems to be a problem? You talked about a hundred nanoseconds. Is there any way to get below that? I mean, you need a better clock in order to time this one, don't you?

DAVIS: A bank of pulsars is clearly the answer. Failing that, a cesium bank is the answer, and the way it's used that may be true.

TAYLOR: I think the way to look at it is that we're comparing the best estimates we have of pulsar time and atomic time. If they disagree, all we can say is they disagree. We don't know which one is wrong--and until you can build a larger bank of atomic clocks, or have other equally timeable pulsars to referee the disagreements, there is no way to tell.

FISHER: Is there a 220-day term in the ephemeris equations anywhere? That must be quite a clue.

DAVIS: Just to throw this out to confuse the issue, the orbit of Venus is certainly within the errors.

KULKARNI: I was just wondering: you put this rock around the clock...

DAVIS: Backer put the rock around the clock, let's get that straight.

KULKARNI: I haven't worked it out but one possibility is this K giant near the radio position. It could be a binary, and perhaps what you're seeing is a small modulated delay in the changing gravitational field.

TAYLOR: You realize that this is being recorded.

DAVIS: I like that.--Actually, I think that's too small for a solar-mass type binary, even being only a few arc-seconds from the line of sight.

KULKARNI: You mean the predicted effect is too small.

DAVIS: I think it requires incredibly precise alignment along the line of sight.

THE 6.1 MILLISECOND BINARY PULSAR

V. Boriakoff
National Astronomy & Ionosphere Center, Ithaca, NY

R. Buccheri
Istituto di Fisica Cosmica e Informatica, Palermo, Italy

F. Fauci
University of Palermo, Italy

K. Turner

M. M. Davis
National Astronomy & Ionosphere Center, Arecibo, PR

ABSTRACT

The 6.1 millisecond binary pulsar P1953+29 has been studied for approximately one year. This represents slightly over three cycles of the 117.3 day orbital period. Results of timing and other experiments in progress is presented. The results of some optical counterpart searches is also presented.

A continuing radio search for fast pulsars that were counterparts of the point gamma-ray sources identified by the European satellite COS-B (listed, for example, in Swanenburg et al, 1981) was started in 1980. Observations were done with the 305 meter radiotelescope at Arecibo, PR, with sampling rates of up to 0.5 milliseconds. A description of the search is done elsewhere in this volume. The 6.1 millisecond period binary pulsar P1953+29 was discovered within the error box of the gamma-ray source 2CG065+00. A set of initial parameters, a preliminary VLA map and some considerations were presented in Boriakoff, Buccheri and Fauci, 1983 (hereafter BBF). Since April 1983, monitoring of the pulsar parameters has been carried out with one observation approximately every two weeks. With the 117.3 day orbital period this means that we have data for somewhat more than three orbits.

1. Pulse morphology

The 430 MHz pulse profile (template) used for processing timing data is shown in Figure 1.

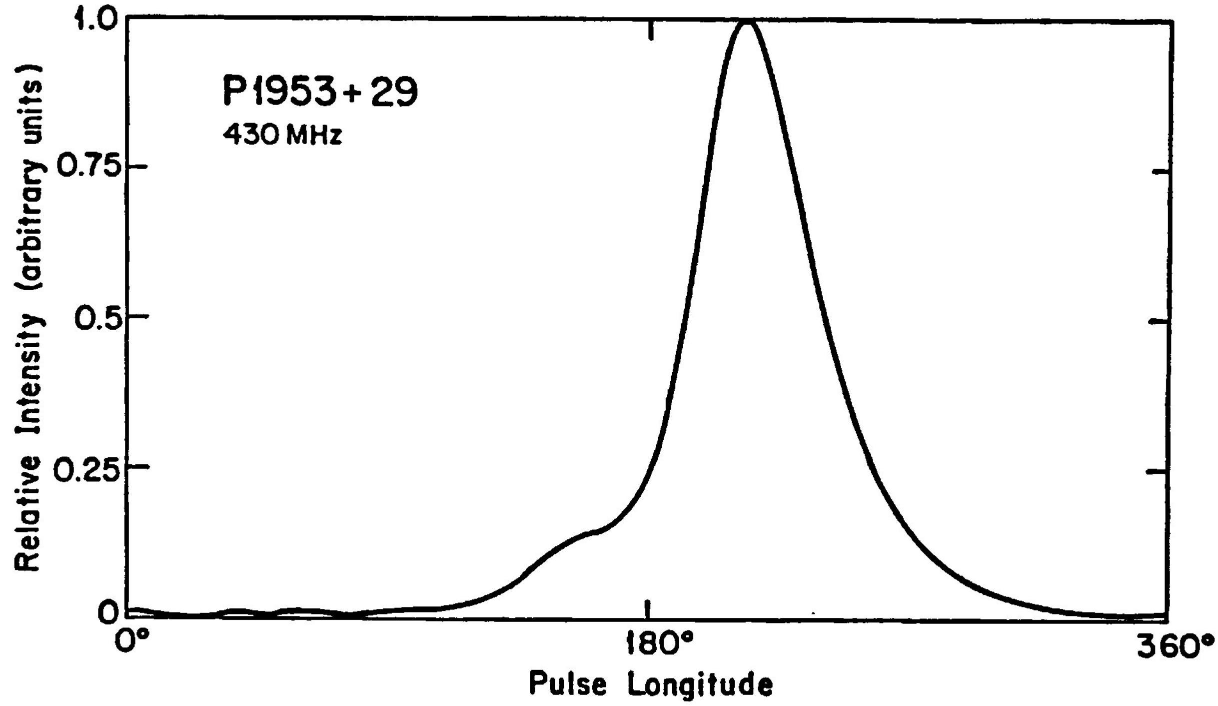


Figure 1. P1953+29 average pulse profile at 430 MHz (2,496,000 pulses, one circular polarization, 20 microsec sampling, post-detection dedispersion of a 31 x 20 KHz filter bank output, dispersion delay in one filter = 220 microsec, time constant = 140 microsec).

It is the result of averaging of 2,496,000 pulses with a dedispersed bandwidth of 620 KHz. To be noticed is the absence of a feature that could be identified as an interpulse, which seemed a possibility in BBF. Another noticeable feature is the extent of the emission vs. longitude: it is at least 130 degrees longitude to 0.1 of the peak value, but radiation can be seen to baseline 6 sigma in something like 200 degrees. Polarization properties are presented in another paper of this volume. Two peaks are clearly visible; they match components observed at other radio frequencies but clearly different components have different spectral indices. The spectral index of the total energy of the pulse is relatively large: 2.3. The strong peak seen in 430 MHz has a substantially steeper spectrum than the other two components seen in 1385 MHz (BBF).

2. Timing

The fitting of timing parameters to the pulse frequency as derived from the time-of-arrival observations has provided the pulse and orbital parameters listed in Table 1. The initial fit covers the April 1983 to May 1984 period, and was done assuming a purely circular orbit. Figure 2 plots the observed and fitted pulse frequencies vs. the modified JD.

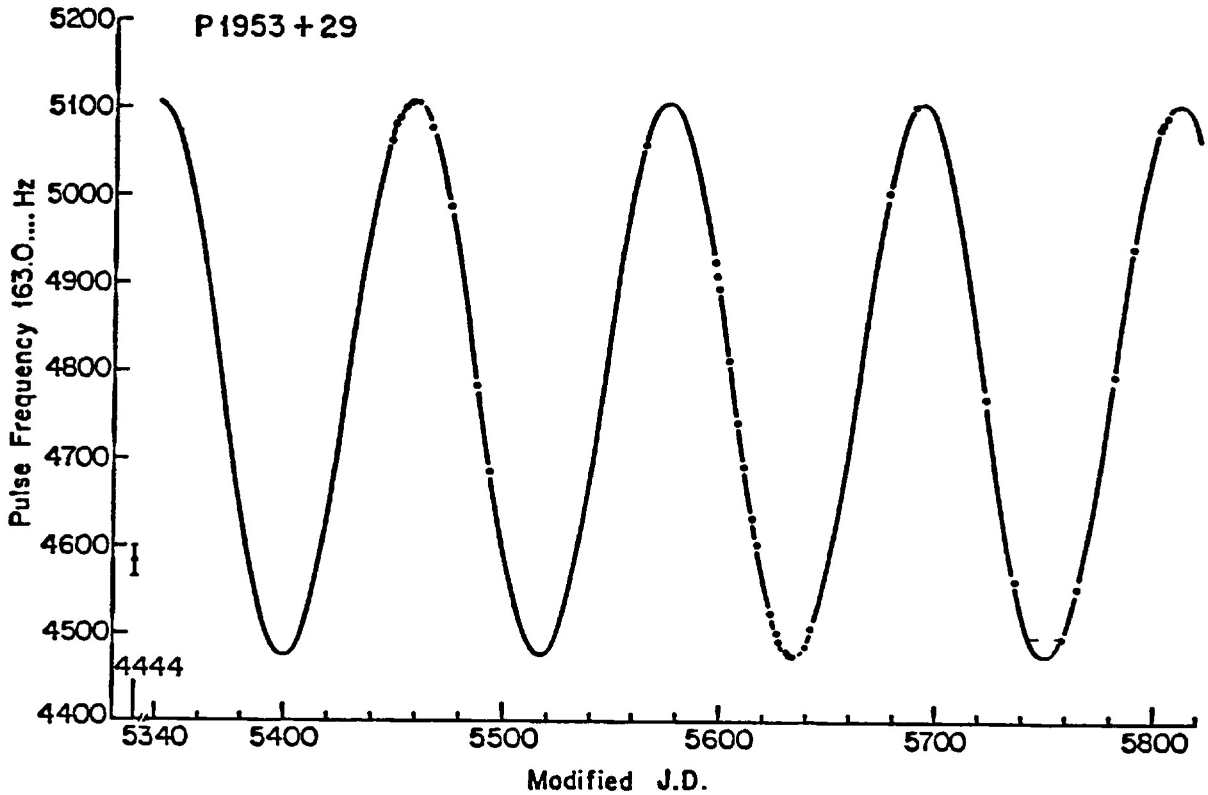


Figure 2. Observed and fitted pulse frequencies of P1953+29. Purely circular orbit is assumed. The error bars for all the observations (except the 1980 one, mJD = 4444) are smaller than the indicated dots.

The extrapolation of the pulse frequency with these pulse and orbital parameters to the initial search observation in July 1980 predicts a frequency that turns out to be the same as the observed 1980 value. This would mean a $\dot{P}$ of zero. To obtain a more realistic upper limit to the $\dot{P}$ value we assumed that the pulse frequency in 1980 was that of the upper end of the error bar of that observation, with this assumption we obtained the $\dot{P}$ value of 4.2 x 10 exp (-17) sec/sec. Fitting with orbital parameters for an elliptical orbit has decreased the chi-square of the fit only slightly, indicating that the orbit is circular, or very nearly circular

Of course, fitting pulse frequency does not provide a very accurate method for the determination of the pulse and orbital parameters. A substantially more accurate method is the fitting of the individual pulse arrival times. Computations using the PEP311 MIT ephemeris and its more up-to-date versions are now in progress.

The more precise determination of the orbital parameter implies a more accurate determination of the mass function. The relationship between the pulsar mass, the companion mass and cos(i) (i is the angle between the orbital plane and the plane of the sky) are shown in Figure 3. From it we see that the most probable mass of the companion is approximately 0.2 solar masses.

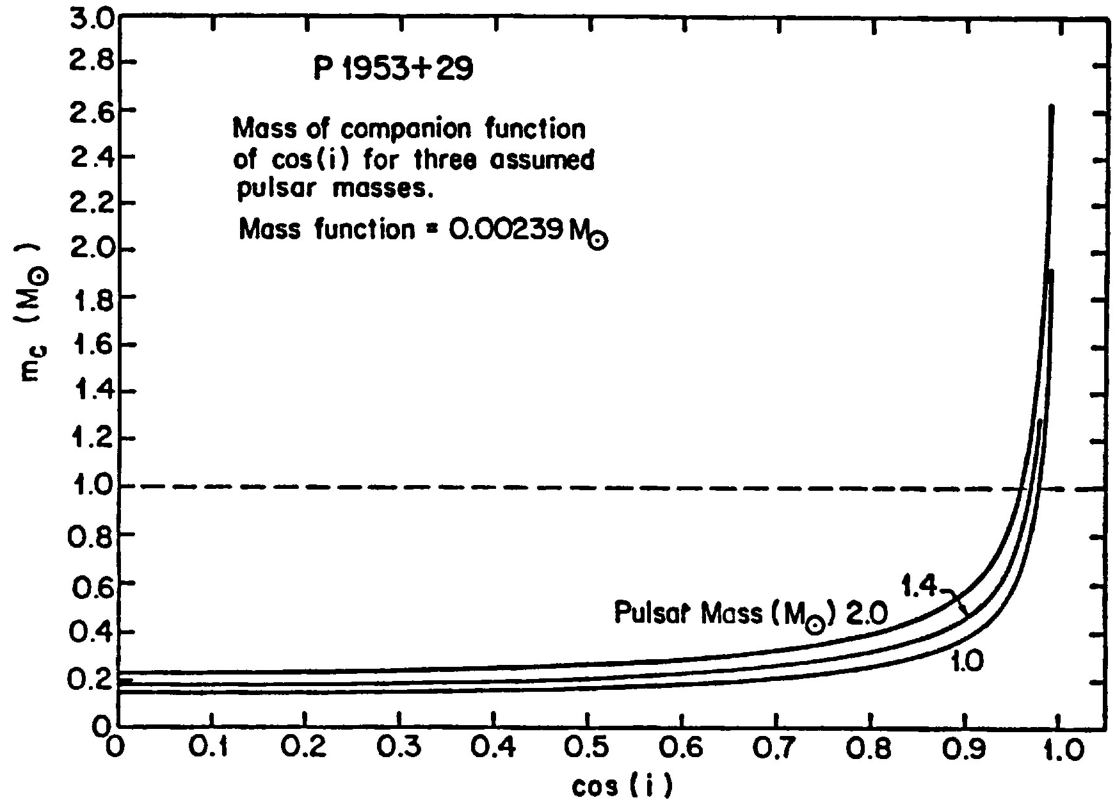


Figure 3.

3. VLA observations and optical searches

Two observations with the VLA of the area surrounding P1953+29 were done. The first one (reported in BBF) showed possible indications of extended emission areas near the pulsar. A second observation carried out in the C configuration at 1465 and 1635 MHz for six hours of integration provides a more accurate position, as noted in Table 1. It is clear from the VLA map that to a flux of 0.1 mJy (equivalent to approximately 10% of the source equivalent continuum flux) there is no extended emission surrounding the pulsar.

The new position makes the identification of the pulsar with optical objects somewhat more definite. Both Pedersen et al (1983) and Djorgovski and Spinrad (1983) have identified two (and perhaps one more) objects within the original VLA error bars. They are tentatively identified as reddened stars, but no spectral information on them is yet available. The new VLA position is located very close to the star designated in Pedersen et al as star 1. It is a 20.1 magnitude (visible) star. Its 1950.0 coordinates are given by Pedersen et al as : RA = 19h 53m 26.71s Dec = 29 deg 00' 43.9", with an error of 0.3 arcsec in both coordinates. The star's position is less than one VLA position sigma (one sigma =

formal fit error multiplied by three) at both 1465 and 1635 MHz. Conversely, both VLA positions are separated from the star's position less than 2 sigma of the star's position error. This makes the case for identification very strong. Pedersen et al have taken very fast sampled data at the Danish 1.5 m telescope at La Silla, Chile, of the three objects inside the old VLA error box, including star 1. That data is being processed in a pulse periodicity search. However, the most likely candidate for the optical star is the radio-invisible companion. A very bright white dwarf (absolute magnitude = 10.2) with no interstellar absorption would be a 22.9 magnitude object. This raises the possibilities that the distance is overestimated, or that the companion star is much brighter; for example, from being in the very early stages after accretion when it is still burning residual hydrogen in the shell (Paczynski 1983). Work on the spectral identification of star 1 is in progress.

4. Identification of P1953+29 with 2CG-65+00

No real identification is possible until the position of the gamma ray source is known to a much higher accuracy and/or enough photons are collected with accurate arrival times to allow meaningful folding profile searches. However, an interesting consideration is to compare the ratio of the gamma ray emitted energy and the energy loss of the pulsar (given by its $\dot{P}$) with the same ratio for the Crab pulsar. As in BBF, we assume for this computation that 2CG065+00 is the gamma-ray counterpart of P1953+29 and that the $\dot{P}$ of P1953+29 is equal to the upper limit estimated here. We also assume that the distance to P1953+29 is 3.5 kpc, and that the beaming factor in gamma rays is the same for both pulsars (= $1/4\pi$). Then:

For the Crab pulsar (P0531+21):

$$\frac{\dot{E}_{\text{gamma rays}}}{\dot{E}_{\text{total}}} = 6.7 \times 10 \exp(-5)$$

For P1953+29:

$$\frac{\dot{E}_{\text{gamma rays}}}{\dot{E}_{\text{total}}} = 90.5 \times 10 \exp(-5)$$

As we see the ratios are not too different; from this argument the possibility of identification cannot be excluded.

The Arecibo Observatory is part of the National Astronomy and Ionosphere Center which is operated by Cornell University under contract with the National Science Foundation. This research has been partially supported by the Italian National Research Council under the Ufficio Relazioni Internazionali.

TABLE 1.

P1953+29 MILLISECOND BINARY PULSAR PARAMETERS

VLA 1465 MHz position (1950.0):	
RA = 19h 53m 26.673 s	Error = 0.054s
Dec = 29deg 00' 44.10"	Error = 0.84"
l = 65.84deg	
b = 0.444deg	
Period: P = 6.133166msec	Error = 0.000005msec on JD = 2445428.66
Period derivative:	$\dot{P} < 4.2 \times 10^{-17}$ sec/sec
Characteristic age:	$P/2\dot{P} > 2.3 \times 10^{6}$ years
Magnetic field:	$B < 1.6 \times 10^{10}$ gauss
Velocity-of-light cylinder radius:	292.6 Km
Projected orbital peak velocity:	Kp = 5.815 Km/sec
Dispersion Measure	DM = 104.5 pc/cm**3
Distance	3.5 Kpc (assuming an average electron density <n> = 0.03)

As a continuum source:

Flux at 1385 MHz:	1.0 mJy	Error = 0.5 mJy
Flux at 430 MHz:	15.0 mJy	Error = 5 mJy
Spectral index:	2.3	Error = +0.8 -0.7
Orbital period:	P_{orb} = 117.3 days	Error = 0.1 day
Eccentricity:	e < 0.01	

If we assume a circular orbit (eccentricity e = 0) then:

Pulsar orbit projected semi-major axis: $(a_p)(\sin(i))$ = 9,830,828 Km = 31.29 light sec

Mass function: $(((m_c)(\sin(i))^{3})/((m_p+m_c)^{2})$ = 0.00239 solar masses

REFERENCES

Boriakoff, V.; Buccheri, R.; Fauci, F.; (BBF) 1983, Nature, 304, 417-418.

Djorgovski, S.; Spinrad, H. 1983, Nature, 306, 569-571.

Paczynski, B. 1983, Nature, 304, 421-422.

Pedersen, H.; Tarenghi, M.; Cristiani, S.; Salvati, M. 1983, Nature, 306, 568-569.

Swanenburg, B.N.; Bennet, K.; Bignami, G. F.; Buccheri, R.; Caraveo, P.; Hermsen, W.; Kanbach, G.; Lichti, C. G.; Masnou, J.L.; Mayer-Hasselwander, H.A.; Paul, J. A.; Sacco, B.; Scarsi, L.; Wills, R.D. 1981, Ap. J. Letters, 243, L69-L73.

DISCUSSION OF BORIAKOFF'S PAPER

VAN DEN HEUVEL: Were these magnitudes corrected for extinction or not? Because these things are right in the galactic plane.

BORIAKOFF: Very little is known about most of the stars in the field. There are no spectra. All the efforts are directed towards periodicities. I think we'll have a little bit more later. But I think that the upper limits for pulsed light emission are 2 to 3% of the light flux.

CHENG: Is there a timing position for the pulsar?

BORIAKOFF: No. We have started counting pulses from day to day, but we don't have final values yet. We are reducing the first thousand arrival times.

TAYLOR: Is there any special reason why that has been more difficult than in other cases?

BORIAKOFF: Not particularly.

NARAYAN: Has the interpulse been confirmed in this pulsar?

BORIAKOFF: No. Most definitely in the 430 MHz pulse profile, you can see to a very high degree that there's nothing. It's possible that at 1400 MHz there might be something because of variable spectral index.

MANCHESTER: What's the separation of the outer components at 1400 MHz?

BORIAKOFF: Its's somewhat less than these two components at 430 MHz. This is, I think, 0.15 of a period. It's about 0.13 at higher frequencies. It decreases its separation with increasing frequency as many classical pulsars do.

TAYLOR: But in fact it is the opposite of the 1913+16 binary, in the sense that the pulse becomes in this case more complex at the higher frequency, rather than simpler.

KULKARNI: Your $\dot{P}$ definitely rules out the gamma-ray source association.

BORIAKOFF: No, it's not definite; because if you compare the amount of energy that the Crab loses as gamma-rays to this case, you are perhaps a factor of 2 less than the Crab right now.

KULKARNI: If you assume all of the energy loss is in gamma-rays, how much is that compared to the COS-B luminosity?

BORIAKOFF: The ratio of the gamma-ray flux to spindown energy loss is 1.5×10^{-5} for the Crab, and it's about twice that for this one.

POLARIMETRY OF THE TWO FASTEST PULSARS

Daniel R. Stinebring

National Radio Astronomy Observatory*

Valentin Boriakoff[1]
James M. Cordes[1,2]
William Deich[1,2]
Alexander Wolszczan[1]

[1]National Astronomy and Ionosphere Center*
and [2]Astronomy Department, Cornell

Abstract

We report recent polarization observations of the millisecond pulsars PSR 1937+214 and PSR 1953+290. The PSR 1937+214 data, obtained at 431 and 1384 MHz, are fully dedispersed and have a time resolution of 4 microseconds. At the higher frequency the main pulse consists of two separate components. At the lower frequency both the main pulse and the interpulse are preceded by emission features; these features have roughly the same amplitude ratio as the main pulse and the interpulse. The interpulse position angle at 431 MHz has a slope and central value almost identical to that of the main pulse. This strongly supports a double-pole model for the interpulse.

The preliminary data we present for PSR 1953+290 show little linear polarization at either 430 or 1400 MHz. Further observations are needed in order to understand the connection between the three pulse components visible at 1400 MHz and the single component present at 430 MHz.

*The National Radio Astronomy Observatory is operated by AUI under contract with the National Science Foundation. The National Astronomy and Ionosphere Center is operated by Cornell University under contract with the National Science Foundation.

Observations

PSR 1937+214 The observations were made with the 305-m telescope at the Arecibo Observatory in April 1984. We used the pre-detection dedispersing technique developed by Hankins and Rickett (1975) and employed in similar observations by Cordes and Stinebring (1984). Improved recording equipment allowed us to record single pulses over a 250 kHz bandwidth with a 20% duty cycle. We will discuss only the average waveform results here. The resultant waveforms have 4 microsecond time resolution and are completely dedispersed. The Stokes parameters were formed in the post-processing from the RHC and LHC signals and their cross-products. The pulse is broadened due to multi-path scattering in the interstellar medium by approximately ≈ 25 microseconds at 431 MHz and insignificantly at 1384 MHz. The parallactic rotation of the feed has not been corrected for, resulting in a depolarization that is estimated to be approximately 10% of the linear polarization at 431 MHz and about 20% at 1384 MHz.

PSR 1953+290 These observations were made at Arecibo in October 1983 using post-detection dedispersion techniques. At 430 MHz the 32-channel filter bank had an individual channel width of 20 kHz, and at 1400 MHz the channel bandwidth was 250 kHz. The dedisperser has been described by Boriakoff (1973). Since this instrument does not dedisperse 4 channels simultaneously, we switched the input to the dedisperser in synchronism with the averaging cycle of the data-taking. Each polarization channel was accumulated for approximately 2 seconds, the data recorded, and the next polarization channel was switched into position. The resulting data were separated into 4 polarization channels and were converted into Stokes parameters using adding polarimetry techniques (Rankin, Campbell, and Spangler 1976; Weisberg, et al., 1980; Stinebring, et al. 1983).

Results

PSR 1937+214 The polarization data at 431 MHz have a much higher signal to noise ratio than previously available data (Stinebring and Cordes 1983). This allows us to follow the position angle swing over a much larger portion of the main pulse and interpulse (see Figure 1). It can be seen that the central value of the position angle in the interpulse is almost identical to that of the main pulse. The two pulses also have nearly the same sign and value of position angle slope (2.4 ± 0.2 deg/deg)

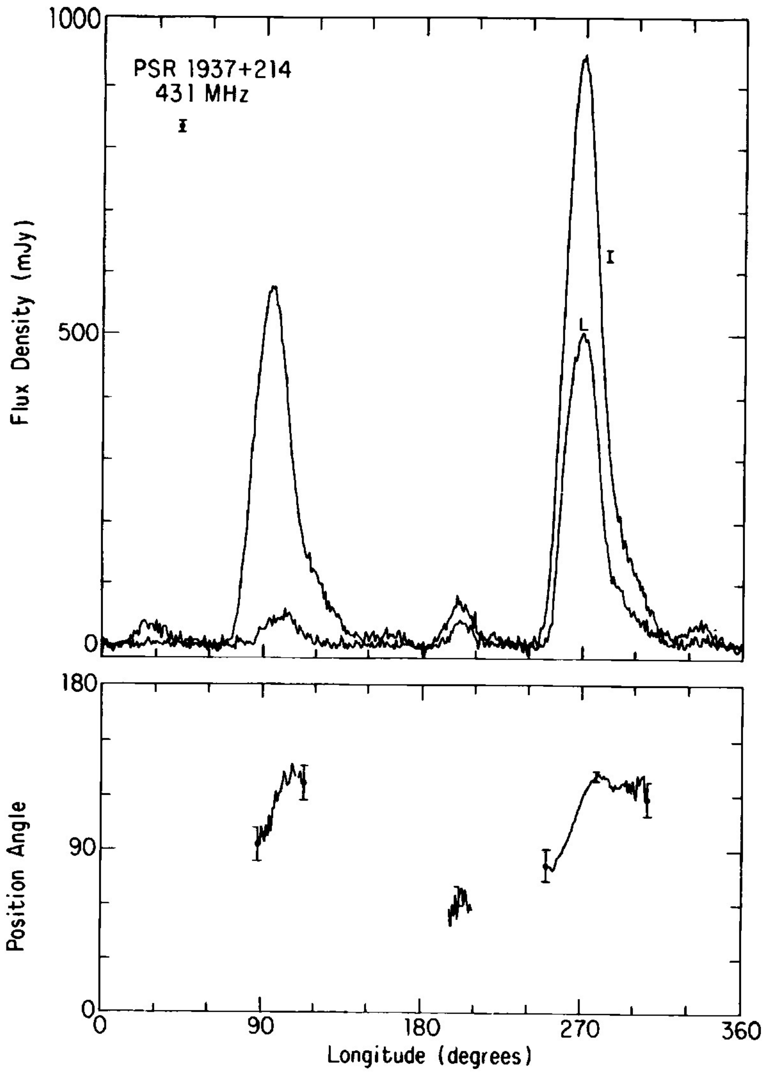


Figure 1. 431 MHz polarization observation of PSR 1937+214. The total intensity, I, and the linear polarization, L, are shown in the upper panel for the full pulse period. The position angle is plotted whenever the linear polarization exceeds 3 times the rms linear polarization fluctuations in the off-pulse region. The flux density scale is approximate and the position angle is not absolute.

A number of other emission features are evident in Figure 1. Although it is possible that these features are an artifact of the data processing, we currently believe that they are real. The two most prominent features precede the main pulse and the interpulse by 70° and have approximately the same pulse energy ratio with respect to each other as do the main pulse and the interpulse. It is difficult to tell whether or not the position angle of the emission feature preceding the main pulse connects smoothly with the main pulse position angle or not. No circular polarization greater than 5% of the total intensity was found.

The high frequency data displayed in Figure 2 show that the shoulder of the main pulse seen in lower-resolution profiles (Stinebring 1983) is a second pulse component. An expanded plot of the main pulse is shown in Figure 3. Both the main pulse and the interpulse show hints of conal emission (Rankin 1983), where we are interpreting the trailing component of the main pulse as the trailing portion of the emission cone. The position angle is continuous across the two components of the main pulse, and the leading edge of the main pulse is sharply depolarized. We can also see that the position angles at the center of the main pulse and the interpulse are separated by about 90°, in agreement with earlier work (Stinebring 1983).

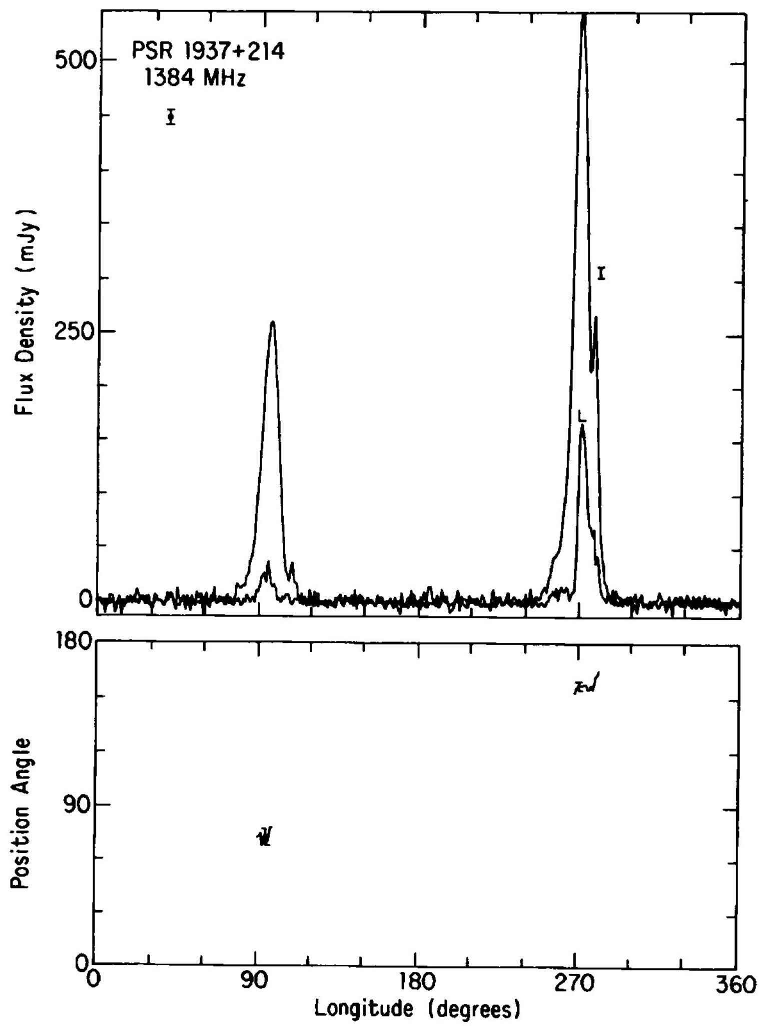


Figure 2 1384 MHz polarization observation of PSR 1937+214. The total intensity, I, and the linear polarization, L, are shown in the upper panel for the full pulse period. The position angle is plotted whenever the linear polarization exceeds 3 times the rms linear polarization fluctuations in the off-pulse region. The flux density scale is approximate and the position angle is not absolute.

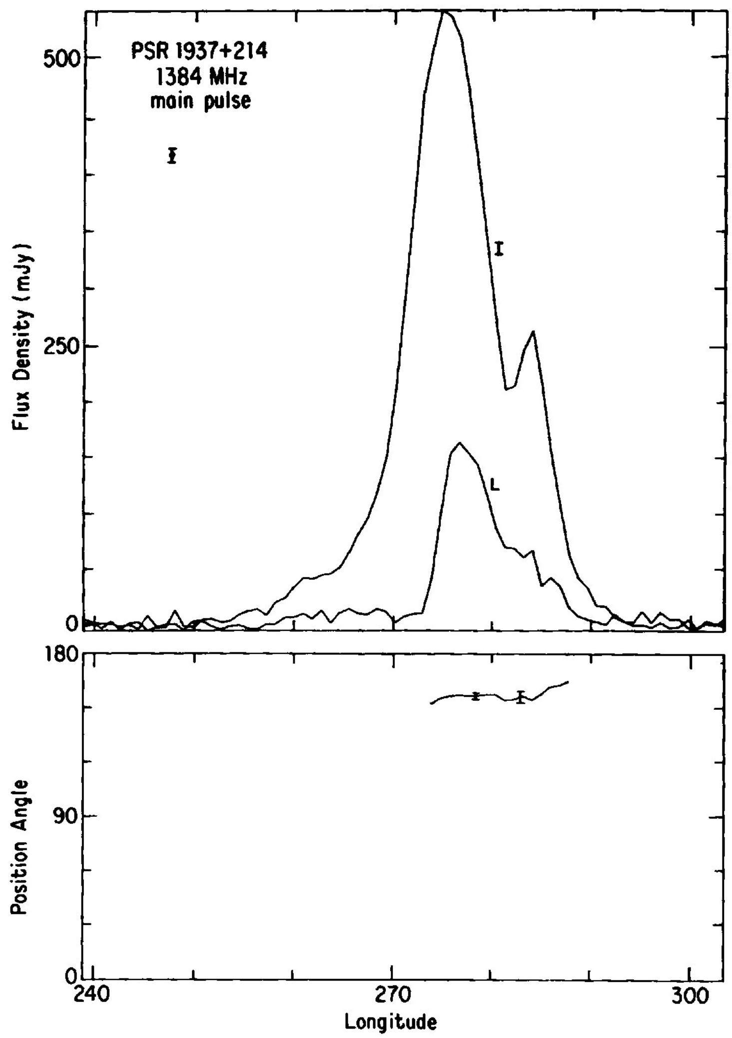


Figure 3. Expanded time scale plot of the data in Figure 2. The component on the trailing edge of the pulse is clearly seen as well as a much weaker analogous component on the leading edge of the pulse. These may two sides of a cone of emission. Notice the sharp depolarization on the leading edge of the pulse, possibly due to the presence of orthogonal polarization modes.

PSR 1953+290 This first look at the polarization properties of the second fastest pulsar shows no significant linear or circular polarization at either frequency (Figures 4 and 5). The total intensity profiles are qualitatively similar with the higher signal to noise ratio data of Boriakoff, et al. (1983). Unfortunately, we have no observations of a reference source to ensure that we accurately measured the polarization, so a confirmation of the lack of polarization is needed. Although probably unrelated to this question, there are non-noiselike features in the data, particularly the "drop-outs" in the low-frequency data, whose source has not yet been determined.

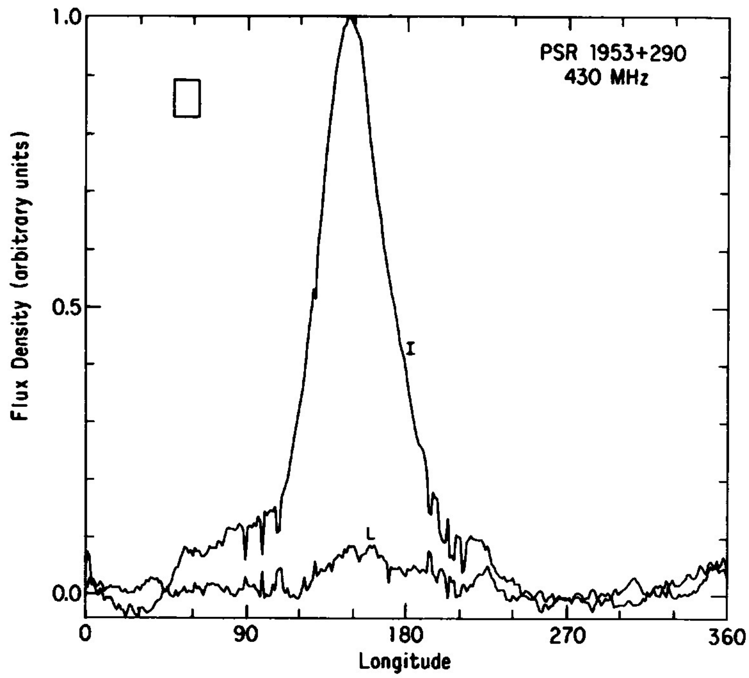
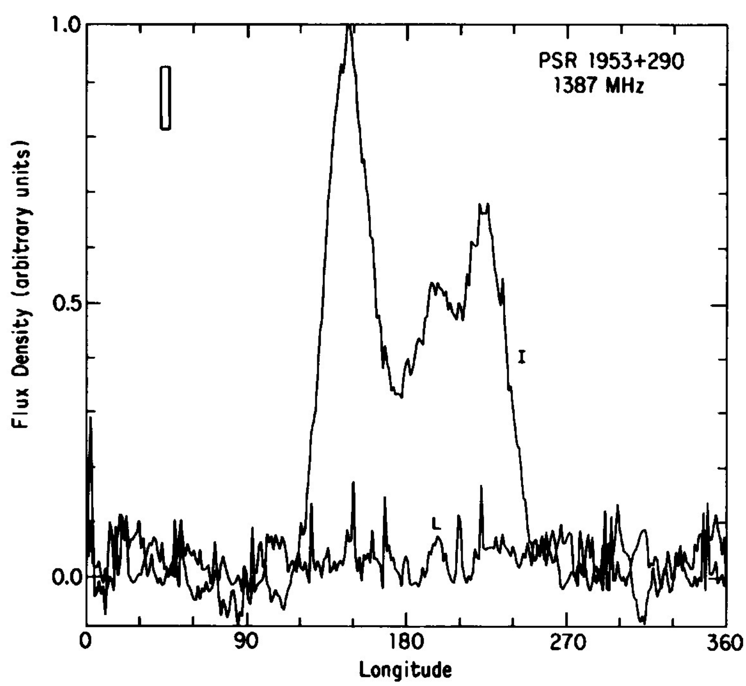


Figure 4 430 MHz polarization observations of PSR 1953+290. The total intensity, I, and the linear polarization, L, are shown across the full pulse period. The circular polarization was less than 5% of the total intensity and is not shown. The "drop-outs" visible on the edges of the pulse are believed to be an artifact of the data processing. The rectangle in the upper left hand corner of the plot indicates the dispersion smearing time and ± 1 sigma error values.

Figure 5 1387 MHz polarization data for PSR 1953+290. Only the total intensity and the linear polarization are plotted. The circular polarization is less than 5% of the total intensity. The rectangle in the upper left hand corner of the plot indicates the dispersion smearing time and the ± 1 sigma error values.



Interpretation

PSR 1937+214 The polarization data lend support to a two-pole interpretation for the interpulse emission. The low-frequency position angle signature is that which would be produced if two magnetic axes swept past our line of sight and our line of sight passed between the magnetic pole and the rotational axis. The presence of additional emission features between the main pulse and interpulse complicates this interpretation. It is possible, however, that these features are portions of extended conal emission associated with the main pulse and interpulse. If this is the case, the low-frequency emission features have a high-frequency counterpart in the conal outriders seen on the edges of the main and interpulse. Although speculative, this interpretation is plausible since an exaggerated flaring of the open field lines is expected in this pulsar. This, in turn, would give rise to a flaring of the conal emission components if low frequencies are emitted significantly further from the star than high frequencies. Multi-frequency timing observations indicate, however, that emission at the two frequencies occurs within a 4 km radial slab (Cordes and Stinebring 1984). See Gil (1984) for an alternate interpretation of these polarization data.

PSR 1953+290 Average polarization observations of pulsars are most useful as an indicator of underlying magnetic field orientation. The absence of polarization in this pulsar leaves us with little additional information about the geometry of the system. Total intensity observations at these two frequencies do not indicate which of the three pulse components seen at high frequency should be identified with the low-frequency peak. Higher signal to noise ratio polarimetry would assist in such an identification. Since its short period and large duty cycle make this an extremely interesting pulsar, further polarization observations are warranted.

We would like to thank Richard Murphy and Phil Perillat of the Arecibo Observatory for assistance with the data-taking programs.

REFERENCES

Boriakoff, V., Buccheri, R., and Fauci, F. 1983, *Nature*, 304, 417.
Boriakoff, V. 1973, NAIC report #38, Cornell University.
Cordes, J. M. and Stinebring, D. R. 1984, *Ap. J.*, 277, L53.
Gil, J. 1984, these proceedings.
Hankins, T. H. and Rickett, B. J. 1975, *Meth. comp. Phys.*, 14, 55.
Rankin, J. M., Campbell, D. B., and Spangler, S. R. 1976, NAIC report #46, Cornell University.
Rankin, J. M. 1983, *Ap. J.*, 274, 333.
Stinebring, D. R. 1983, *Nature*, 302, 690.
Stinebring, D. R. and Cordes, J. M. 1983, *Nature*, 306, 349.
Stinebring, D. R., Cordes, J. M., Rankin, J. M., Weisberg, J. M., and Boriakoff, V. 1984, *Ap. J. Suppl.*, 55, 247.
Weisberg, J. M., Sellgren, K., and Rankin, J. M. 1979, NAIC report #113, Cornell University.

DISCUSSION OF STINEBRING'S PAPER

BORIAKOFF: I would like to comment that the 6 millisecond pulsar also has sporadic strong emission between the main pulses that does not appear in the long term average but does appear in very short averages.

TAYLOR: An interpulse?

BORIAKOFF: No, it's wider. It's essentially a bridge between the two pulses.

STINEBRING: Which you can see in single pulses?

BORIAKOFF: No, you don't see it in single pulses with our present sensitivity. But with short integrations, surely. And it's variable.

HANKINS: It's a little risky to say this with the microphone turned on, but in the one successful observation of the Crab that I have at 6 cm, I see the same thing: two bumps between the main and interpulses, broad bumps, quite strong.

MANCHESTER: On that position-angle business with the main and interpulses on 1937+21, I doubt very much whether you can say that they don't join up given the uncertainty of the extrapolation.

STINEBRING: I think it would at least be fair to say that there's no obvious indication that there's a bridge of emission. If it were a single-pole model I would expect to see a shallower rotation, across the main pulse and interpulse, and see some sort of connection between the two. Even stretching things, I don't see how they can be joined up very convincingly.

BACKER: The flattening out on the end: is that from interstellar scattering? A somewhat similar scattering effect is seen in Vela, isn't it?

STINEBRING: Yes. I should have pointed out that the tail we're seeing here that we haven't removed has the signature of interstellar scattering.

AN OPTICAL SYNCHROTRON NEBULA AROUND THE X-RAY PULSAR 0540-693 IN THE LARGE MAGELLANIC CLOUD

Gary A. Chanan*,+ and David J. Helfand*
Columbia Astrophysics Laboratory

Stephen P. Reynolds†
National Radio Astronomy Observatory

ABSTRACT

We report the discovery of extended optical continuum emission around the recently discovered 50 ms X-ray pulsar in the supernova remnant 0540-693. Exposures in blue and red broadband filters made with the CTIO 4m telescope and prime focus CCD show a center-brightened but clearly extended nebula about 4" in diameter (FWHM), while an image in an [OIII] filter shows an 8" diameter shell (as reported earlier) which encloses the continuum source. The extinction-corrected magnitudes B = 17.5 and I = 16.4 both correspond to flux densities which lie directly on the extrapolation of the observed X-ray power-law spectrum, suggesting that the emission from $10^{14.5}$ Hz to 10^{18} Hz is synchrotron radiation from a single population of particles. Line emission is shown to be only a small contaminant in the broadband images. Thus 0540-693 is a system very similar to the Crab Nebula and represents the second detection of optical synchrotron radiation in a supernova remnant. Any point source component in the central nebula must have B > 20; the Crab pulsar at this distance would have B ≈ 23.

INTRODUCTION

The discovery of a 50 ms X-ray pulsar in the supernova remnant 0540-693 in the Large Magellanic Cloud (Seward, Harnden, and Helfand 1984 [hereafter SHH]) confirms the suggestion of Clark <u>et al.</u> (1982) that this is a Crablike remnant powered by a central pulsar and that the (unpulsed) X-rays represent synchrotron emission. Optical observations of this object are then of immediate importance to test this hypothesis, determine or constrain the range of synchrotron frequencies and hence of injected particle energies, establish the physical size of the nebula, and in general to advance our understanding of particle acceleration by pulsars. In the following we report the results of such observations, which include the unambiguous detection of optical synchrotron radiation from this supernova remnant, only the second example of this phenomenon found to date.

---

*Alfred P. Sloan Foundation Research Fellow

+Visiting astronomer, Cerro Tololo Inter-American Observatory, supported by the National Science Foundation under contract No. AST 78-27879.

†The National Radio Astronomy Observatory is operated by Associated Universities, Inc. under contract to the National Science Foundation.

OBSERVATIONS AND DATA REDUCTION

All observations were made at the prime focus of the CTIO 4m telescope using an RCA CCD detector with 0".6 by 0".6 pixels covering a 3' by 5' field of view. The object was observed in March 1984 in each of three separate filters: a standard B filter, a narrow band [OIII] filter centered at 5000 Å and 70 Å in width, and a "long pass" filter with RG780 response, similar to I. Details of the observations and the data reduction procedures are described in Chanan, Helfand, and Reynolds (1984).

The images in the three filters are shown in Fig. 1a-c. The effective seeing for all these exposures was good; the intensity profiles of stars in the field have FWHM = 1".2 to 1".4. The image in the 5000 Å filter (Fig. 1c) reveals a shell-like structure roughly 8" in diameter, as reported earlier by Mathewson et al. (1980) and shown by them to be due predominantly to the doublet [OIII] λλ4959, 5007. The shell appears brighter to the west and may in fact be broken on the eastern limb. The images in the B and I (Figs. 1a-b) bands both reveal centrally condensed yet clearly extended emission, enclosed by the [OIII] shell but apparently displaced from its center by 1" - 2" to the southwest (see below; cf. SHH).

The fluxes in the B and I bands were determined as described in Chanan, Helfand, and Reynolds (1984). The B flux was corrected for the "leakage" of the strong [OIII] doublet into this filter (a 13% effect). Existing spectra of the object, which evidently did not succeed in detecting the continuum, show that the [OIII] λλ4959,5007 feature is by far the strongest line present so that this is virtually the only line contamination in this band: Mathewson et al. (1980) quote an Hβ/[OIII] ratio of < 1/60, and Dopita (1984) gives the combined strengths of [OIII] λ4363 and the [SII] doublet λλ4068, 4076 (the only lines he detected in the B band) as 5% of the [OIII] doublet. There is no indication of any line contamination in the I band.

Clark et al. (1982) report a hydrogen column density $N_H = 1.8\times10^{21}$ based on the observed X-ray spectrum for this source. (No uncertainty is quoted for this quantity, but based on other observations reported in the same work we adopt ±30% as a representative value). The nominal N_H - A_V relation of Gorenstein (1975) then gives A_V = 0.81 mag, so that extinction is a significant effect, and we adopt this value below, scaling to other wavelength bands as in Allen (1976). The 30% uncertainty in N_H, which translates into a 30% uncertainty in the B flux and a 17% uncertainty in the I flux, is by far the dominant source of error in these latter quantities. The results of the broadband photometry, with and without extinction corrections, are given in Table I. The uncorrected point source limit for this object is B > 20; the Crab pulsar at this distance (and extinction) would have B ≈ V ≈ 23 (see Lynds, Maran, and Trumbo 1969).

The observed luminosity in the [OIII] filter (corrected for the continuum) is 9×10^{34} ergs s^{-1}, intermediate between that of Cas A, 7×10^{36} ergs s^{-1}, (Peimbert and van den Bergh 1971), and W50 (a supernova remnant almost certainly containing a neutron star), 7×10^{30} ergs s^{-1} (Kirshner and Chevalier 1980). Chevalier (1984) has noted that the strong [OIII] emission from this remnant makes the supernova a candidate for iron core collapse, unlike the Crab, which more likely involved collapse of an oxygen-neon-magnesium core.

DISCUSSION

Figure 2 shows east-west slices (west is to the left) through the center of the remnant for each filter; the point response function (in B) is shown for comparison. The profiles have been aligned with respect to a bright star observed in all three filters. For the B and [OIII] filters, slices through both uncorrected and corrected images are shown. The similarity of the B and I images is evident. The corrected B image has a full width at half maximum of 4".2 (or 1.1 pc for an assumed LMC distance of 55 kpc) and a full width at 10% maximum of 7".4 (2.0 pc); all values here and throughout are accurate to about 0.6 pixels or 0".4. The corresponding values for I show no significant differences. By contrast, the [OIII] image clearly shows a broader, limb brightened shape. Note that the bump just to the west of center of the uncorrected [OIII] image is removed by the correction for the underlying continuum, although the latter is based on integrated intensities only. The implication is that this "feature" is due entirely to continuum leak. The corrected [OIII] profile has full widths of 6".9 (1.8 pc) and 9".4 (2.5 pc) at 50% and 10% of maximum intensity, respectively.

The results of the continuum photometry are shown on a log flux density - log frequency plot in Figure 3. Also shown are the power law X-ray spectrum with α = 0.8 (Clark et al. 1982) from the Einstein solid state spectrometer (SSS), and several radio points (Mills, Turtle, and Watkinson 1978; Milne, Caswell, and Haynes 1980), although the latter are likely dominated by larger scale emission. It can be seen that the optical continuum points lie directly on the extrapolation of the X-ray spectrum, so that a single power law with α = 0.8 apparently characterizes the spectrum over 3 1/2 orders of magnitude.

We can see no other reasonable explanation for the apparently continuous power-law spectrum between $\sim 10^{14.5}$ Hz and 10^{18} Hz than that the emission is synchrotron radiation. Thus 0540-693 is the only stellar-scale object beside the Crab Nebula to show extended optical synchrotron radiation. If 0540-693 were located at the Crab distance of 2 kpc, it would have an angular diameter of about 4', quite similar to that of the latter object. The spectral luminosity of the LMC source at 5500 Å is about an order of magnitude weaker, and the spectral index in the optical about a factor of two larger than that of the Crab (see Kirshner 1974 and Wu 1981).

We can draw some straightforward quantitative inferences from the conclusion that the optical and X-ray emission from 0540-693 is synchrotron radiation. First, the observed spectral index of 0.8 implies a power-law distribution of electrons radiating in the optical to X-ray, with $N(E) \propto E^{-2.6}$. Taking a radius for the nebula (at 10% maximum intensity) of 4", or 1 pc, we find an emitting volume of 1×10^{56} cm^3. Standard arguments (see, e.g., Pacholczyk 1970) then give the equipartition magnetic field as 2×10^{-4} gauss, similar to that inferred for the Crab Nebula. The total magnetic and relativistic-electron energy in the nebula is then 1×10^{47} erg, or $\lesssim$ 2% of the pulsar's output integrated over its lifetime of about 1000 years. The electrons which radiate in the optical and X-ray then have energies of order 1 and 70 erg, and synchrotron loss times of 1300 y and 23 y respectively. The optically emitting electrons can thus easily cross the nebula in a loss-time, requiring v/c of only $\lesssim$ 1%. The X-ray emitting electrons, however, probably cannot cross the nebula in a loss-time; if they are injected near the center rather than being accelerated somehow in situ, the X-ray nebula should be smaller than the optical, consistent with the observation that most of the flux in the HRI comes from a region smaller than 4" in size (SHH). The absence of breaks in the spectrum between optical and

X-ray implies that the portion of the electron spectrum responsible is dominated by synchrotron losses, since the loss time is less than the age of the nebula for all but the lowest-energy electrons. The effect of synchrotron losses on a continuously injected distribution of particles is to steepen the injected spectrum by one power, so we infer an injection spectrum of electrons proportional to $E^{-1.6}$, very similar to the distribution responsible for the Crab Nebula's radio emission of $E^{-1.5}$.

A synchrotron origin for the optical and X-ray emission therefore leads to quite reasonable inferences, and the pulsar is easily capable of powering the observed emission with a fraction of its energy output. The conclusion that the optical emission is synchrotron radiation and the measured sizes of the nebula and the surrounding [OIII] shell, together with the parameters of the X-ray pulsar (SHH), can be used to constrain strongly the evolution of the nebula and of the pulsar itself (see Reynolds 1984).

We thank J. A. Tyson and P. Seitzer for many helpful discussions, and F. Seward and R. Harnden for communicating their results prior to publication. Two of us (GAC and DJH) thank the Alfred P. Sloan Foundation for support, and DJH also gratefully acknowledges Air Force Grant AFOSR 82-0014.

REFERENCES

Allen, C.W. 1976, Astrophysical Quantities, 3rd edition, (London: Athlone).
Chanan, G.A., Helfand, D.J., and Reynolds, S.P. 1984, submitted to Ap. J. (Letters).
Chevalier, R.A., 1984, this volume.
Clark, D.H., Tuohy, I.R., Long, K.S., Szymkowiak, A.E., Dopita, M.A., Mathewson, D.S. and Culhane, J.L. 1982, Ap. J., **255**, 440.
Dopita, M.A. 1984, in IAU Sympos. No. 108: Structure and Evolution of the Magellanic Clouds, ed. S. van den Bergh and K.S. de Boer (Dordrecht: Reidel), p. 255.
Gorenstein, P. 1975, Ap. J., **198**, 95.
Kirshner, R.P. and Chevalier, R.A. 1980, Ap. J. (Letters), **242**, L77.
Kirshner, R.P. 1974, Ap. J., **194**, 323.
Lynds, R., Maran, S.P., and Trumbo, D.E. 1969, Ap. J. (Letters), **155**, L121.
Mathewson, D.S., Dopita, M.A., Tuohy, I.R. and Ford, V.L. 1980, Ap. J. (Letters), **242**, L73.
Mills, B.Y. and Turtle, A.J. 1984, in IAU Sympos. No 108: Structure and Evolution of the Magellanic Clouds, ed. S. van den Bergh and K.S. de Boer (Dordrecht: Reidel), p. 283.
Mills, B.Y., Turtle, A.J. and Watkinson, A. 1978, MNRAS, **185**, 263.
Milne, J.K., Caswell, J.L. and Haynes, R.F. 1980, MNRAS, **191**, 469.
Pacholczyk, A.G. 1970, Radio Astrophysics, (San Francisco: Freeman).
Peimbert, M. and van den Bergh, S. 1971, Ap. J., **167**, 223.
Reynolds, S.P. 1984, this volume.
Seward, F.D., Harnden, F.R. and Helfand, D.J. 1984, submitted to Ap. J. (Letters).
Srinivasan, G. and Bhattacharya, D. 1984, Current Science, **53**, 513.
Wu, C.-C. 1981, Ap. J., **245**, 581.

TABLE 1

CONTINUUM OBSERVATIONS OF 0540-693

	B	I
exposure time		
total......................	2000 s	1200 s
individual frames..........	100 s	30 s
effective wavelength...........	4400 Å	7900 Å
without extinction correction		
magnitude..................	$18^{m}.46 \pm 0^{m}.10$	$16^{m}.93 \pm 0^{m}.09$
flux density...............	0.154±0.015 mJy	0.431±0.039 mJy
point source limit.........	$20^{m}.1$	$18^{m}.8$
with extinction correction		
magnitude..................	$17^{m}.39 \pm 0^{m}.32$	$16^{m}.37 \pm 0^{m}.17$
flux density...............	$0.41^{+0.14}_{-0.10}$ mJy	$0.72^{+0.12}_{-0.10}$ mJy

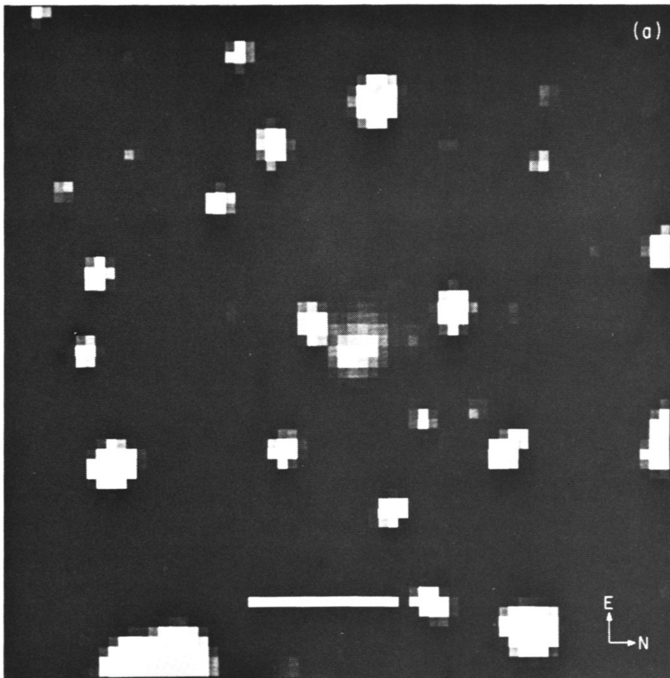
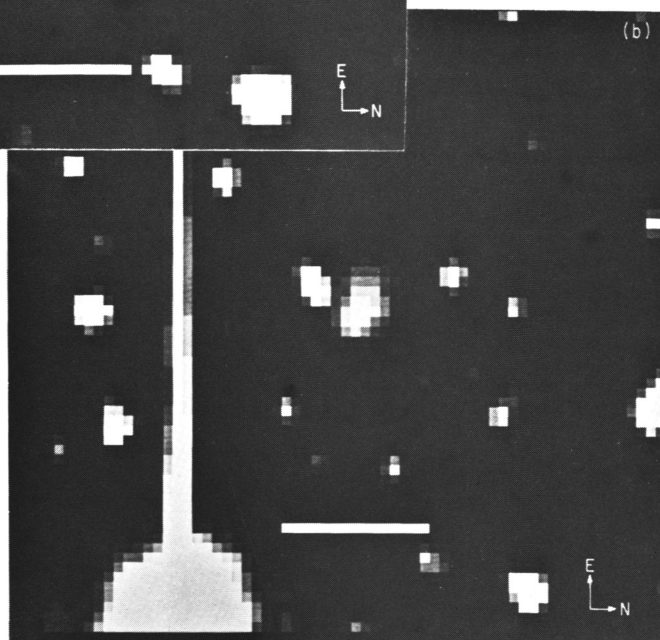


Fig. 1a. CCD image of 0540-693 in B filter. Nebula is center-brightened but non-stellar. The bar is 9" long. North is to the right; east is up.

Fig. 1b. Same as 1a, but in RG780 filter (similar to I band). The spike on the bright star is due to saturation in the CCD.



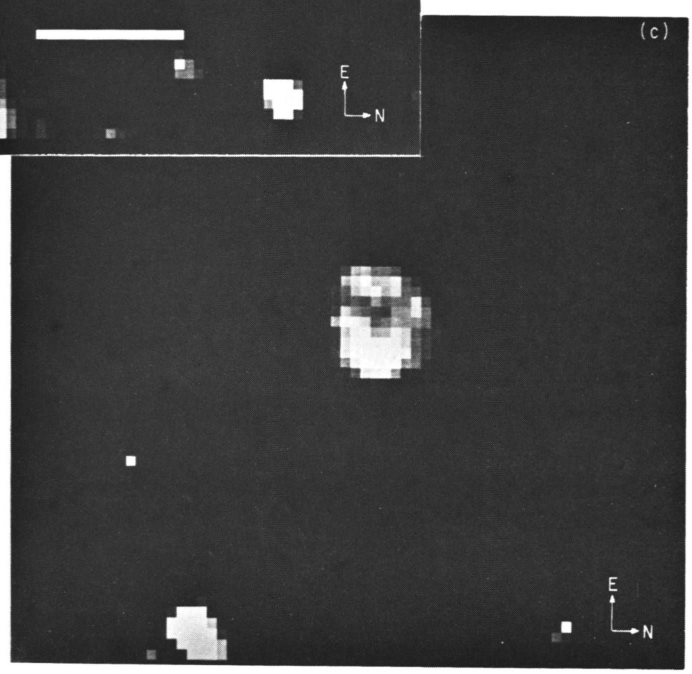
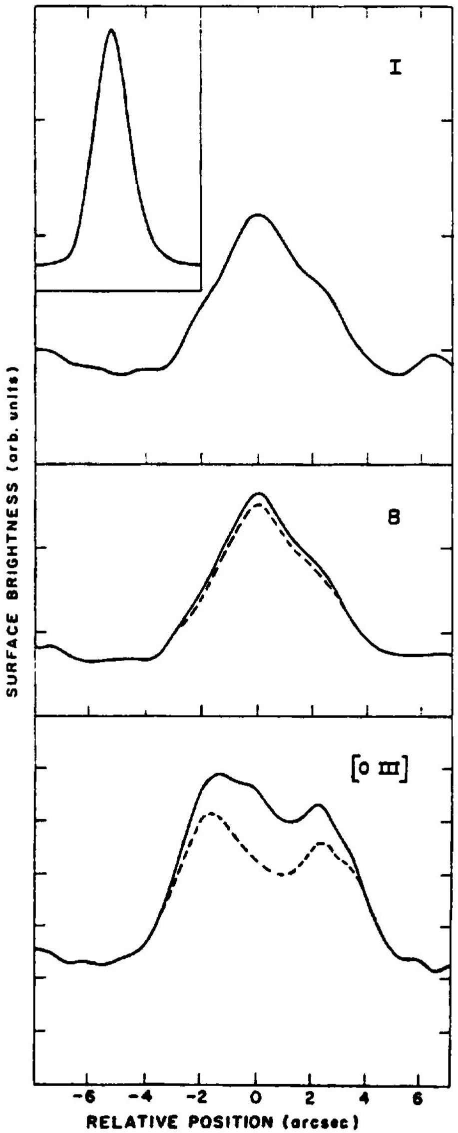


Fig. 1c. Same as 1c, but in narrow filter containing the [OIII] doublet. Note the ring-like structure.



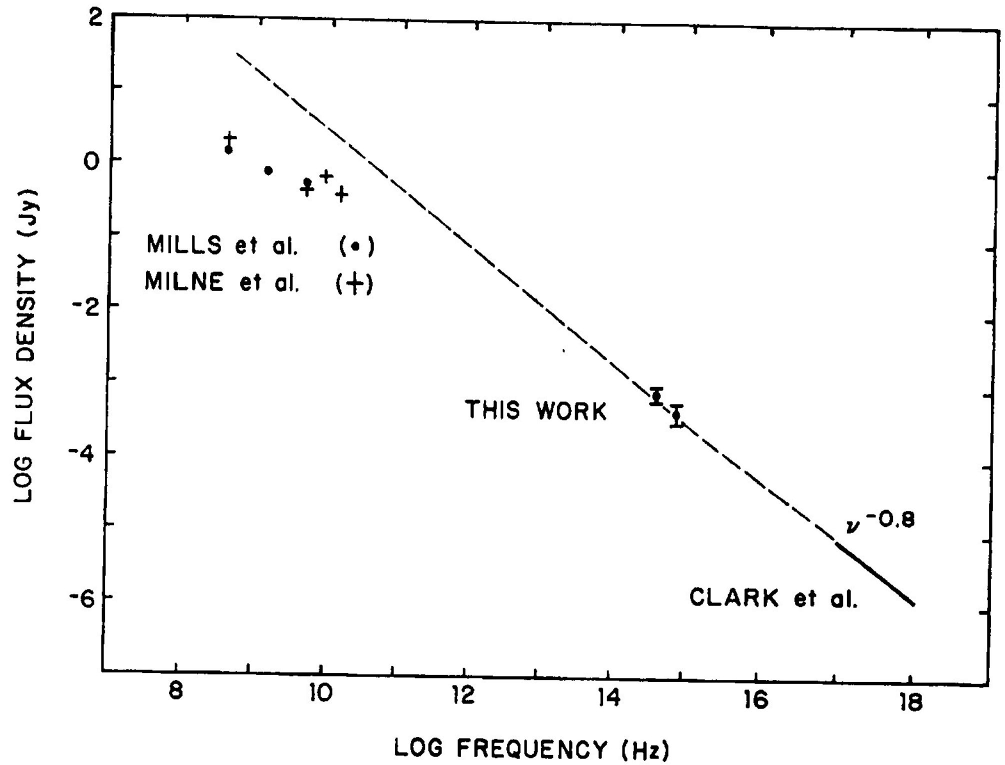


Figure 2. (LEFT). East-west slices through the center of the nebula in the three filters. West is to the left. Dashed curves have been corrected for unwanted line contribution in B and unwanted continuum contribution in [OIII]. Insert is point response function.

Figure 3. (ABOVE). Spectrum of 0540-693 over 8 decades in frequency. Radio points are probably dominated by larger scale emission shell and thus represent an upper limit to the nebular emission.

DISCUSSION OF CHANAN'S PAPER

TAYLOR: Your last point about the spectral break is that the simple physics you just told us is consistent with the break point being where you said, but it could also be higher.

CHANAN: Yes.

KULKARNI: Is there a radio pulsar?

CHANAN: None has been reported. If you put the Crab pulsar there, at 400 MHz I think it would be about 1 mJy.

MANCHESTER: We've searched for this radio pulsar both at Parkes and Molonglo: Parkes at 1.4 GHz and Molonglo at 843 MHz. We set an upper limit of about half a mJy at both frequencies. That was searching a range of ten times the uncertainty in the extrapolated period.

CHANAN: The Crab would not be that strong at 1400 MHz.

CHENG: I wonder if you know if the X-ray people are trying to monitor it--to get the long-term timing behavior.

CHANAN: As I said, if they could see it with EXOSAT or with some other flying satellite they would get $\ddot{P}$--the braking index--immediately. I believe they are making an effort to do that.

RADHAKRISHNAN: I want to call your attention to a work by Srinivasan and Bhattacharya that just appeared in Current Science on this object.

CHANAN: OK, I think Steve is going to comment on this in his talk.

OPTICAL OBSERVATIONS OF THE MILLISECOND PULSARS PSR 1937+214 AND PSR 1953+29

T.J. Loredo[a]
G.R. Ricker[a]
S.A. Rappaport

Massachusetts Institute of Technology

J. Middleditch[a]

Los Alamos National Laboratory, Los Alamos, NM

We report here the results of photometric and time-resolved optical observations of the fields of the recently discovered ultra-fast radio pulsars, PSR 1937+214 and PSR 1953+29 (Backer et al. 1982; Boriakoff et al. 1983). Deep images of the fields reveal no conspicuous optical counterpart for PSR 1937+214, though a star with m_V~20.5 is coincident with the position of PSR 1953+29. Time-resolved images of the fields of both objects, obtained with a new stroboscopic technique, have yielded upper limits on the pulsed near-infrared emission from each object. We briefly discuss constraints on the physical models for these systems derived from our optical studies.

The observations reported herein were carried out in September 1983 at the Cassegrain focus of the Mayall four meter telescope on Kitt Peak using the MASCOT (MIT Astronomical Spectrograph/Camera for Optical Telescopes) dual CCD camera (Ricker et al. 1981). Only images taken under photometric conditions are reported here. The seeing was typically 1.5 arc seconds FWHM during the observations. Additional observations performed in June 1983 at the 1.3 meter McGraw-Hill telescope on Kitt Peak are consistent with the results presented here.

Deep images of the field of PSR 1937+214 were obtained with R and I filters in the Mould filter system and a Kodak Wratten 87C filter (hereafter designated as a Z filter). A 1500 second exposure of PSR 1937+214 in the I band is shown in Figure 1. In this picture and all others presented in this work, the CCD pixel size of 0.48 arc seconds has been artificially decreased by a factor of two by simple linear interpolation. All recently measured positions of both the pulsar and the star labeled A in Figure 1 are listed in Table 1. The VLA position of the pulsar is indicated on the figure southwest of the star labeled A; the combined radio and optical positional uncertainties amount to an error of about ± 0.7 arc seconds. Star A is the candidate originally proposed by Djorgovsky (1982), which has since been discovered to be a normal K-giant star (Middleditch et al. 1983; Lebofsky and Rieke 1983; Djorgovsky and Spinrad 1983). The R, I, and Z magnitudes of this star and the other labeled stars in Figure 1 are given in Table 2; also listed are

[a] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

the three-sigma detection limits for our best images in each color. No stellar image within the error box with an R, I, and Z magnitude less than 24, 22, and 22 respectively, is detected.

* * * * *

TABLE 1
Astrometry of Pulsar Fields

PSR 1937+214 field	RA(1950)	Dec(1950)
PSR 1937+214 VLA (Backer et al. 1982)	19h 37m 28.72s±0.03	21 28' 1.3"±0.5
PSR 1937+214 VLA (Becker & Helfand 1983)	19h 37m 28.74s±0.02	21 28' 1.8"±0.2
PSR 1937+214 Timing (Taylor 1984)	19h 37m 28.7455s	21 28' 1.459"
Star A (Middleditch et al. 1983)	19h 37m 28.85s	21 28' 3.2"
Star A (Manchester et al. 1984)	19h 37m 28.80s±0.03	21 28' 3.7"±0.5
PSR 1953+29 field		
PSR 1953+29 VLA (Boriakoff 1984)	19h 53m 26.67s±0.05	29° 00' 44.1"±0.8
Star A (this work)[b]	19h 53m 26.70s±0.02	29° 00' 44.2"±0.3

[b]Positions of field stars provided by S. Djorgovsky (1983).

* * * * *

TABLE 2
Photometry of PSR 1937+214 Field

Star	Magnitudes (±0.1) R	I	Z
A	19.6	17.3	17.1
B	19.8	16.8	16.7
C	18.5	16.6	16.7
D	21.4	17.5	16.9
3 σ limit	23.9	22.0	22.2

* * * * *

We observed the field of PSR 1953+29 using V, R, and I filters of the Kron-Cousins system and the Z filter described above. A 1200 second exposure of this field in the I band is shown in Figure 2. The radio position is indicated on the figure and coincides with the position of a star (denoted as star A) whose V, R, I, and Z magnitudes are 20.6, 19.6, 17.4, and 17.6 respectively. The 1400 MHz VLA position and the position of star A are listed in Table 1; the two positions differ only by 0.4 arc seconds. The magnitudes of this and other labeled stars in the field are listed in Table 3 along with the three-sigma detection limits for our best images. These results are consistent with those published by Djorgovsky and Spinrad (1983) and by Pederson et al. (1983).

TABLE 3
Photometry of PSR 1953+29 Field

Star	Magnitudes (±0.1)			
	V	R	I	Z
A	20.6	19.6	17.4	17.6
B	20.4	19.1	17.2	17.9
C	c	c	c	c
D	c	21.5	19.1	20.3
E	17.5	16.7	15.9	16.5
F	18.8	17.8	16.4	16.9
G	20.7	18.5	16.2	16.4
H	18.6	17.8	17.1	17.6
I	19.2	18.2	17.0	17.8
J	19.2	18.2	16.9	17.3
K	16.7	16.0	15.1	15.8
3 σ limit	21.9	23.0	22.0	21.6

[c] magnitude not measurable

* * * * *

A VRI color-color diagram of the stars in this field is shown in Figure 3[d]. Also indicated on this diagram is the main sequence of Johnson (1966) and a reddening line determined from Schild's (1977) interstellar reddening law. Intrinsic lines corresponding to giants, supergiants, and degenerate dwarfs all lie very close to the main sequence curve shown. The length of the reddening line corresponds to the reddening expected at a distance of 7 kpc, if we adopt a visual extinction law which is the same as that toward the Crab pulsar (0.8 mag/kpc, Miller 1973). Though the reddening line is approximately parallel to the main sequence, all stars measured in the field either lie on the main sequence or can be dereddened onto it, with the exception of the candidate star A. The point labeled A' indicates the intrinsic Johnson colors of star A if it were at a distance of 7 kpc. For comparison the intrinsic colors of the Crab pulsar are also indicated (Kristian et al. 1976, Middleditch et al. 1983).

Finally, we note that no nebulosity is observed in the field of either millisecond pulsar. The limits on nebulosity in the R band are ~ 24 and 23 magnitudes per square arc second for the fields of PSR 1937+214 and PSR 1953+29, respectively.

Time-resolved images of the fields of both pulsars were produced using a new stroboscopic technique. Since a detailed description of the technique will be published later (by Ricker et al.), only a brief description will be given here. A mirror was placed in the optical path of the MASCOT spectrographic channel at the position usually occupied by a reflection

[d] For this diagram, all colors have been transformed to the Johnson VRI system using the transformations of Bessell (1979) and Cousins (1976).

grating. This mirror was attached to a galvanometric servomechanism that could accurately rotate the mirror through small angles at frequencies up to several hundred Hz. The mirror scans the image of a star back and forth across part of a column of the CCD array. As a result, normal stars will appear as line images along columns of the CCD image. However, if a star is pulsing, and if the mirror is oscillated at a frequency which is harmonically related to the star's pulsation frequency, the scanned image of the pulsing star will have a different structure. If the star's optical emission is 100% pulsed, its image will appear as one or more dots or anomalously short smears, depending on the pulse profile. If the optical emission of the star is only partially pulsed, its image will appear as a full smear with bumps on it. During the observations, a microcomputer attached to a rubidium standard atomic clock was used to coherently adjust the oscillating frequency of the mirror to match the topocentric pulsar frequency at the observatory.

To test the technique, we observed the Crab pulsar, PSR 0531+21, with the scanning system described above. An unscanned image of the field of the Crab pulsar is shown in Figure 4, while a 180-second scanned image of the same field appears in Figure 5. In both images, the nebulosity of the supernova remnant is apparent. In the scanned image, the Crab pulsar is clearly identified and the main pulse and interpulse are easily distinguished. Both images were taken in the Z band.

A scanned image of the field of PSR 1937+214 is shown in Figure 6. No pulsing from any object in the vicinity of the pulsar position is apparent in this 1800 second Z-band exposure. In an effort to detect low-level pulsations from an object close to or within the seeing disk of star A, we performed a chi-squared fit of the scanned image of this star to a template scanned image of an unpulsed star (the template was formed from the scanned image of star D). The residuals after subtracting the best-fit scanned image from star A are shown in Figure 7. For comparison, the residuals of a fit of the template to star B are also shown in the same frame. A similar analysis was performed on other images of this same field which were taken with deliberately shifted temporal phases of the scanning mirror. None of the residuals was found to shift in a manner which is consistent with the known phase shift of the mirror. From this analysis we can place a three sigma upper limit of 1.6% of the intensity of star A on pulsed emission (for an assumed duty cycle of $\lesssim 1/8$) from anywhere within the seeing disk of star A.

Scanned images of the field of PSR 1953+29 are presented in Figures 8 and 9; the exposure time was 1200 seconds. Note that these images are rotated 45° with respect to Figure 2. The residuals of fits of the scanned images of star A and B to a template scanned image (derived from star F) are shown in Figure 9. An analysis of these images allows us to place a three sigma upper limit of 3.4% on the fraction of pulsed emission from star A. Longer integration times, and hence better pulsation limits, were prohibited by the relative inaccuracy of the PSR 1953+29 pulse ephemeris which results from the fact that the binary orbital parameters are not yet well determined.

A summary of the results of searches for optical pulsations from the two millisecond pulsars is given in Table 4.

* * * * *

TABLE 4
Summary of Searches for Optical Pulsations

	Filter	Mag. Limit (3σ)	% of Star A[e]
PSR 1937+214			
Middleditch et al. 1983	Red (0.8μm)	23.6	4.6
	IR (1.85μm)	16.3[f]	3.5
Manchester et al. 1984	Red (0.59μm)	24.0	0.9
This work	"Z" (0.9μm)	21.6	1.6
PSR 1953+29			
This work	"Z" (0.9μm)	21.3	3.4

[e]Designated in Figure 1 for PSR 1937+214 and Figure 2 for PSR 1953+29.

[f]Under the assumption that the published limit corresponds to a 1σ confidence level.

* * * * *

Pacini (1971) and Pacini and Salvati (1983) have advanced an argument that would allow one to estimate the dependence of the optical luminosity of a pulsar on its period and period derivative. They have shown that if the optical emission is attributed to incoherent synchrotron processes occurring near the velocity of light cylinder, the luminosity per frequency interval should scale like $\dot{P}^{13/6}/P^{47/6}$. Scaling from the observed optical luminosity of the Crab Pulsar, we can write this dependence as

$$m_v = -2.17 + 19.58 \log(\frac{P}{ms}) - 5.42 \log(\frac{\dot{P}}{10^{-15}}) + 5 \log (\frac{d}{kpc}) + A_v ,$$

where the last two terms are corrections for the distance, d, and the interstellar absorption, respectively. Assuming that the extinction law toward both millisecond pulsars is the same as that for the Crab pulsar (0.8 magnitudes per kpc), and employing the recently measured distances to the pulsars of 5 kpc for PSR 1937+214 and 7 kpc for PSR 1953+29 (Heiles et al. 1983; Backer 1984), we find an expected visual magnitude for both of these pulsars of $\gtrsim 30$. This value falls far below our detection limit.

Models for the evolution of the PSR 1953+29 binary system (see, e.g., Joss and Rappaport 1983) suggest that the companion star is a low-mass ($\sim 0.3 M_\odot$) helium degenerate dwarf. In this model, the progenitor of the helium-dwarf was the degenerate core of a red giant which ascended the giant branch while transferring its hydrogen-rich envelope to the neutron star companion over an interval of $\sim 10^8$ years. (The neutron star was presumably spun up to its rotation period of ~6 msec during this mass-transfer phase.) Near the end of the mass-transfer phase, the red giant would have an effective temperature of ~3500 K and an absolute visual magnitude $M_V \sim 0.8$ (Joss and Rappaport 1983). At a distance of ~7 kpc such a star would have an apparent visual magnitude $m_V \sim 21$, for an assumed visual extinction $A_V \sim 6$. This approximates the observed value of m_V for star A (Fig. 2). However, variations in the plasma column density as the pulsar orbits its companion would be readily detected if there were any significant residual extended atmosphere surrounding the degenerate star. Once the envelope of the red giant has been completely removed, the underlying degenerate dwarf will cool rapidly (see, e.g., Lamb and van Horn 1975). A degenerate dwarf of mass 0.3-0.4 $M_\odot$ and radius ~0.02 $R_\odot$ will have $m_V \gtrsim 28$ for effective temperatures $\lesssim 2\times10^5$ K and for an assumed distance of 7 kpc and $A_V \sim 6$. Thus, if star A in Figure 2 is identified with the PSR 1953+29 binary system, we cannot easily account for the observed value of $m_V \sim 20.6$ with either pulsar emission from the neutron star or optical emission from the low-mass companion.

In summary, we can make no positive identification of an optical counterpart to either of the ultra-fast radio pulsars. No candidate appears at the location of PSR1937+214 down to a limiting red magnitude of >23. A star with $m_V = 20.6$ appears at the location of PSR 1953+29; although its colors are uncommon, they do not match those of any unusual star (such as the Crab pulsar) or any well-characterized stellar class of which we are aware. Furthermore, this star is brighter than expected for the binary companion of the pulsar. No optical pulsations have been detected from the location of PSR 1937+214 which lies near the seeing disk of a star with $m_R = 19.6$ (star A in Figure 1) which is probably a K-giant. The 3σ upper limit on pulsations is 1.6% of the intensity of this star. No pulsations were detected from the star contained within the radio error box of PSR 1953+29 with a 3σ upper limit on pulsations of 3.4% of the intensity of star A in Figure 2.

We thank our colleagues who contributed significantly to this work. Jim Deveny, Bill Schoening, Alan Bird, Bob Barnes, and Skip Andree of the staff at Kitt Peak National Observatory assisted us in many ways at the 4m telescope. Roland Vanderspek of MIT also assisted us throughout the run at the 4m telescope. At the McGraw-Hill telescope, Matt Johns and John Thorstensen were actively involved in setting up the instrument and in carrying out the observations. Mark McPike of the General Scanning Corporation provided us with much valuable technical information about the galvanometric scanner we used, and helped us obtain equipment on short notice. W. Kendall Melville of MIT's Parson's Laboratory for Water Resources and Hydrodynamics generously lent us his scanner driver electronics on several occasions. Doug Mink, John Doty, and Steven Rosenthal all made significant software contributions to the project. Valentin Boriakoff and Joseph Taylor both provided us with unpublished information on the ephemerides of the millisecond pulsars. We thank Barbara Cooper for her able preparation of this manuscript.

Kitt Peak National Observatory is operated by AURA, Inc., under contract with the NSF. This work was supported in part by NASA under grants NSG 7339 and NSG 7643.

REFERENCES

Backer, D.C. 1984, preprint.

Backer, D.C., Kulkarni, S.R., Heiles, C., Davis, N.M. and Goss, W.M. 1982, Nature, 300, 615.

Becker, R.H. and Helfand, D.J. 1983, Nature, 302, 688.

Bessell, M.S. 1979, Pub. A. S. P., 91, 589.

Boriakoff, V., Buccheri, R. and Fauci, F. 1983, Nature, 304, 417.

Cousins, A.W.J. 1976, Mem. R. A. S., 81, 25.

Djorgovsky, S. 1982, Nature, 300, 618.

Djorgovsky, S. 1983, personal communication.

Djorgovsky, S. and Spinrad, H. 1983, Nature, 306, 569.

Heiles, C. Kulkarni, S.R., Stevens, M.A., Backer, D.C., Davis, M.M. and Goss, W.M. 1983, Ap. J. (Letters), 273, L75.

Johnson, H.L. 1966, Ann. Rev. Astron. Astrophys., 4, 193.

Joss, P.C. and Rappaport, S.A. 1983, Nature, 304, 419.

Kristian, J., Clardy, K.D., and Westphal, J.A. 1976, Ap. J. (Letters), 206, L143.

Lamb, D.Q. and Van Horn, H.M. 1975, Ap. J., 200, 306.

Lebofsky, M.J. and Rieke, G.E. 1983, IAU Circ. No. 3809.

Manchester, R.N., Peterson, B.A. and Wallace, P.T. 1984, preprint.

Middleditch, J., Cudaback, D., Oliver, B., Pennypacker, C., Lebofsky, M.J., Rieke, G.H., McGraw, J.T., Dearborn, D., Wisniewski, W., and Chini, R. 1983, Nature, 306, 163.

Middleditch, J., Pennypacker, C. and Burns, M.S. 1983, Ap. J., 273, 261.

Miller, J.S., 1973, Ap. J. (Letters), 180, L83.

Pacini, F. 1971, Ap. J. (Letters), 163, L17.

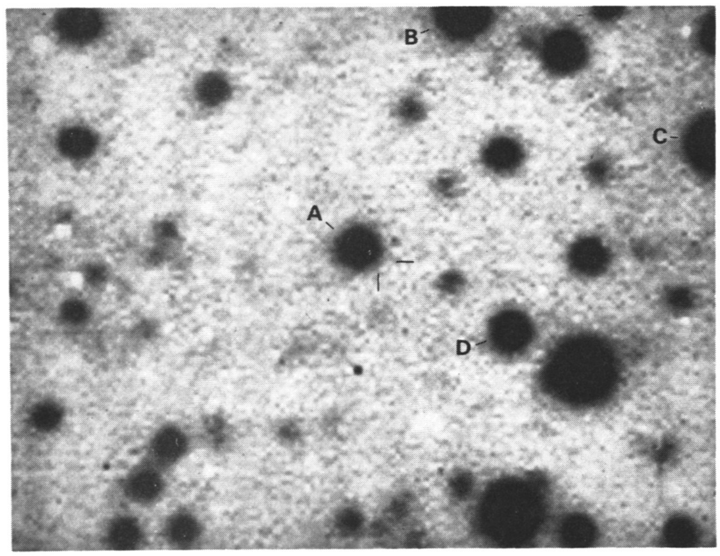
Pacini, F. and Salvati, M. 1983, Ap. J., 274, 369.

Pederson, H., Tarenghi, M., Crisiani, S. and Salvati, M. 1983, Nature, 306, 568.

Ricker, G.R., Bautz, M.W., Dewey, D. and Meyer, S.S. 1981, NASA/JPL Proceedings S. P. I. E., 290, 190.

Schild, R.E. 1977, Astr. J., 82, 589.

Taylor, J.H. 1984, this conference.

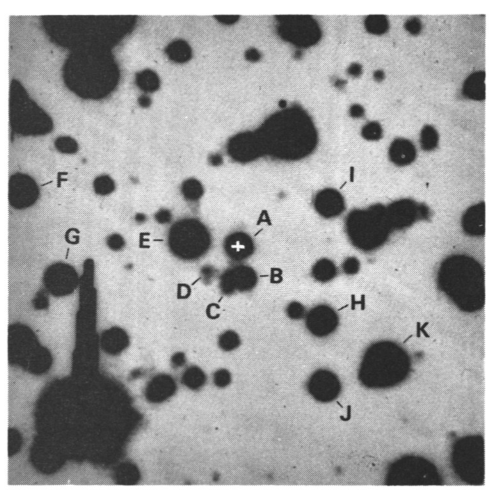


15"

Figure 1. PSR 1937+214 field, R filter.

N

E



15"

Figure 2. PSR 1953+29 field, I filter.

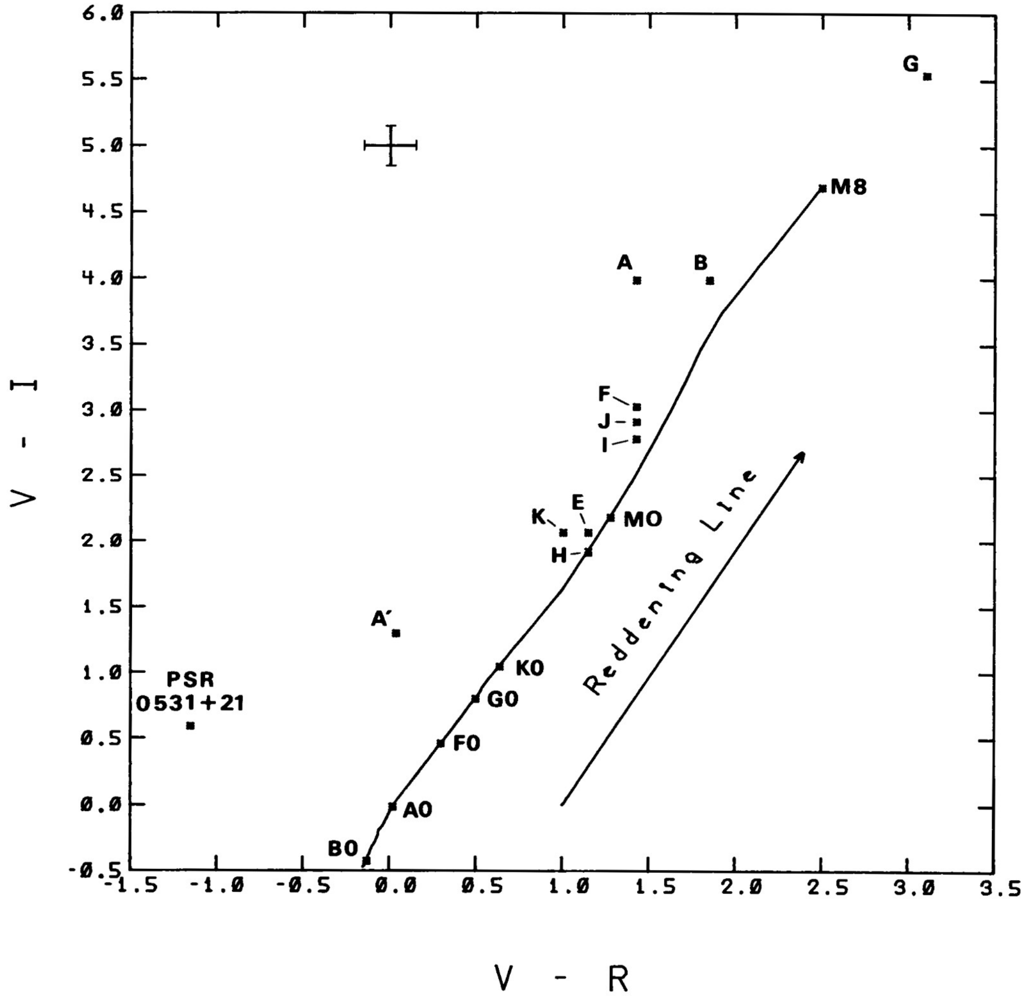
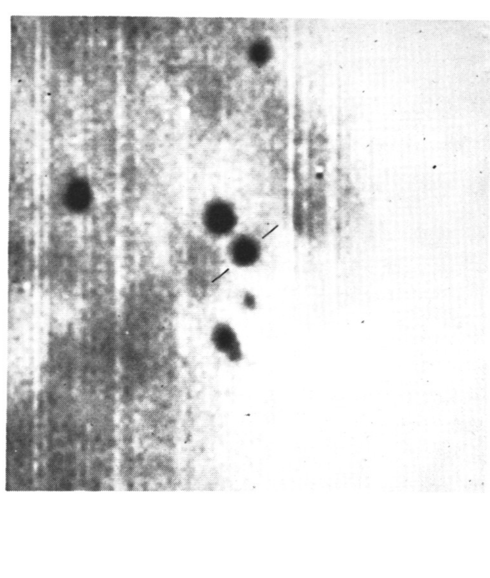
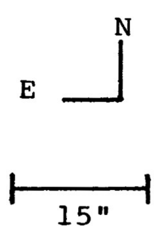


Figure 3. VRI color-color diagram for stars in the field of PSR 1953+29.





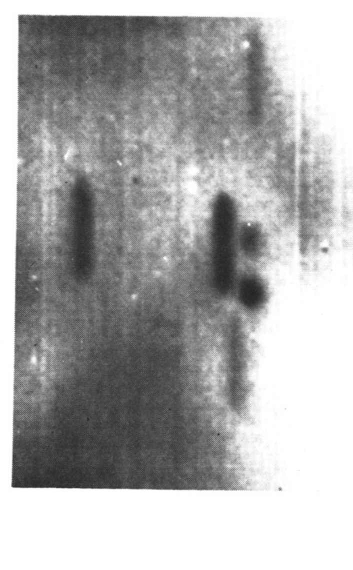


Figure 4. PSR 0531+21 field, Crab Pulsar indicated.

Figure 5. Scanned PSR 0531+21.

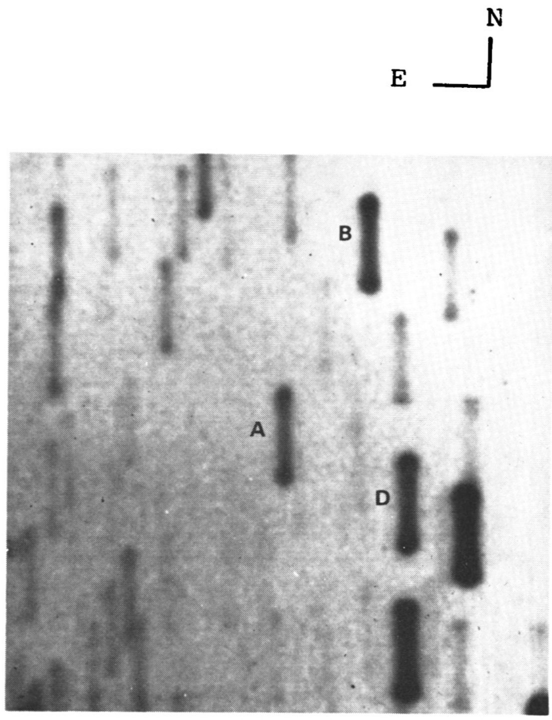


Figure 6. PSR 1937+214 field, scanned.

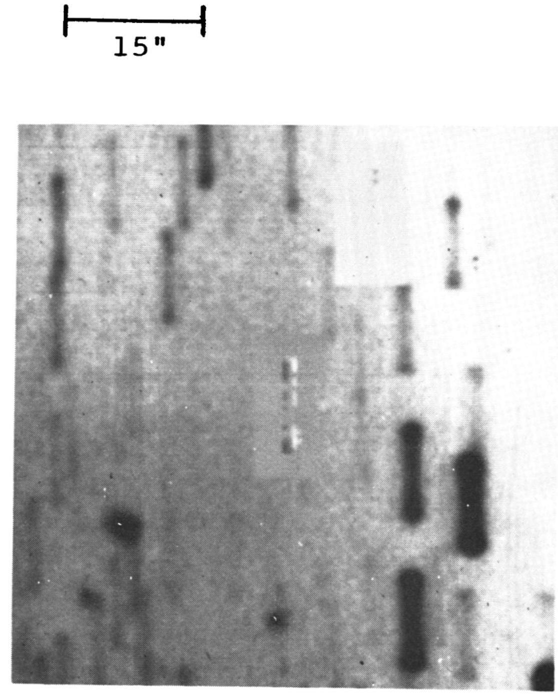


Figure 7. PSR 1937+214 field, residuals of fits of A & B to a template made from star D (see text).

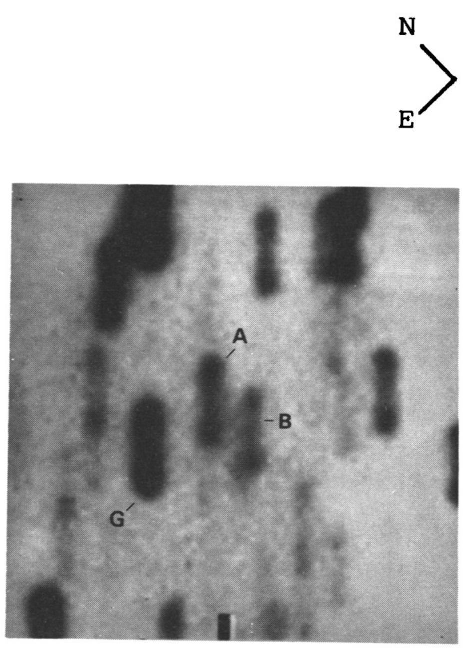


Figure 8. PSR 1953+29 field, scanned.

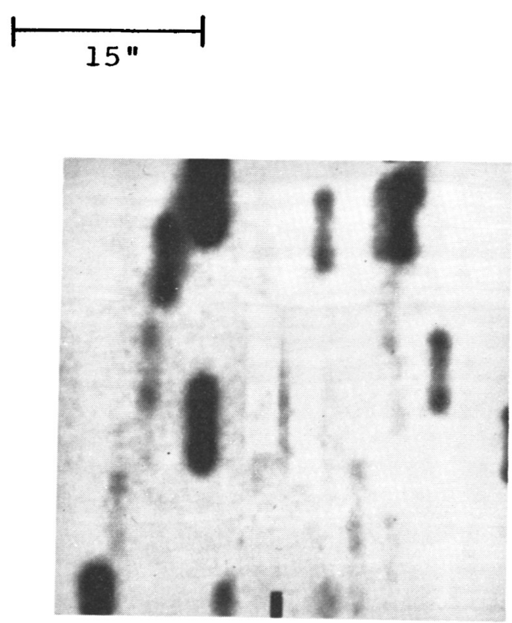


Figure 9. PSR 1953+29 field, residuals of fits of A & B to a template made from star F (see Fig. 2 and text).

DISCUSSION OF LOREDO'S PAPER

TAYLOR: I was astonished by your last statement about the period scaling just because a factor of 20 in period from the Crab to this one, to the tenth power, surely would more than compensate for a larger distance.

LOREDO: Pacini's latest paper gives the scaling relation as optical emission proportional to $\dot{P}^2\ P^{-10}$.

TAYLOR: What about other optical work existing?

MANCHESTER: I should say something about our observations. I think most of you know that we sent out an IAU telegram announcing a pulsed detection of this millisecond pulsar in the optical band from AAT observations in April and May of last year. That was based on the alignment of two pulsed components in observations made on different days. Unfortunately, we subsequently discovered that there were clock problems at the AAT and the alignment went away when we put in what we believe was the correct clock epoch. Because of this uncertainty we had another observing session in September of last year, when the conditions were a little better. Of course this object (1937+21) is pretty far off for the AAT, and our seeing is not quite as good as at Kitt Peak. We couldn't find any evidence for pulsations at all in the September observations. We integrated for several hours, and can put an upper limit on the pulsed magnitude of somewhere between 25 and 26 in the optical. I have a slightly different number for Pacini's prediction. It's a pity that Franco's not here-- but depending on exactly what you assume about beaming, I think the prediction is round about 30th magnitude. So we're still several magnitudes above that.

TAYLOR: And your limit of 25 or 26 applies to a region down and to the right of the brighter star?

MANCHESTER: That's at your position.

TAYLOR: With how big a diaphragm?

MANCHESTER: Three arc seconds. In our first observation we thought we had something from this star. We looked at that again but we couldn't see anything, so we looked at the radio position and concentrated on that. This has been written up--the paper has been submitted to Nature.

TAYLOR: I'd like to say this talk was indeed absolutely splendid senior thesis work.

No Detectable Millisecond Pulsar in the 1913+16 system

Shrinivas R. Kulkarni, U. C. Berkeley
and
M. M. Davis, Arecibo Observatory
and
J. H. Taylor, Princeton University

ABSTRACT

The observed absence of eclipses and the rate of advance of periastron in the 1913+16 system constrain the companion of PSR1913+16 to be a compact object, such as a helium main-sequence star, or a rapidly rotating white dwarf. On evolutionary grounds it has been argued that the companion must be another neutron star. In an attempt to find whether the companion was a fast pulsar that went undetected in previous slow-period searches, we fast-sampled an 8 MHz dedispersed signal from the 1913+16 system and looked for pulses. We report the absence of any fast pulsar with a flux density greater than 1/3 that of the binary pulsar and a rotation rate smaller than 2500 Hz. We are currently in the processing of improving the limit on the flux density.

INTRODUCTION

The binary millisecond pulsar system, 1913+16, is of great interest since it can and has been used for quantitative testing of the predictions of general relativity and other relativistic theories of gravity (see Weisberg and Taylor 1984 for the latest update). The nature of the companion is an important parameter in the quantitative comparision of observations with theory since the various general relativistic phenomena can be confused by classical effects arising from the shape of the companion which could be distorted by spin-induced or tidal forces.

There are several reasons to believe that the companion must be a compact object. It has been shown that the constraints of the orbital size, the lack of eclipses, and the absence of rapid apsidal motion rule out the possibility that the companion is a main-sequence star (Roberts, Masters and Arnett 1976). The remaining possibilities are that the companion is either a He star, a white dwarf, a neutron star, a black hole or a compact object belonging to a new class of compact stars that is yet to be discovered. Smarr and Blandford (1976), Webbink (1975) and more recently van den Heuvel and Taam (1984) conclude that the most likely candidate is a neutron star. It is interesting to note that the most recent analysis of the timing observations are completely consistent with the assumption of a clean binary system and a very compact companion (Weisberg and Taylor 1984). Taylor *et al.* (1976) carried out an extremely sensitve pulsar search at 430 MHz and set a stringent pulsed flux-density limit of 60 μJy from the companion. This search was sensitive to pulse-periods between 8 ms and 4 s. In view of the discovery of a millisecond pulsar by Backer *et al.* (1982) we thought it worthwhile to repeat the 1976 pulse search and specifically look for millsecond-period pulsars.

OBSERVATIONS

The observations were conducted at the Arecibo Observatory on 14th and 16th April, 1984. On both occasions, the observations were conducted at 1385 MHz. In order to increase our signal-to-noise ration, we took advantage of the known dispersion measure of 1913+16. An 8 MHz signal centered at 1385 MHz, in each circular polarization, was dedispersed using the Boriakoff digital dedisperser. After some amplification and smoothing, the dedispersed stream was sampled at 400 μs. The effective time-constant was such that frequencies up to 2500 Hz were passed to the sampler - considerable aliasing was allowed. In addition we also sampled the detected and smoothed output of a 2 MHz signal (mainly for evaluating the signal-to-noise ratio of a pulsed calibrator singal). On both these runs we also observed the 1.5 ms pulsar in the same manner except that the the dedisperser setting was changed to the dispersion measure of 1937+21.

RESULTS

Blocks of data, each 8K samples long, corresponding to 3.3 s, were Fourier transformed. The resulting 4K amplitude spectra were added to yield an incoherent average of the full data (about 45 minutes for each run). The amplitude spectra, after bandpass correction, as a function of fluctuation frequency (in Hz) are plotted in Figs. 1a and 1b. In the case of Fig. 1a, the bandpass shape needed for the bandpass correction was derived by a simple polynomial fit whereas in the case of Fig. 1b the bandpass shape was determined by a boxcar-averaging procedure. The former is computationally inexpensive but clearly results in a rather approximate correction. In both the cases the signal-to-noise ratio is roughly constant across the spectra.

The various harmonics of 1913+16 are marked in arabic numerals in the Figs. 1a and 1b. The spikes at multiples of 60 Hz arise from the 60 Hz power supply. A look at Figs. 1a and 1b does not show any peak greater than about a third the height of the strongest peak of 1913+16. In Fig. 1a, the strong peak at 8 Hz and marked with an asterisk does not arise in any celestial source since the same peak was seen in the 1937+21 data which was taken on the same day.

Clearly the flux limit can be improved by taking much longer transforms. In the longer transforms we will have to account for the Doppler shift of the companion due to the orbital motion. We are currently in the process of doing this.

DISCUSSION

1913+16 itself is a rather weak pulsar (1 mJy at 20 cm). Thus our present present flux-density limit, while not being as stringent as that of Taylor et al. (1976), indicate that the companion is most probably not a pulsar beamed towards us. The beaming fraction is ~ 1 for fast pulsars as compared to 0.2 for slower pulsars (R. Narayan, pers. comm.). Thus if the companion is a neutron star, it is either a) a slow pulsar which is not beaming towards us or b) a pulsar which has now turned off (see van den Heuval and Taam 1984 for a discussion of this point).

The Arecibo Observatory is part of the National Astronomy and Ionospheric Center which is operated by Cornell University under contract from the National Science Foundation.

REFERENCES

Backer, D., Kulkarni, S. R., Heiles, c., Davis, M. M. and Goss, W. M.: 1982, Nature 300:615

Roberts, D. H., Masters, A. R. and Arnett, W. D.: 1976 Astrophys. J. 203:196

Smarr, L. L. and Blandford, R.: 1976, Astrophys. J. 207:574

Taylor, J. H., Hulse, R. A., Fowler, L. A., Gullahorn, G. E. and Rankin, J. M: 1976, Astrophys. J. 206:L53

van den Heuvel, E. P. J. and Taam, R. E.: 1984, Nature 309:235

Webbink, R. F.: 1975, Astron. Astrophys. 41:1

Weisberg, J. M. and Taylor, J. H.: 1984, Phys. Rev. Lett. 52:1348

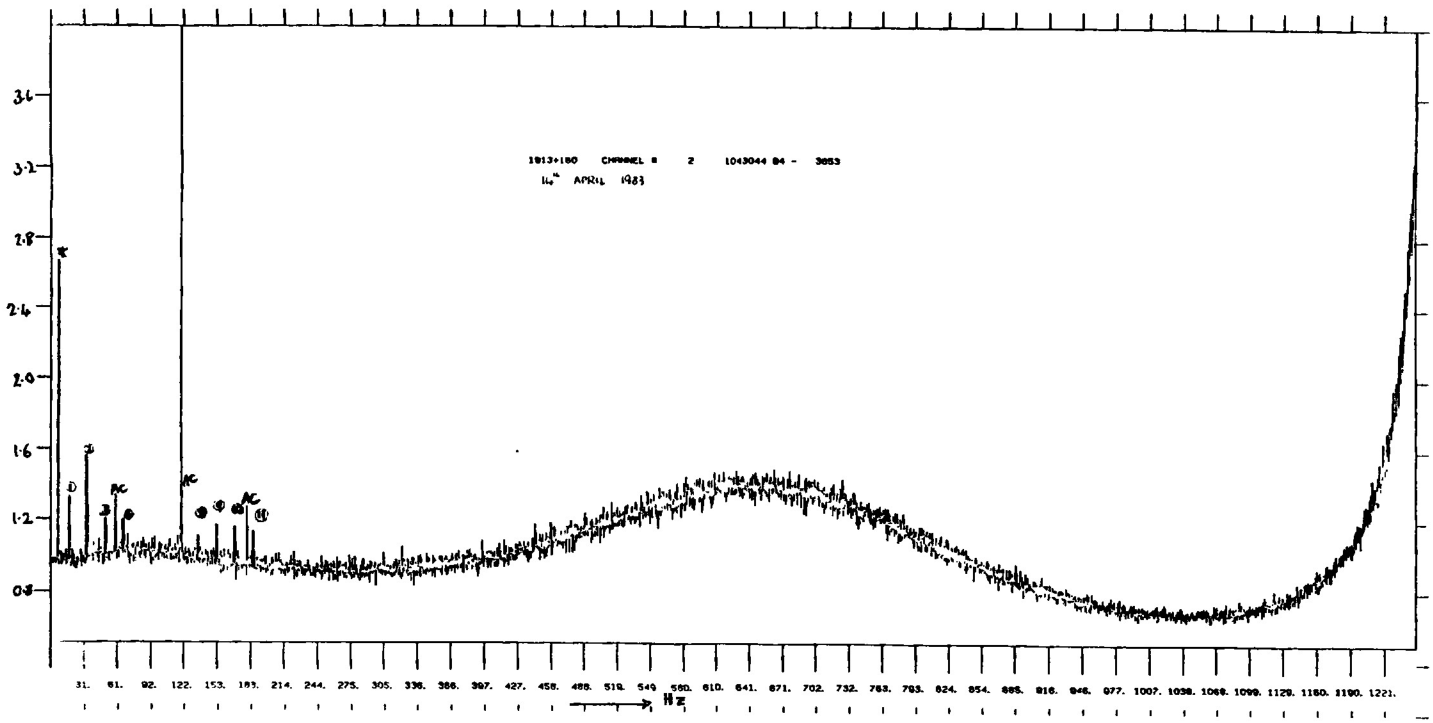

1913+180 CHANNEL # 2 1043044 84 - 3653
14th APRIL 1983
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
AC
Hz

FIG 1A

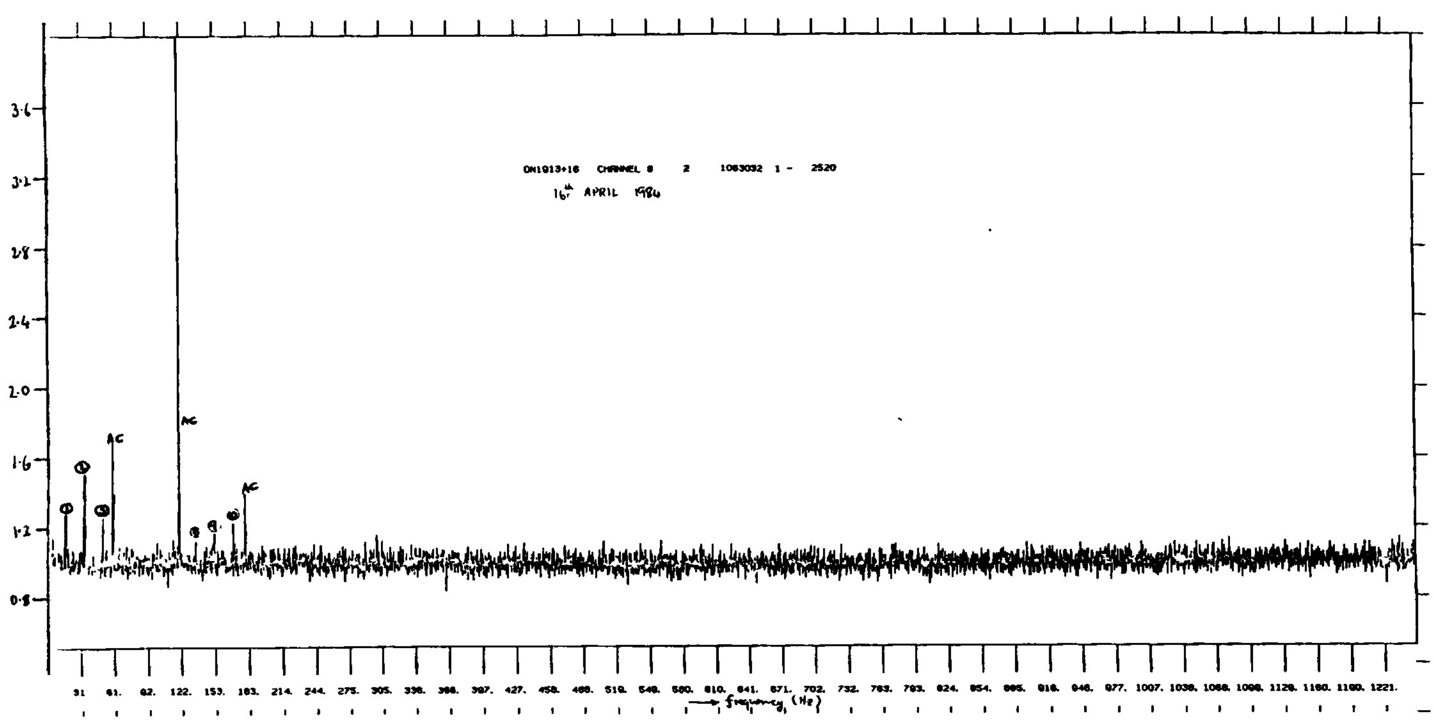

ON1913+16 CHANNEL # 2 1063032 1 - 2520
16th APRIL 1984
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
AC
frequency (Hz)

FIG 1B

A Single Pulse Study of the Millisecond Pulsar P1937+214

A. Wolszczan and J.M. Cordes (NAIC), D.R. Stinebring (NRAO)

Summary

Preliminary results of the search for strong pulses from the millisecond pulsar PSR 1937+214, based on the Arecibo observations of this object at 431 MHz and 1400 MHz are presented. We show that its single pulse behaviour does not differ from that of the "slow" pulsars: detectable single pulse emission is present in nearly every period and strong pulses (about 100 times the noise level) occur approximately every 400 000 periods. Results of the correlation analysis of our data indicate that pulse intensities are correlated over 3-4 periods and that there may be a significant correlation between main pulse and interpulse emission. We also demonstrate that the intensity statistics of the main pulse and the interpulse are practically identical.

1. Introduction

The extremely fast rotation ($P \simeq 1.56$ ms) and weak surface magnetic field ($\sim 10^8$ G) of the millisecond pulsar PSR 1937+214[1] provide a unique opportunity to study the radio emission characteristics arising in unusual magnetospheric conditions. It has been shown that the average pulse properties of PSR 1937+214[2,3,4] appear to be similar to those exhibited by slower pulsars. Here, we present the preliminary results of an analysis of single pulses from this source, aimed to study the details of its radio emission characteristics.

2. Observations and data processing

The observations were made in April and May 1984 with the 305-m Arecibo telescope at 431 MHz and around 1400 MHz. Orthogonal, circularly polarized signals were passed through 250 kHz Butterworth filters, mixed to baseband, split into real and imaginary components and sampled at the 4 μs Nyquist interval. These data were written onto magnetic tape and then dedispersed using a pre-detection dedispersion technique[5] to form four Stokes parameters. Due to hardware limitations, only every 6 consecutive pulse periods out of 50 were available for further processing. The dedispersed total intensity single pulse data were then histogrammed, to yield intensity p.d.f. estimates, and searched for strong pulses. In order to study the intensity correlations with respect to pulse phase and pulse number, appropriate auto- and cross-correlation functions were also computed for the above data.

3. Results

A typical set of single pulse sequences from PSR 1937+214 is shown in Fig. 1 in the form of a time/phase diagram. It strongly suggests that main pulse and interpulse emission is present in nearly every pulsar period. However, strong pulses, whose peak intensities exceed the noise level by about two orders of magnitude, occur approximately every ~400 000 pulsar periods. Examples of such pulses at 431 MHz and 1400 MHz are given in Fig. 2. They show significant phase jitter (e.g. 1384 MHz data) and there is some indication of a double individual pulse structure.

In order to describe the single pulse properties of the millisecond pulsar statistically, we have computed the pulse intensity histograms for the main pulse, the interpulse and for an off-pulse window. These histograms are shown in Figs. 3 and 4. They indicate that the statistics of the main pulse and the interpulse emission are very similar (the histogram widths are different due to different dispersions in intensity). Since the total intensities used to form histograms are the sums of squares of four components of the complex signal[3], they would be χ^2 distributed with 4 degrees of freedom, if the component amplitudes have the statistics of unpolarized Gaussian noise. A comparison of this χ^2 p.d.f. with the observed histograms (Figs. 3,4) clearly shows that they are broader than expected in the case of pure noise. This result is easy to understand in the case of the main pulse and the interpulse histograms as being due to the contribution from a pulsed emission. Apparent deviations of the off-pulse histograms from the unpolarized noise p.d.f. may result either from a polarization of the off-pulse noise, or from some interference effects. The presence of pulsar emission over the entire period would be the most attractive explanation of these discrepancies and we will attempt to verify this in the course of further data analysis.

Our correlation analysis of the single pulse intensity fluctuations of PSR 1937+214 included computations of auto- and cross-correlation functions of intensity versus pulse phase and pulsar period. The results shown in Fig. 5 indicate that the main pulse and the interpulse emission are correlated over at least 3-4 pulsar periods at both radio frequencies and that the main pulse and the interpulse intensities are 80% to 90% correlated within the same period. The estimated autocorrelation halfwidths of both the main pulse and the interpulse are 47 ± 4 μs and 40 ± 4 μs at 431 MHz and 1400 MHz, respectively.

4. Discussion

The results presented here suggest that to first order, the single pulse properties of PSR 1937+214 do not differ from those of "slow" pulsars. Our analysis shows that the millisecond pulsar tends to release its energy in bursts lasting a few pulsar periods, which is characteristic of many pulsars (e.g. PSR 0823+26[6]). Similarly, the main pulse - interpulse intensity correlation shown by PSR 1937+214 has been found in other objects (e.g. PSR 0950+08[7]). The fact that the cross-correlation functions of adjacent pulses peak at zero lag indicates the absence of subpulse drifting in this pulsar. We have not found anything in the main pulse and the interpulse intensity histograms that would make them unusual. In particular, they do not show any bimodality characteristic of the histograms of single pulse intensities of pulsars exhibiting frequent nulls[8] or giant pulses[9].

References

1. Backer, D.C., Kulkarni, S., Heiles, C., Davis, M.M. and Goss, W.M. 1982, Nature, 300, 615.
2. Ashowrth, M., Lyne, A.G. and Smith, F.G. 1983, Nature, 301, 313.
3. Stinebring, D.R. and Cordes, J.M. 1983, Nature, 306, 349.
4. Cordes, J.M. and Stinebring, D.R. 1984, Ap. J. 277, L53.
5. Hankins, T.H. and Rickett, B.J. 1975, Meth. Comp. Phys., 14, 55.
6. Backer, D.C. 1973, Ap. J., 182, 245.
7. Hankins, T.H. and Cordes, J.M. 1981, Ap. J., 249, 241.
8. Ritchings, R.T. 1976, MNRAS, 176, 249.
9. Sutton, J.M., Staelin, D.H. and Price, R.M. 1971, IAU Symp. No. 46, "The Crab Nebula", Davies and Smith (eds.),p. 97.

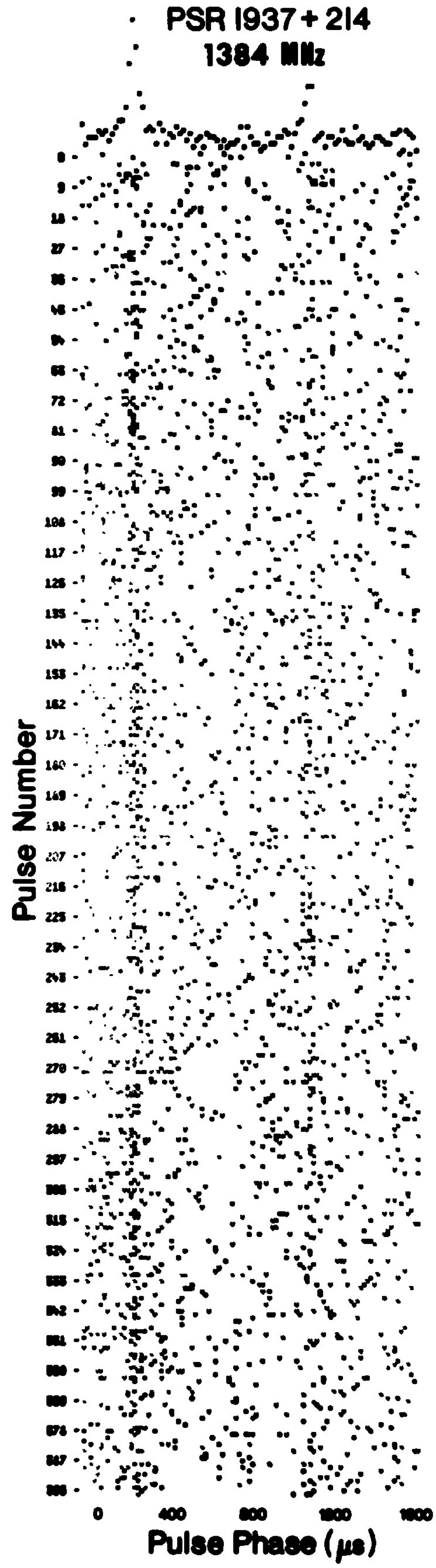


Fig. 1 The time/phase plot of 400 single pulses from PSR 1937+214 at 1384 MHz. Eight grey scale intensity levels are displayed and the average of all 400 pulses is plotted on the top of the figure. Every six pulse periods are consecutive.

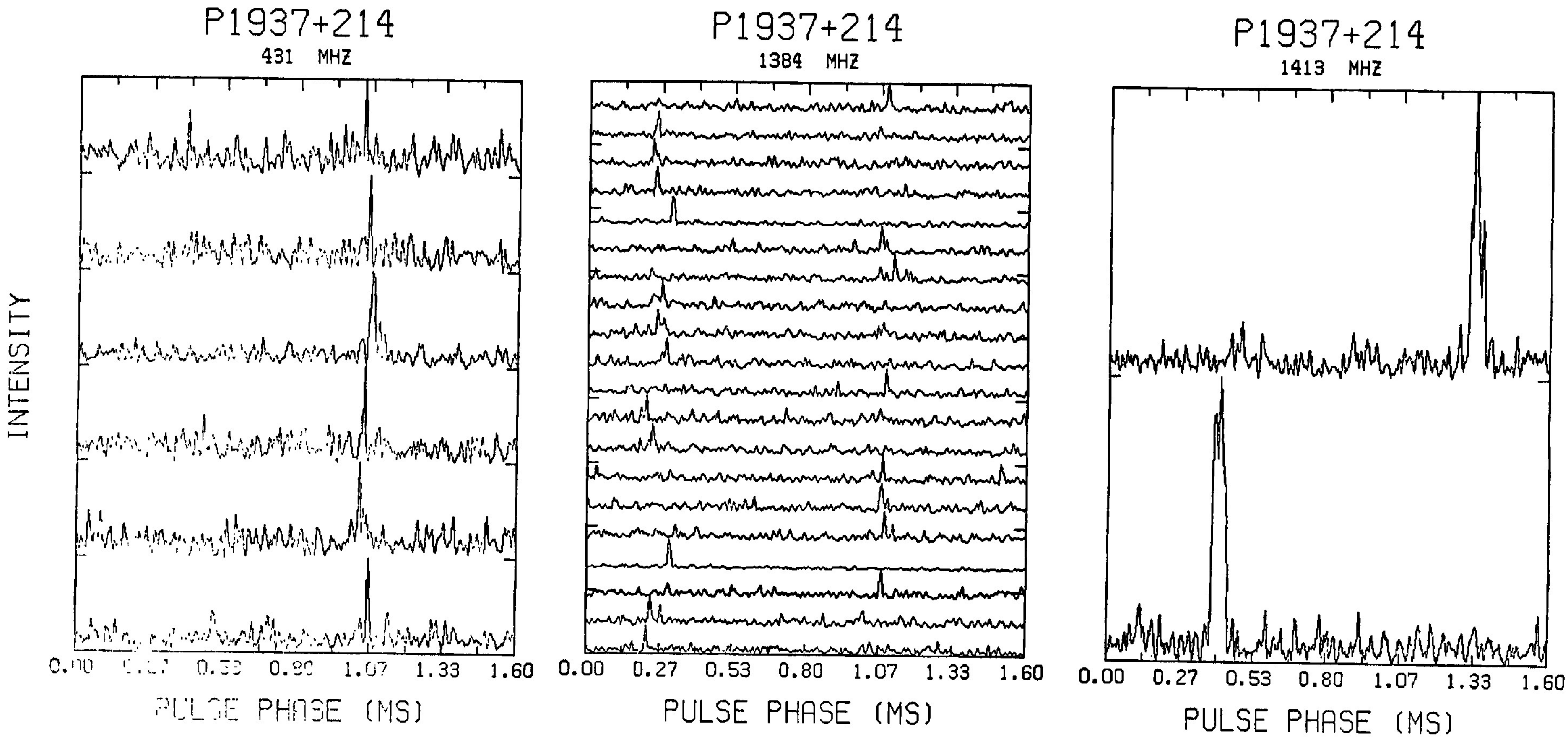


Fig. 2 Examples of strong single pulses from PSR 1937+214. Pulses are normalized individually. At 431 MHz, only the main pulses are displayed. At high frequencies, the main pulses are on the left and the interpulses on the right of the diagram.

P1937+214

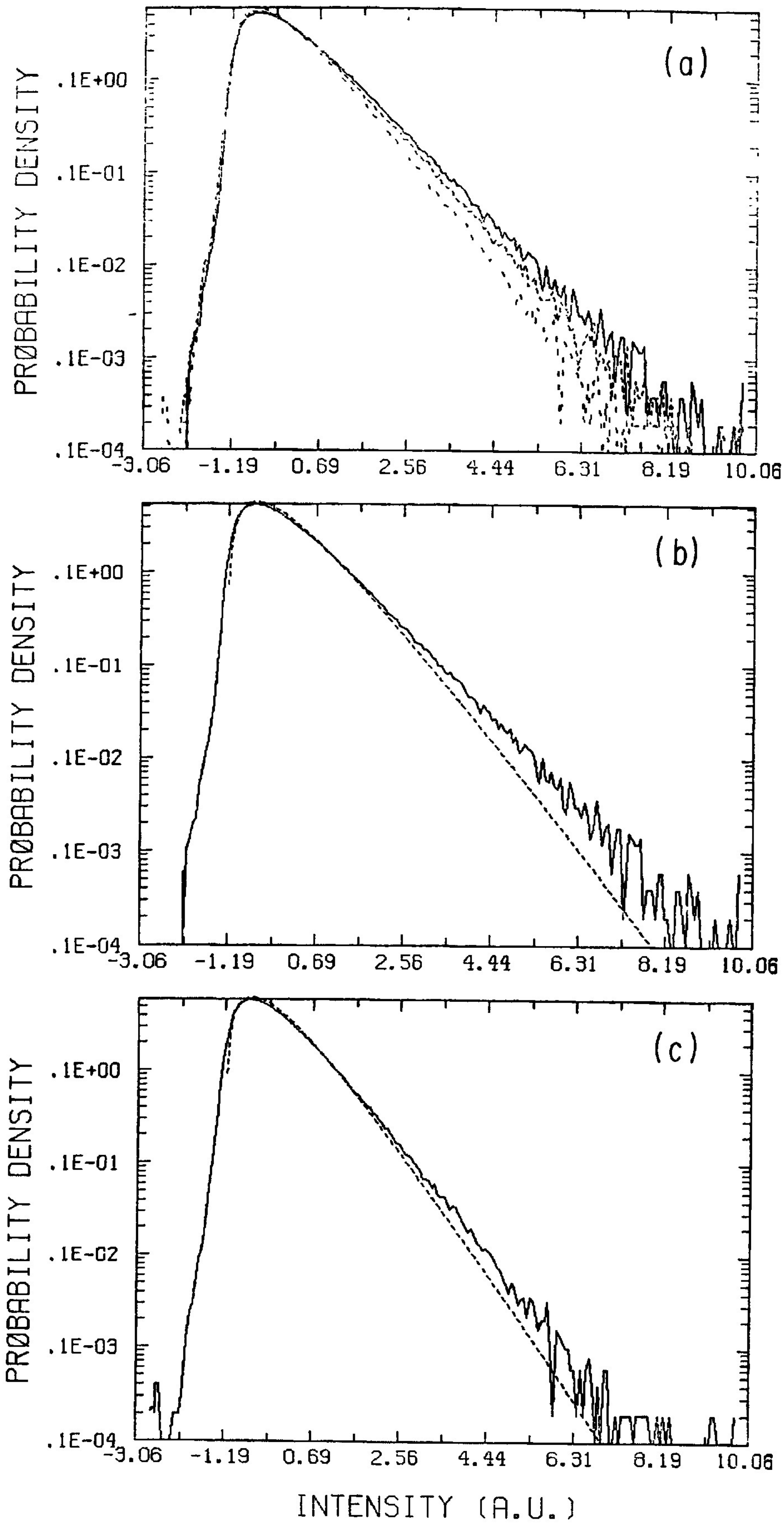


Fig. 3 Intensity histograms of 35 000 pulses from PSR 1937+214 at 431 MHz. (a) main pulse (———), interpulse (----) and off-pulse (-- --), (b) comparison of the main pulse histogram (——) with the theoretical χ^2 distribution with 4 degrees of freedom (----), (c) same as (b) for off-pulse histogram.

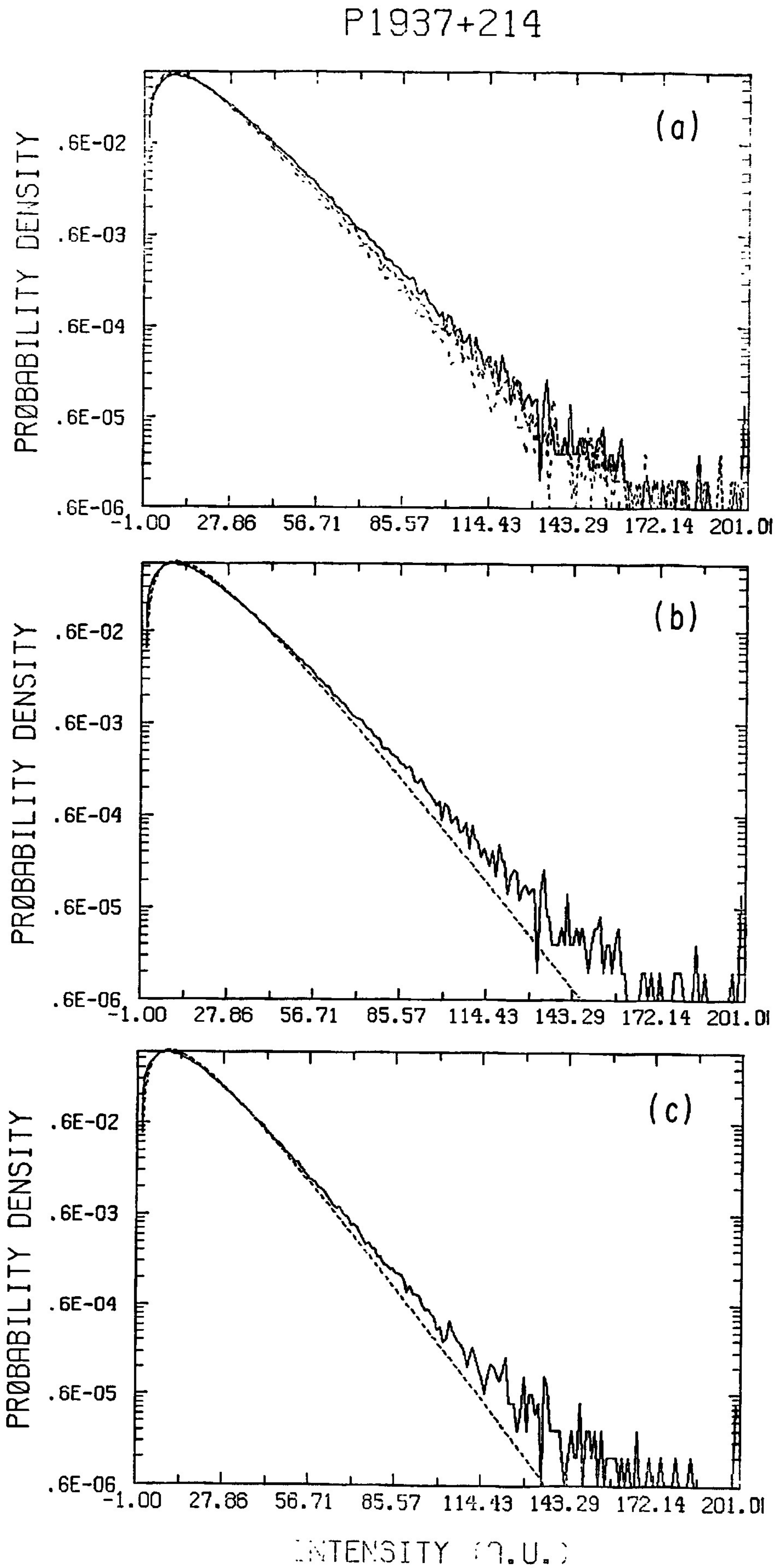


Fig. 4 Intensity histograms of 24 000 pulses from PSR 1937+214 at 1413 MHz (see caption to Fig. 3).

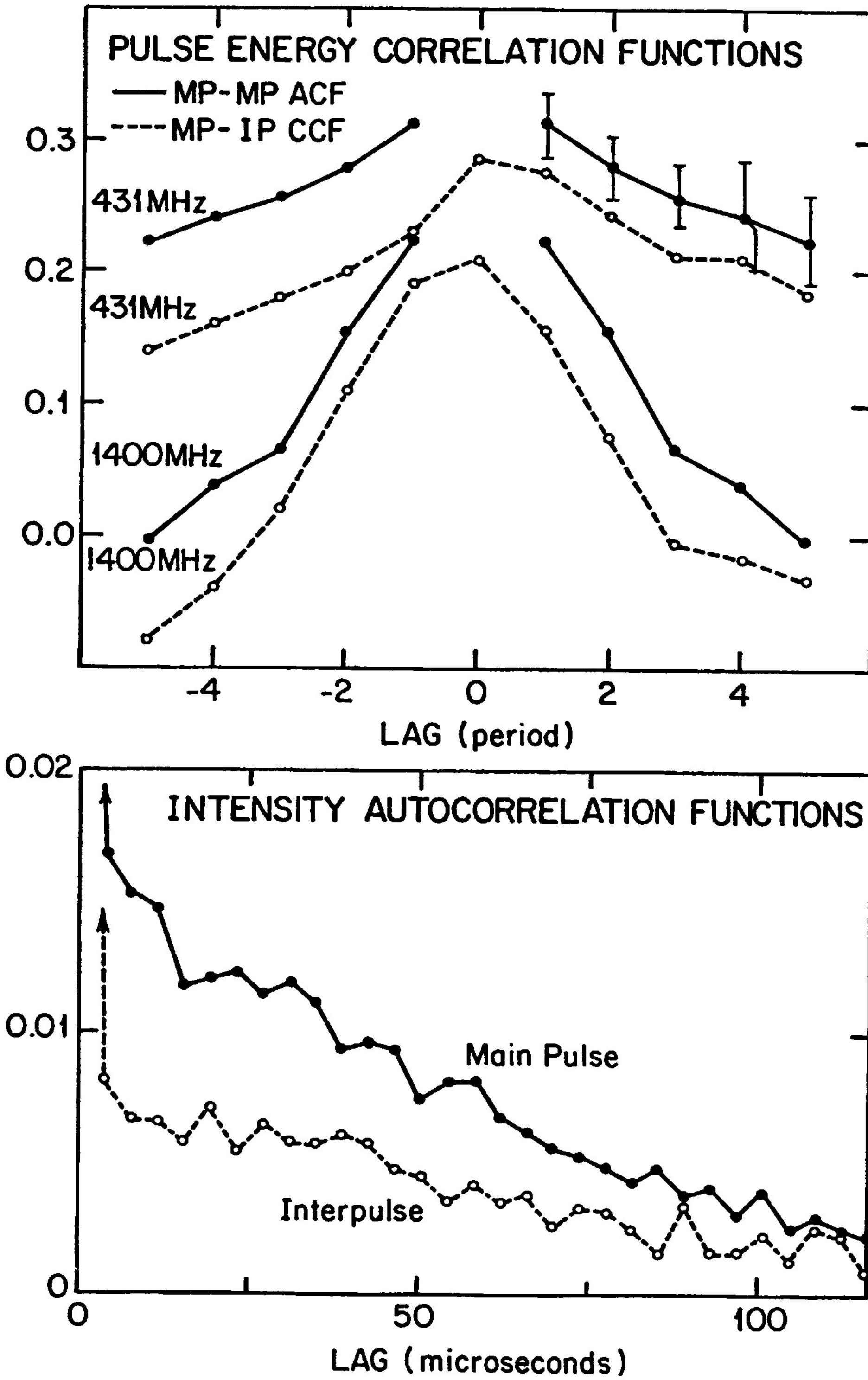


Fig. 5 Average intensity correlation functions for 24 000 pulses from PSR 1937+214. (a) Main pulse energy auto-correlations and cross-correlations between the main pulse and the interpulse versus pulsar period, (b) auto-correlations of the main pulse and the interpulse versus pulse phase.

II. LIFE HISTORY OF MILLISECOND PULSARS

THE ORIGIN OF NEUTRON STARS

Roger A. Chevalier

Department of Astronomy
University of Virginia, Charlottesville, VA 22903

ABSTRACT

Neutron stars are the likely outcome of the electron capture induced collapse of the O-Ne-Mg cores of 8 - 10 $M_{\odot}$ stars and the photodisintegration induced collapse of the Fe-Ni cores of more massive stars. Stars with mass > 100 $M_{\odot}$ do not leave neutron star remnants. Carbon ignition in the core of a 4 - 8 $M_{\odot}$ star is likely to lead to complete disruption, but collapse may be a possibility. The cores of stars with initial mass $\lesssim$ 10 $M_{\odot}$ can become white dwarfs in binary systems. The O-Ne-Mg white dwarfs probably form neutron stars. Observations which bear on these theoretical scenarios are reviewed.

INTRODUCTION

The existence of neutron stars in the Galaxy has been clear since the discovery of pulsars in the late 1960's. The detailed mechanisms by which neutron stars form have remained obscure. One problem that has been encountered is that C-O (carbon-oxygen) cores tend to disrupt completely due to energy input from nuclear burning. Another problem is that in the collapse of the central core of a star, it is necessary to eject the matter outside the core in order to avoid the formation of a black hole. Until recently, there appeared to be severe difficulties with obtaining an explosion.

This review is divided into three parts. The first part discusses the formation of neutron stars from the collapse of the cores of relatively massive, single stars. The second part deals with the collapse of white dwarfs, and the final part discusses the observational evidence for the various types of neutron star formation mechanisms.

MASSIVE SINGLE STARS

The possible final states of a star are a white dwarf (WD), a neutron star (NS), a black hole (BH), or complete disruption.

Evolutionary computations should show which final state applies to a star of a particular initial mass. Table 1 summarizes our present knowledge of the fate of single stars (see Carr, Bond, and Arnett 1984). Neutron stars are possible final states for stars in three different mass ranges and I discuss these in turn.

Table 1
SINGLE STARS

Mass ($M_\odot$)		Fate
0.5 - 4	Planetary nebula	CO WD
4 - 8	Mass loss	CO WD
	or	
	Degenerate Carbon ignition	Disruption or NS?
8 - 10	O - Ne - Mg core	NS
12 - 100	Fe - Ni core	NS or BH
10^2 - 10^5	Pair unstable O core	Disruption or BH
> 10^5	Never dynamically stable	Disruption or BH

a) 4 - 8 $M_\odot$ Stars

If stars in this range do not lose mass, they evolve to degenerate C ignition. However, mass loss can allow a white dwarf remnant with mass < 1.4 $M_\odot$. Estimates of the upper mass limit for white dwarf formation can be obtained from observations of white dwarfs in open clusters. A recent estimate of the upper mass limit is 8^{+3}_{-2} $M_\odot$ (Reimers and Koester 1982).

It is possible that degenerate C ignition does not occur in the 4 - 8 $M_\odot$ range. However, it may occur for 6 - 8 $M_\odot$ stars and it is likely to be important for white dwarf evolution in some cases. Calculations of degenerate C ignition go back to the detonation calculations of Arnett (1969), but the final outcome is still uncertain. The evolutionary process and its associated computational difficulties have been summarized by Müller and Arnett (1984). The C - O degenerate core grows as a result of mass addition by the He burning shell. The increased core mass leads to contraction, heating, and increased temperature in the core. Initially the energy input from nuclear reactions ($^{12}C + {}^{12}C$ burning) is small compared to energy losses by neutrinos. When the temperature reaches about 4 x 10^8 K, these two rates are approximately equal. This is the initial point of instability. The C burning rate is highly temperature dependent so a steep temperature gradient develops. This gives rise to convective instability. While there are convective motions, the core remains in approximate equilibrium. However the temperature continues to increase and eventually the timescale for the temperature increase is about equal to the sound-travel time across the core. This point of thermal runaway occurs when $T \approx 10^9$ K. Equilibrium is no longer possible and a burning front moves out through the star. If the burning front is supersonic, it is a detonation wave; if it is subsonic, it is a deflagration wave.

One-dimensional computations of this evolution have treated the convection with a mixing length formalism. A difficulty is that the temperature gradient can become so steep that the temperature scale length is less than the mixing length. The formalism breaks down under these circumstances. Another difficulty is that the burning front may be spread over several computational zones, which increases the effective speed of the burning front. It appears to be for these reasons that Arnett (1969) obtained the detonation and complete disruption of the core. More recent computations have shown the possibility of deflagration waves. However, the mixing length, which is an uncertain parameter, is related to the speed of the deflagration wave. Nomoto, Sugimoto, and Neo (1976) found a variety of possible outcomes depending on their choice for the velocity of the burning front. Their choice of parameters always led to complete disruption, but there may be some region of parameter space which allows electron captures to compete with nuclear energy generation and leads to collapse. This would require a slow deflagration wave.

In order to overcome some of the difficulties with one-dimensional computations, Müller and Arnett (1982, 1984) have undertaken two-dimensional computations of degenerate C ignition. For numerical reasons (the large number to timesteps involved), they could not start their calculations at the point of instability. They started at the thermal runaway stage by assuming that a certain amount of mass was at the "flash" temperature -- 2.8×10^9 K. In one model, they assumed 5×10^{-3} $M_\odot$ was at this temperature and a spherical detonation resulted. With 5×10^{-5} $M_\odot$ at this temperature, a non-spherical deflagration front developed. Based on computations with different grid-resolution, they concluded that the actual front is turbulent, inhomogeneous but (on average) roughly spherical. All their computations led to complete disruption of the core. However, there may be the possibility of collapse if the initial mass at thermal runaway is very small. Computations between the point of instability and of thermal runaway need to be carried out.

Recent computations of degenerate C ignition have shown the complete disruption of the core. This outcome has been preferred, based on the observational evidence that Type I supernovae result in the disruption of the progenitor. The question of whether a neutron star is a possible outcome has not yet been definitively answered.

b) 8 - 10 $M_\odot$ Stars

Stars with mass > 8 $M_\odot$ burn carbon under nondegenerate conditions and go on to develop O - Ne - Mg cores. When the O - Ne - Mg core mass reaches 1.37 $M_\odot$, Ne burning is expected (Nomoto 1984a). In stars with mass $\lesssim$ 10 $M_\odot$, the core becomes degenerate before Ne ignites. Thus, degenerate O - Ne - Mg cores develop in the mass range 8 - 10 $M_\odot$, which corresponds to He cores in the range 2.0 - 2.5 $M_\odot$.

Evolutionary calculations show that once the He burning shell reaches M = 1.375 $M_\odot$, there are rapid electron captures on ^{24}Mg and ^{20}Ne (Miyaji et al. 1980; Nomoto 1984a). These captures induce the collapse of core. Hillebrandt, Nomoto, and Wolff (1984) have followed the collapse through bounce of the outer core and explosion for a 9 $M_\odot$ star. The outer ~ 0.1 $M_\odot$ of the core was ejected with a total energy of about 2 x 10^{51} ergs. The mass cut for the collapse was at 1.2 $M_\odot$, but a rarefaction wave may increase this mass. The explosion was especially energetic for two reasons: the steep density gradient at the He burning shell and the effect of O burning in decelerating matter infalling on the core.

c) 12 - 100 $M_\odot$ Stars

The evolution of stars with mass just above 10 $M_\odot$ is complex and has not yet been definitively calculated (Nomoto 1984a). However, stars in the mass range 12 - 100 $M_\odot$ probably develop Fe - Ni cores with masses of about 1.5 $M_\odot$. Collapse of the core is induced by nuclear photodisintegrations. A compact object does form, but unless there is an explosion of the outer parts of the core, collapse to a black hole is inevitable. Investigations of the possible explosion have emphasized the core bounce mechanism, but the computations have generally not shown an explosion (for a review, see Hillebrandt 1982). A major problem is the energy loss of the outgoing shock wave to the dissociation of heavy nuclei. Another factor is that unlike the O - Ne - Mg cores, the structure does not change at the core - envelope boundary.

There have been two recent developments which are promising for explosion and neutron star formation. The first concerns the Fe - Ni core masses of massive stars at the time that collapse starts. The standard initial collapse configurations came from the Weaver, Zimmerman, and Woosley (1978) calculations for the evolution of 15 $M_\odot$ and 25 $M_\odot$ stars. The calculations have been repeated by Weaver, Woosley, and Fuller (1984) with revised nuclear reaction rates and improved numerical zoning. The new results show a decrease in the Fe core masses. For example, the core mass of the 25 $M_\odot$ model went from 1.61 $M_\odot$ (old) to 1.35 $M_\odot$ (new). The decreased mass is expected to reduce the effects of energy loss to nuclear dissociation, but the detailed implications of the change for core bounce have not yet been investigated.

The second development is the calculation of core collapse to late times (Wilson and Bethe 1984). The initial bounce of the core takes place on a timescale of less than 10 msec. Wilson found in his computations that the outgoing bounce shock stalled on this timescale. It became an accretion shock due to the infalling outer core. With time the density at the accretion shock decreased. On the other hand, the flux of neutrinos diffusing out of the core remained relatively constant. Eventually, the heating of the postshock gas by the neutrinos was able to re-energize the shock wave and generate an explosion with energy $2 - 4 \times 10^{50}$ ergs. The timescale for the explosion was about 0.5 sec. The resulting neutron star masses (uncorrected for neutrino losses) were 1.48 (old 10 $M_{\odot}$), 1.76 $M_{\odot}$ (old 15 $M_{\odot}$) and 1.66 $M_{\odot}$ (new 25 $M_{\odot}$), where "old" and "new" refer to the computations of Weaver, Woosley, and their collaborators. It can be seen for the 25 $M_{\odot}$ model that the neutron star mass is about 0.3 $M_{\odot}$ larger than the initial Fe core mass due to the prolonged period of infall. These computations show an interesting new mechanism for explosion and it is important for other workers to confirm them.

WHITE DWARFS

Most of the mechanisms for the collapse of white dwarfs involve accretion onto white dwarfs in binary systems. Depending on the initial stellar masses and the binary separation, the accreting white dwarf can be primarily composed of He, C - O, or O - Ne - Mg. Table 2 summarizes the possible outcomes of the various types of accreting white dwarfs.

Table 2
WHITE DWARFS IN BINARIES

Type of WD		Fate
He	Detonation	Disruption
C - O	Detonation	Disruption
	Deflagration	Disruption or NS?
	Crystallization and collapse	NS
O - Ne - Mg	Collapse	NS

A He white dwarf can result from a relatively low mass star. As the He core approaches a mass of 0.7 $M_\odot$, He ignition occurs and a detonation wave passes through the star (Nomoto and Sugimoto 1977). The nuclear energy generation is much larger than the binding energy and complete disruption is the result.

Accretion onto C - O white dwarfs offers a variety of possible outcomes, depending on the details of the accretion process (Fujimoto and Taam 1982; Nomoto 1984b). I consider here accretion of H or He at a rate $\dot{M}$. For $\dot{M} \lesssim 10^{-9}$ $M_\odot$ yr^{-1}, the outcome depends on the mass of the C - O core, M_{c-o}. If $\dot{M}_{c-o} \lesssim 1.2$ $M_\odot$, there is detonation of the accumulated He layer. In general, the He detonation transfers sufficient energy to the C - O core to disrupt it. However, for M_{c-o} close to 1.2 $M_\odot$, a white dwarf is a possible remnant. If $M_{c-o} \gtrsim 1.2$ $M_\odot$, central C ignition occurs and the outcome will be like that of the cores of 4 - 8 $M_\odot$ stars discussed above. However, a white dwarf accreting H at this low rate may never reach the critical mass because of mass loss from H flashes (novae).

For $10^{-9} < \dot{M} \lesssim 5 \times 10^{-8}$ $M_\odot$ yr^{-1}, the detonation of the accumulated degenerate He layer is able to drive a detonation wave into the C - O core. The result is a double detonation which completely disrupts the star. For $5 \times 10^{-8} < \dot{M} \lesssim 10^{-6}$ $M_\odot$ yr^{-1}, central C ignition occurs. This regime has been considered plausible for the occurrence of Type I supernovae. For $\dot{M} > 10^{-6}$ $M_\odot$ yr^{-1} the accumulation of He is faster than it can burn, so an extended envelope develops. The eventual outcome should be central C ignition.

None of the above explosive phenomena for accreting C - O white dwarfs may leave a neutron star remnant. However, they do not take into account the possible crystallization of the white dwarf (Isern et al. 1983). Isern et al. estimate that crystallization occurs if the central temperature $T_c \lesssim 5 \times 10^7$ K; this requires cooling over a time $\gtrsim 10^9$ years. Crystallization can have two important consequences. The first is separation of the carbon and oxygen. The C - O forms into a solid in the ratio $^{12}C/^{16}O \approx 2$ by number, but the abundances of C and O are about equal by mass. The leftover O may fall to the center of the core. Then there is either collapse induced by electron captures on ^{16}O or off-center C ignition. The outcome of the first process is a neutron star and that of the second is unclear. The second consequence applies whether or not the element separation occurs. If there is ignition at the center of a solid core, the burning front must propagate by conduction instead of convection (Isern, Labay, and Canal 1984). While the propagation of a conduction front is not well understood, it is likely that it is relatively slow so that electron captures can compete with energy generation by nuclear reactions. Core collapse and neutron star formation is likely; the neutron star mass may vary depending on the amount of the core that was solid at the time of central ignition.

Accretion onto O - Ne - Mg white dwarfs can give rise to neutron star formation in the same way as that described for the cores of 8 - 10 $M_\odot$ stars. In general, a strong explosion involving the outer $\sim 0.1\ M_\odot$ of the core is expected. The explosion might be avoided if the white dwarf is relatively rapidly rotating, as is expected if it accretes mass from a disk. In this case the collapse and bounce is stalled by rotation and the neutron star forms on a dissipative timescale (e.g. Tohline 1984).

I have discussed accretion of H and He onto white dwarfs at moderate rates. Another possibility that has recently been proposed is the merging of a double white dwarf system (Iben and Tutukov 1984; Webbink 1984). If the system has two C - O white dwarfs, rapid accretion of C - O is expected. The final outcome of this and other white dwarf binaries has yet to be explored.

The above discussion concerns white dwarfs in binary systems. There have also been suggestions that collapse or explosion might occur for single white dwarfs under particular circumstances. One idea uses the fact that a rapidly rotating white dwarf can have a mass greater than the Chandrasekhar limit for a nonrotating star. Ostriker (1971) suggested that a strongly magnetic, rapidly rotating white dwarf would lose angular momentum due to magnetic dipole radiation. However, such a white dwarf may be difficult to form because of its strong coupling to slowly rotating matter outside of the core.

Durisen (1973) noted that uniformly rotating white dwarf models exist only for masses $M < M_* \approx 1.5\ M_\odot$. A differentially rotating white dwarf can have $M > M_*$. Viscous evolution indicates that all the angular momentum will be transferred out of the core to the outermost mass elements. The growth in mass of the almost uniformly rotating core will lead to an increase in the central density.

Another mechanism uses the fact that a hot white dwarf can have a mass somewhat higher than the mass limit for a cool star (e.g. Shklovsky 1978). As the star cools, the central density increases. The problem with this mechanism is the very small mass range available to the hot white dwarf (within about $10^{-4}\ M_\odot$ of the mass limit).

The final outcome of these single star scenarios depends on the composition of the white dwarf. A C - O white dwarf undergoes central C ignition and probable disruption. An O - Ne - Mg white dwarf undergoes collapse and neutron star formation.

OBSERVATIONAL EVIDENCE

a) Extragalactic Supernovae

Extragalactic supernovae have been observed to be intense sources of radio emission, which is likely to be synchotron emission (Weiler et al. 1983). Pacini and Salvati (1981) and Shklovsky (1981) suggested that the emission is related to a newly born pulsar. The initial rotation period of the pulsar would have to be $\lesssim$ 10 msec (Bandiera, Pacini, and Salvati 1983). A problem with this interpretation is the large amount of free-free absorption by the supernova envelope; it is necessary for the envelope to have completely fragmented. Chevalier (1982) suggested that the emission is unrelated to a central pulsar, but is due to the interaction of the supernova with the circumstellar wind from the progenitor star. This model not only fits the detailed radio light curves, but also is consistent with observations of the supernovae at other wavelengths (Chevalier 1984).

The effects of absorption are smaller at optical wavelengths so that a central pulsar might be observed soon ($\lesssim$ 1 year) after the explosion. Middleditch and Kristian (1984) searched for optical pulsations in the frequency range 0 - 500 Hz from SN 1885, SN 1970g, SN 1979c, SN 1980k, and SN 1981b. They found no pulsations and set a luminosity limit of about 10^5 $L_\odot$. This is approximately the luminosity that would be expected for a rapidly rotating neutron star with a normal pulsar magnetic field.

The optical light curves of both Type II and Type I supernovae are well explained without invoking energy input from a central pulsar. In fact, models for the light curves of Type I supernovae support the hypothesis of the complete disruption of the progenitor star (Chevalier 1981; Weaver, Axelrod, and Woosley 1980; Sutherland and Wheeler 1984). If a pulsar is present inside of a supernova, it should transfer energy to the supernova gas. This gas may radiate with a characteristic signature. The strongest limits on pulsar energy input may come at late times (several years) when the optical luminosity is low.

b) Supernova Remnants

The Crab Nebula and its central pulsar are the most prominent association between a neutron star and a supernova remnant. The abundances in the nebula and the total mass of He are consistent with a progenitor star in the mass range 8 - 10 $M_\odot$ (Nomato 1983). This would make it an electron capture supernova with a total energy of about 2 x 10^{51} ergs. The low energy in the observable nebula implies the presence of a fast envelope which has not yet been observed. If the currently observed braking index for the Crab pulsar applies to its whole evolution, the initial pulsar period was 19 msec.

A recently discovered pulsar-supernova remnant association is the 50 msec X-ray pulsar in the remnant 0540-693 in the LMC (Seward, Harnden, and Helfand 1984). The supernova remnant is of the oxygen-rich variety (Mathewson et al. 1980), so that the progenitor star probably had a mass $\gtrsim 15\ M_{\odot}$. Thus the neutron star formation probably involved Fe-core collapse. From models for the nebula and pulsar, Reynolds (1984) deduced that the initial pulsar period was 34 ± 5 msec.

Cas A and the remnants of SN 1006, SN 1572, and SN 1604 show no sign of a central neutron star; there are no pulsations, sychrotron nebulae, or thermal X-rays from a hot neutron star. The lack of pulsations can be attributed to beaming effects and the lack of synchrotron nebulae can be attributed to the pulsar's slow rotation or small magnetic field. However, the lack of thermal X-ray emission from a compact source in the SN 1006 and SN 1572 remnants suggests that a neutron star is not present (Nomoto and Tsuruta 1983; van Riper 1983). These remnants are thought to be the result of Type I supernovae, which may involve central C ignition in a C - O white dwarf.

Another remnant of interest is G 109.1 - 1.0, which has radio and X-ray shells (Gregory et al. 1983), and a central 7 sec X-ray pulsar (Fahlman and Gregory 1983) which has a high probability of being associated with the shell (Helfand and Becker 1984). The pulsar appears to be in a binary system with a low mass companion. The presence of a neutron star in a low mass binary with evidence for an explosion suggests the collapse and bounce of an O - Ne - Mg white dwarf. With the small mass ejection, it would not have been an optical supernova. One difficulty with this suggestion is that the neutron star may not be able to accrete mass from its companion so soon ($\sim 10^4$ yr) after the explosion. The companion is not expected to be filling its Roche lobe (van den Heuvel, private communication).

c) Pulsars and X-Ray Sources

Most pulsars and Population I X-ray sources are probably the result of core collapse of stars with initial mass in the range 8 - 100 $M_{\odot}$. The pulsar birthrate, 1 per 20 to 50 years in the Galaxy (Lyne 1982) is approximately equal to the birthrate of these stars and to the rate of Type II supernovae (Tammann 1982). The spatial distribution of pulsars is consistent with their formation from a young stellar population (Lyne 1982). One problem with this pulsar origin is lack of evidence for central sources in supernova remnants (Helfand and Becker 1984) and the estimated low birthrate of objects like the Crab Nebula (Srinivansan et al. 1984). There are two possible solutions. The first is that newly formed neutron stars generally have small magnetic fields (Blandford, Applegate, and Hernquist 1983). The second is that most pulsars are born slowly rotating (Srinivasan et al. 1984).

Other mechanisms for neutron star formation proceed at a lower rate. The Population II or bulge X-ray sources may involve the collapse of an O - Ne - Mg white dwarf in a binary (van den Heuvel 1981), although these binaries may also be the result of capture. The collapse of a white dwarf in a binary system is also indicated by evolutionary considerations for some of the binary pulsars (e.g. Blandford and de Campli 1981).

The initial periods of the pulsars in the Crab Nebula and 0540 - 693 are about 19 msec and 34 msec, respectively. The lack of objects like the Crab Nebula may imply that its pulsar is an exceptionally fast rotator. The implication is that most core collapses do not form rapidly rotating neutron stars. This may be the result of a coupling of stellar cores with envelopes by means of a magnetic field. Rapidly rotating neutron stars are more likely to form from the collapse of white dwarfs which have been accreting from a disk. DQ Her (period = 71 sec) is one example of a rapidly rotating white dwarf in a binary system.

REFERENCES

Arnett, W. D. 1969, Ap. Space Sci, 5, 180.

Bandiera, R. Pacini, F., and Salvati, M. 1983, subm. to Ap. J.

Blandford, R. D., Applegate, J. H., and Hernquist, L. 1983, M.N.R.A.S., 204, 1025.

Blandford, R. D. and De Campli, W. M. 1981, in IAU Symp. 95, eds. W. Sieber and R. Wielebinski (Dordrecht: Reidel), 371.

Carr, B. J., Bond, J. R., and Arnett, W. D. 1984 Ap. J., 277, 445.

Chevalier, R. A. 1981, Ap. J., 246, 267.

Chevalier, R. A. 1982, Ap. J., 259, 302.

Chevalier, R. A. 1984, Ann. N.Y. Acad. Sci., 422, 215.

Durisen, R. H. 1973, Ap. J., 183, 215.

Fahlman, G. G. and Gregory, P.C. 1983, in IAU Symp. 101, eds. I. J. Danziger and P. Gorenstein (Dordrecht: Reidel), p. 445.

Fujimoto, M. Y. and Taam, R. E. 1982, Ap. J., 260, 249.

Gregory, P. C., Braun, R., Fahlman, G. G., and Gull, S. F. 1983, in IAU Symp. 101, eds. I. J. Danziger and P. Gorenstein (Dordrecht: Reidel), p. 437.

Helfand, D. J. and Becker, R. H. 1984, Nature, 307, 215.

Hillebrandt, W. 1982 in Supernovae: A Survey of Current Research, eds. M. J. Rees and R. J. Stoneham (Dordrecht: Reidel), p. 123.

Hillebrandt, W., Nomoto, K., and Wolff, G. W. 1984, Astr. Ap., 133, 175.

Iben, I. and Tutukov, A. V. 1984, Ap. J. Suppl., 55, 335.

Isern, J., Labay, J. and Canal, R. 1984, Nature, 309, 431.

Isern, J., Labay, J., Hernanz, M., and Canal, R. 1983, Ap. J., 273, 320.

Lyne, A. G. 1982 in Supernovae: A Survey of Current Research, eds. M. J. Rees and R. J. Stoneham (Dordrecht: Reidel), p. 405.

Mathewson, D. S., Dopita, M. A., Tuohy, I. R., and Ford, V. L. 1980 Ap. J. (Letters), 242, L73.
Middleditch, J. and Kristian, J. 1984, Ap. J., 279, 157.
Miyaji, S., Nomoto, K., Yokoi, K., and Sugimoto, D. 1980, Publ, Astr. Soc. Japan, 32, 303.
Müller, E. and Arnett, W. D. 1982, Ap. J. (Letters), 261, L109.
Müller, E. and Arnett, W.D. 1984, subm. to Ap. J.
Nomoto, K. 1983, in IAU Symp. 101, eds. I. J. Danziger and P. Gorenstein (Dordrecht: Reidel), p. 139.
Nomoto, K. 1984a, Ap. J., 277, 791.
Nomoto, K. 1984b, in Collapse and Numerical Relativity (Dordrecht: Reidel), in press.
Nomoto, K. and Sugimoto, D. 1977, Pub. Astr. Soc. Japan, 29, 765.
Nomoto, K., Sugimoto, D. and Neo, S. 1976, Ap. Space Sci., 39, L37.
Nomoto, K. and Tsuruta, S. 1983, in IAU Symp. 101, eds. I. J. Danziger and P. Gorenstein (Dordrecht: Reidel), p. 509.
Ostriker, J. P. 1971, Ann. Rev. Astr. Ap., 9, 353.
Pacini, F. and Salvati, M. 1981, Ap. J. (Letters), 245, L107.
Reimers, D. and Koester, D. 1982, Astr. Ap., 116, 341.
Reynolds, S. P. 1984, this volume.
Seward, F. D., Harnden, F. R., Jr., and Helfand, D. 1984, IAU Circ. No. 3928.
Shklovsky, I. S. 1978, Sov. Astr. A. J., 22, 413.
Shklovsky, I. S. 1981, Sov. Astr. Letters, 7, 263.
Srinivasan, G., Bhattacharya, D., and Dwarakanath, K. S. 1984, preprint.
Sutherland, P. and Wheeler, J. C. 1984, Ap. J., 280, 282.
Tammann, G. in Supernovae: A Survey of Current Research, eds. M. J. Rees and R. J. Stoneham (Dordrecht: Reidel), 371.
Tohline, J. 1984, this volume.
Van den Heuvel, E. P. J. 1981, in IAU Symp. 93, eds. D. Sugimoto, D. Q. Lamb, and D. N. Schramm (Dordrecht: Reidel), p. 155.
Van Riper, K. A. 1983, in IAU Symp. 101, eds. I. J. Danziger and P. Gorenstein (Dordrecht: Reidel), p. 513.
Weaver, T. A. Axelrod, T. S., and Woosley, S. E. 1980, in Type I Supernovae, ed. J. C. Wheeler (Austin: University of Texas), p. 113.
Weaver, T. A., Woosley, S. E., and Fuller, G. M. 1984, in Numerical Astrophysics: In Honor of J. R. Wilson, eds. J. Centrella, L. Smarr, and J. LeBlanc (Science Books Intern.: Portola CA), in press.
Weaver, T. A., Zimmerman, G. B. and Woosley, S. E. 1978, Ap. J., 225, 1021.
Webbink, R. F. 1984, Ap. J., 277, 355.
Weiler, K. W. Sramek, R. A., van der Hulst, J. M., and Panagia, N. 1983, in IAU Symp. 101, eds. I. J. Danziger and P. Gorenstein (Dordrecht: Reidel), p. 171.
Wilson, J. R. and Bethe, H. A. 1984, preprint.

DISCUSSION OF CHEVALIER'S PAPER

RUDERMAN: What would you be willing to say now about predicted birth rates for neutron stars in the galaxy?

CHEVALIER: One would guess that most or all Type II supernovae would give rise to a neutron star; so that would be something like one per 40 or 50 years. With the other types of formation mechanisms I've talked about here, they are probably at a rate which is lower than that of Type II supernovae; so I think they would be a small perturbation on that total rate.

STINEBRING: You mentioned that it was hard to form rapidly rotating, highly magnetized white dwarfs. Why is that?

CHEVALIER: If you have a highly magnetic system, the core might be connected with the outer parts of the star, so that you would never get it rapidly rotating to begin with.

MANCHESTER: The Crablike remnant in the LMC, 0540-693: What type of supernova do you think that was?

CHEVALIER: It would have been the explosion of a massive star, so probably a Type II--although I think that the comparable system, Cas A (at least as far as having the oxygen-rich material) was probably neither a Type II nor a Type I, but some kind of a faint explosion, perhaps because it lost its envelope. So 0540-693 would have been the explosion of a massive star, probably at least 15 solar masses. It could well have been a Type II, but not necessarily.

MANCHESTER: I'm a bit confused about what produces Type II and what produces Type I, then. What type of explosion produces Type II?

CHEVALIER: The explosion of a star in the mass range 8 - 100 solar masses. But if you have a lot of mass loss from the star before the explosion as seems to have occurred for Cas A, you may not have a red-supergiant envelope, and you get a fainter explosion, perhaps by 6 or 7 magnitudes. So, depending on whether there's a lot of mass loss, such an explosion may or may not be a Type II supernova. The Type I's are thought to come from the explosion of white dwarfs in binary systems, although that's still debatable.

VAN DEN HEUVEL: What about these models of Iben and Tutukov, who tried to make (in my opinion in a very nice way) neutron stars by the coalescence of two white dwarfs which came from a very wide binary of intermediate mass?

CHEVALIER: Yes, there are a lot of possibilities there; I just didn't have the time to talk about them.

VAN DEN HEUVEL: They get a high rate.

CHEVALIER: The other reason that I didn't talk about it is that it is not really clear what the outcome of that process is--whether it is a complete explosion, or whether you get a neutron star left. The picture I showed about the white dwarfs assumed that the accreting material was hydrogen or helium. Iben and Tutukov mainly look at two carbon-oxygen white dwarfs coming together, so one accretes a lot of carbon and oxygen onto a C - O white dwarf, and a lot of things can happen. The final outcome of that state is not really clear yet.

BACKER: What would brake the neutron star spin-up in a core collapse, to keep its period to ten milliseconds rather than one?

CHEVALIER: It's not during the collapse, but in the pre-supernova stage, that if there is a coupling between the core and the envelope, the kinds of angular momentum you have left wouldn't be that large.

BACKER: Just like star formation.

RUDERMAN: Don't you feel that when numerical calculations include angular momentum it will not make that much difference?

CHEVALIER: Well, if a magnetic field is also put in, it's very hard to say. There have been some attempts to do the calculation of a rapidly rotating core of a 25 solar mass star, by Bodenheimer and Woosley, but their boundary condition was not very well done: they just mocked up a central collapse. They ended up with a 3 - 4 solar mass black hole and most of the material spewed out in a plane perpendicular to the rotation axis. That's one of the only attempts to put rotation into the final evolution of a star. But they didn't consider the interaction between the core and the outer parts of the star.

MODELS FOR THE FORMATION OF BINARY AND MILLISECOND RADIO PULSARS

Edward P.J. van den Heuvel

Astronomical Institute University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam The Netherlands

ABSTRACT

The peculiar combination of a relatively short pulse period and a relatively weak surface dipole magnetic field strength of binary radio pulsars finds a consistent explanation in terms of: (i) decay of the surface dipole component of neutron star magnetic fields on a timescale of $(2-5).10^6$ yrs, in combination with: (ii) spin up of the rotation of the neutron star during a subsequent mass-transfer phase.

The two observed classes of binary radio pulsars (very close and very wide systems, respectively) are expected to have been formed by the later evolution of binaries consisting of a neutron star and a normal companion star, in which the companion was (considerably) more massive than the neutron star, or less massive than the neutron star, respectively. In the first case the companion of the neutron star in the final system will be a fairly massive white dwarf, in a circular orbit, or a neutron star in an eccentric orbit. In the second case the final companion to the neutron star will be a low-mass ($\sim 0.3\ M_{\odot}$) helium white dwarf in a wide and nearly circular orbit.

In systems of the second type the neutron star was most probably formed by the accretion-induced collapse of a white dwarf. This explains why PSR 1953+29 has a millisecond rotation period and why PSR 0820+02 has not. Binary coalescence models for the formation of the 1.5 millisecond pulsar appear to be viable. The companion to the neutron star may have been a low-mass red dwarf, a neutron star, or a massive ($> 0.7\ M_{\odot}$) white dwarf. In the red-dwarf case the progenitor system probably was a CV binary in which the white dwarf collapsed by accretion.

INTRODUCTION

Four binary radio pulsars and one single millisecond pulsar are known, listed in table 1. One of the binary radio pulsars, PSR 1953+29, is also a millisecond pulsar. Three of the binary radio pulsars as well as the single millisecond pulsar differ from the majority of the radio pulsars in having an unusually short pulse period P in combination with a very low spindown rate $\dot{P}$ (see table 1).

This indicates that they have an unusually weak surface dipole magnetic field, as the strength B_s of this field is expected to be proportional to $(\dot{P}\,.P)^{1/2}$ (see next section). As a result they occupy peculiar positions in the B_s vs. P diagram - and its equivalent: the $\dot{P}$ vs. P diagram - of radio pulsars, as can be seen in figure 1 (see also Backus et al. 1982).

A model in which the peculiar (P, B_s) combination of PSR 1913+16 is linked to the evolutionary history of its binary system was proposed by Smarr and Blandford (1976) and further worked out by Srinivasan and Van den Heuvel (1978, 1982), Radhakrishnan and Srinivasan (1981), Sutantyo (1981) and Alpar et al. (1982). In this model the neutron star is already fairly old (> 10^7 yrs), but later in its life underwent spin up by accretion, when its companion evolved to the giant stage. At this moment the surface magnetic field of the old neutron star had already partly decayed and the result of the accretion was: a rapidly rotating neutron star with an unusually weak surface dipole magnetic field. After the end of the nuclear evolution of the companion, this "recycled" neutron star became observable as a radio pulsar in a binary. This explanation for the origin of PSR 1913+16 was considerably strengthened by the discovery of the second binary radio pulsar PSR 0655+64 which exhibits a similarly abnormal (P, B_s) combination (Damashek et al. 1982; Taylor 1981; Blandford and De Campli 1981; Van den Heuvel 1981). This led Radhakrishnan and Srinivasan (1981) to suggest that there is an entire class of "recycled" radio pulsars (see also Damashek et al. 1982). After the discovery of the 1.5 msec pulsar the existence of a class of "recycled" pulsars was independently suggested by Alpar et al. (1982), and a number of authors has suggested a variety of ways in which finally a single pulsar might remain (for a review see Ruderman and Shaham 1983a). The emphasis in this paper will be on a critical discussion of the binary recycling models for the origin of the binary and millisecond pulsars.

Table 1. Some important properties of the four binary radio pulsars and the single millisecond pulsar, together with estimates of their surface magnetic field strengths and of the masses of the companions in the binary systems.

Name	P_{orb}(d)	e	Mass function ($M_\odot$)	Most likely companion mass ($M_\odot$)	P_{pulse} (s)	B_s(G)	Ref.
PSR 1913+16	0.32	0.617	0.1322	1.40 ± 0.05	0.059	2×10^{10}	(1)
PSR 0655+64	1.03	0.000	0.0712	1.00 ± 0.30	0.196	8.6×10^{10}	(2)
PSR 0820+02	1232	0.012	0.00301	0.2 - 0.4	0.865	3.3×10^{11}	(3)
PSR 1953+29	~ 117	< 0.05	0.00272	0.2 - 0.4	0.0061	2.5×10^9 (predicted)	(4,5) (6,7)
PSR 1937+214					0.00155	5×10^8	(8)

(1) Taylor and Weisberg (1982)
(2) Damashek et al. (1982)
(3) Manchester et al. (1983)
(4) Boriakoff et al. (1983)
(5) Buccheri (1983, private commun.)
(6) Helfand et al. (1983)
(7) This paper
(8) Backer (1984).

THE SPIN-HISTORY OF SINGLE AND BINARY NEUTRON STARS

Spindown and magnetic field decay

The energy loss rate of a rotating magnetized neutron star is of order

$$\frac{dE}{dt} = \left(\frac{2}{3} \frac{R^6}{c^2} \right) B_s^{\ 2} \ \Omega^4 \qquad (1)$$

where B_s is the dipole strength of the magnetic field at the stellar surface, Ω is the angular velocity of rotation and R is the stellar radius (see for example Manchester and Taylor 1977).

As expression (1) is equal to the rate of rotational energy loss of the neutron star, one has

$$B_s = \left(\frac{3\, I\, c^3}{8\, \pi^2\, R^6} \right)^{1/2} \cdot (P.\dot{P})^{1/2} \qquad (2)$$

where I is the moment of inertia of the neutron star. The B_s-values in figure 1 (which was adapted from Radhakrishnan and Srinivasan 1981) were derived from the observed P and $\dot{P}$ values of radio pulsars (Manchester and Taylor 1981) under the assumption that all neutron stars have the same moment of inertia $I = 10^{45}$ gm.cm^2, and the same radius, R = 10 km. The figure shows that most radio pulsars have surface dipole magnetic field strengths between $10^{11.5}$ and $10^{13.5}$ G.

Proper motion measurements for several dozens of radio pulsars indicate that pulsars tend to be born with high space velocities, on the average $\sim$ 180 km/sec (Lyne 1981). The observed proper motions tend to be directed away from the galactic plane, indicating that most pulsars are born close to this plane (Gunn and Ostriker 1970). The proper motion together with the distance to the galactic plane yield the "kinetic age" τ_k of the pulsar. It appears that (cf. Manchester and Taylor 1977; Lyne 1981):
(a) practically all pulsars have $\tau_k < 10^7$ yrs, indicating that pulsars turn off on about this timescale; (b) for $\tau_k > 5.10^6$ yrs, the spin-down ages $\tau_{sd} = P/2\dot{P}$ become systematically (much) larger than the kinetic ages.
The latter observations suggest that for true ages $> 5.10^6$ yrs, the spin-down rates $\dot{P}$ decrease much faster than would be expected, according to eq. (2), if the surface dipole magnetic field strength of the pulsar remained constant. The most straightforward interpretation for the rapid drop in $\dot{P}$ for ages $> 5.10^6$ yrs is that the B_s-values of pulsars decay on a timescale of order (2-5).10^6 yrs (Lyne 1981). The alternative suggestion that the decrease of $\dot{P}$ is due to alignment of the rotation axis and the magnetic axis is less likely for a variety of theoretical and observational reasons (see Taam and Van den Heuvel 1984.) The evolutionary tracks in figure 1 were calculated under the assumption that radio pulsars are born in the upper left-hand part of the figure, with a short period and a relatively strong field, and that the dipole strength of the field decays on a timescale τ_D of 2.10^6 yrs or 4.10^6 yrs. When they are young, their large energy loss rate implied by eq. (1) causes them to move rapidly towards the right along a horizontal track. When their age exceeds a few million years, the field decay causes the tracks to curve downwards, becoming nearly vertical in the end.
For pulsars which were born at the same time in the upper left-hand part of the diagram the "timelines" of 10^3 yr, 10^4 yr, 10^5 yr, 10^6 yr, etc. indicate the positions at these respective ages, for $\tau_D = 2.10^6$ yrs. For $\tau_D = 4.10^6$ yrs the corresponding ages are about twice as large.

Turn-off radio pulsars: the "graveyard".

Figure 1 shows that at the right-hand side of a "death line" in the B_s vs. P diagram no radio pulsars are found (the drawn line is the Ruderman-Sutherland, 1975, "deathline"). This in combination with the fact that hardly any pulsars have true ages $> 10^7$ yrs, suggests that when a pulsar on its evolutionary track crosses the "death-line", the emission of its pulsed radiation turns off.
Figure 1 suggests that with the exception of a few peculiar objects such as the binary and millisecond radio pulsars, all radio pulsars are born

with a relatively short period and a relatively strong surface dipole magnetic field, in the range $10^{12-13.5}$ G. (cf. Flowers and Ruderman 1977).

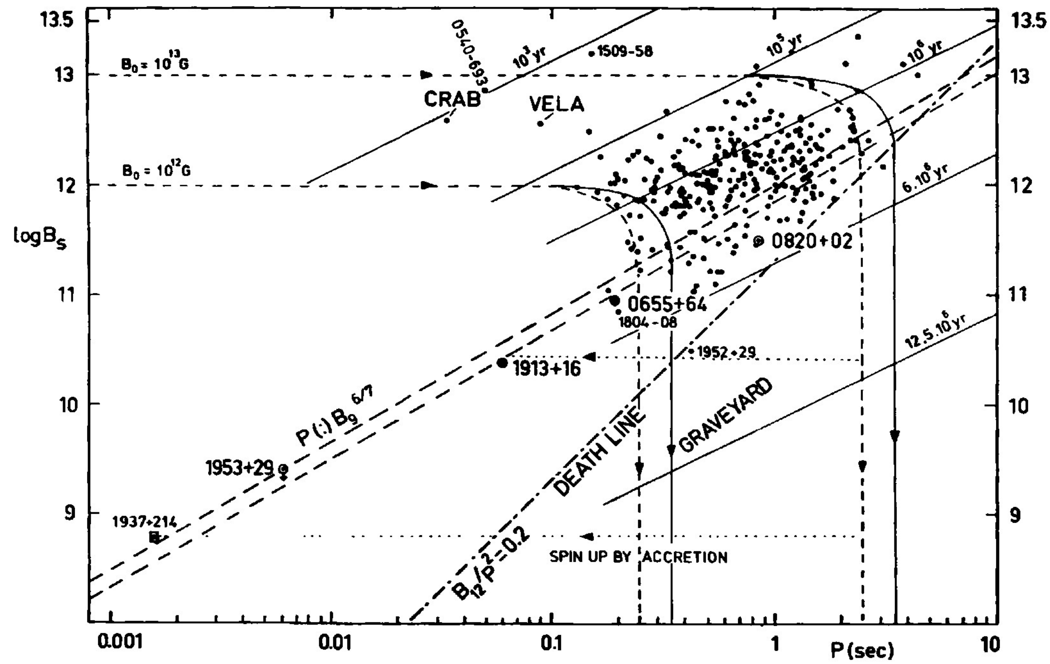


Figure 1. Surface dipole magnetic field strength B_s vs. pulse period P of over 300 radio pulsars, as derived from their observed $\dot{P}$ values. Data for single pulsars are from Manchester and Taylor (1981), Seward et al. (1984) and Backer (1984). Data for the binary pulsars (circles) are from the references listed in table 1. The B_s-value indicated for PSR 1953+29 is the theoretical upper limit (cf. Helfand et al. 1983). The 1.5 msec pulsar is indicated by the square.
Evolutionary tracks of radio pulsars for two initial B_s-values are indicated for assumed exponential decay timescales τ_D of the field strength of 2.10^6 yrs (small-dash curves) and 4.10^6 yrs (full curves). Corresponding timelines indicate - for $\tau_D = 2.10^6$ yrs - the pulsar positions expected at various ages. Further explanation in the text.

Spin-up by accretion in a binary system: predicted and observed pulse periods of "recycled" old neutron stars

A neutron star which is born in binary system with a normal non-degenerate star as a companion is not expected to be observable as a radio pulsar, as even a very tenuous wind or corona will disperse the pulsed signal beyond detectability. In a later stage of its evolution, when the neutron star is already in the "graveyard", the evolutionary expansion of the companion may lead to mass transfer, causing the system to become observable as a pulsating X-ray binary.
In many of the pulsating X-ray binaries the pulse period is observed to be continuously decreasing on a relatively short timescale, of order 10^3 - 10^5 yrs (cf. Rappaport and Joss 1983). This holds especially for systems in which there is clear evidence for the presence of an accretion disk, e.g. Her X-1, Cen X-3 and SMC X-1 (van Paradijs, 1983). This spin-up moves the pulsar back from the "graveyard" into the region

of "living" pulsars in the B_s vs. P diagram. The two dotted horizontal lines in figure 1 depict examples of such spin-up tracks for neutron stars that underwent considerable field decay before the onset of the X-ray phase. That spin-up by accretion may indeed produce very short spin periods is demonstrated by the systems of SMC X-1 and A0538-66 which presently have spin periods of $0\overset{s}{.}71$ and $0\overset{s}{.}069$, respectively, which are still decreasing.

For a given accretion rate $\dot{M}$ the spin up will end when the neutron star reaches its so-called "equilibrium" spin period P_{eq} given by (cf. van den Heuvel 1977; Henrichs 1983):

$$P_{eq} = (2.4 \text{ ms}) \, (B_9)^{6/7} \, . \, M^{-5/7} \, . \, \left(\frac{\dot{M}}{\dot{M}_{Edd}}\right)^{-3/7} \, . \, R_6^{15/7} \qquad (3)$$

where B_9, M and R_6 are the surface dipole magnetic field strength of the neutron star in units of 10^9 G, its mass in solar masses, and its radius in units of 10^6 cm, respectively. $\dot{M}_{Edd}$ is the maximum possible "Eddington-limit" accretion rate = 2.10^{-8} $M_\odot$/yr. Equation (3) shows that for a "standard" neutron star with M = 1, R_6 = 1, the shortest possible spin-period P_{min} that can be reached - for $\dot{M} = \dot{M}_{Edd}$ - depends only on the value of B_9, as $P_{min} \sim B_9^{\ 6/7}$. This relation is indicated in figure 1 by the upper of the two heavily dashed lines (the lower one corresponds to $\dot{M} = 0.5 \ \dot{M}_{Edd}$).

All radio pulsars that originated from spin-up in binary systems are, in this figure, expected to be found in the wedge-shaped region between this line and the "deathline" (Radhakrishnan and Srinivasan, 1981; Alpar et al. 1982). The 1.5 msec radiopulsar as well as the three binary radio pulsars with well-determined $\dot{P}$ values are indeed situated precisely in this predicted region. This gives strong support to the idea that they are old neutron stars that obtained their short pulse periods by spin-up during a preceding mass transfer phase (Alpar et al. 1982). For PSR 1953+29 presently only an upper limit to $\dot{P}$ is known, leading to an upper limit on its B_s-value indicated in the figure. The binary-recycling model predicts that its B_s is smaller than 2.5×10^9 G, corresponding to a $\dot{P} < 10^{-17}$ (Helfand et al. 1983). This prediction can be tested in the near future.

We conclude from the above that:

(i) the observed positions of the binary radio pulsars in the B_s vs. P diagram strongly support the idea that they are relatively old neutron stars that have been spun up by accretion at a time when their surface dipole magnetic fields had already undergone substantial decay;

(ii) during the preceding evolution the mass transfer rate reached a value close to (or possibly larger than) the Eddington limit;

(iii) the companions to these pulsars must already be highly evolved objects near the end of their nucear evolution (as they are already beyond the stage of overflowing their Roche lobes, and presently are not producing any dispersion of the pulsar signals). This means that they are likely to be white dwarfs or neutron stars (or possibly, black holes).

(iv) the position of the 1.5 msec pulsar in the B_s vs. P diagram suggests that it may also have undergone spin up in a binary system.

EVOLUTIONARY MODELS FOR THE TWO TYPES OF BINARY RADIO PULSARS

The four binary radio pulsars seem to fall into two different categories (see table 1 and figure 2). Two of them, PSR 0655+64 and PSR 1913+16, have short orbital periods (< 25 hours) and high mass functions, indicating companion masses > 0.7 $M_{\odot}$ (respectively, about 0.7 to 1.0 $M_{\odot}$ and 1.4 $M_{\odot}$, Damashak et al. 1982; Taylor and Weisberg 1982). The other two, PSR 0820+02 and PSR 1953+29, have long orbital periods (> 117d), nearly circular orbits and low almost identical mass functions of about 3.10^{-3} $M_{\odot}$, suggesting companion masses around 0.2 $M_{\odot}$ to 0.4 $M_{\odot}$ (Taylor 1981, Manchester et al. 1983, Boriakoff et al. 1983). It was pointed out by van den Heuvel and Taam (1984) that these two classes of systems are expected to be formed by the later evolution of binaries consisting of a neutron star and a normal companion star, in which the companion was (considerably) more massive than the neutron star, or less massive than the neutron star, respectively. We will consider these two cases separately.

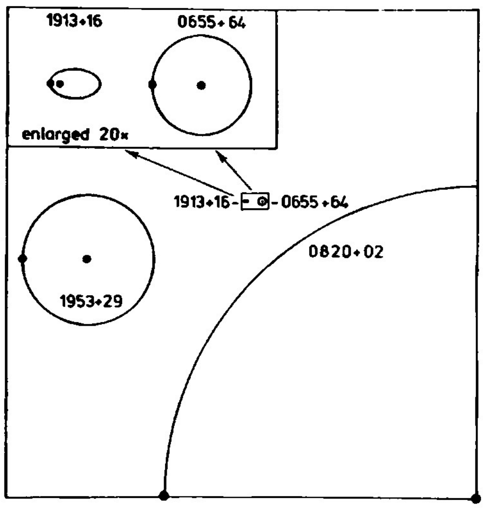


Figure 2. Relative orbital dimensions of the four radio pulsar binaries suggest that there may be two classes of systems: PSR 0655+64 and PSR 1913+16 have orbital dimension that are over 25 times smaller than those of PSR 1953+29 and PSR 0820+02. On the other hand, the former two pulsars have relatively massive companions (~ 0.7 $M_{\odot}$ to 1.4 $M_{\odot}$), whereas the latter two have low-mass companions (0.2 $M_{\odot}$ - 0.4 $M_{\odot}$).

Evolution of a binary consisting of a neutron star and a more massive normal companion: the origin of PSR 0655+64 and PSR 1913+16.

When in this system the companion has a mass several times that of the neutron star (i.e. > 3 - 4 $M_{\odot}$, see below) and the orbit is relatively wide (orbital period > a few weeks) so that at the onset of the mass transfer the companion is a giant with a deep convective envelope, runaway mass transfer is unavoidable (Paczynski and Sienkiewicz 1972). This leads, on a timescale of $\sim 10^3$ yrs, to the formation of an extended convective common envelope in which the neutron star and the evolved core of the companion will spiral towards each other as a consequence of the large frictional drag (Paczynski 1976, Webbink 1979, Taam et al. 1978, Meyer and Meyer-Hofmeister 1979). The duration of this spiral-in process, in which finally the envelope is lost, is expected to be short, $\sim 10^3 - 10^5$ yrs.

The final result is a system consisting of the neutron star and the evolved core of the companion with an orbital period ranging from about one hour to a few days (in analogy to the case of cataclysmic variables). Figure 3 depicts as an example the anticipated evolution of a binary initially consisting of a $M \simeq 5M_{\odot}$ star and a neutron star, with an orbital period of > 80 days. The $5M_{\odot}$ star overflows its Roche lobe when it has exhausted helium in its core (i.e. when it climbs up along the asymptotic giant branch (AGB)). At helium exhaustion it has a 0.95 $M_{\odot}$ degenerate CO core (Paczynski 1970) surrounded by He and H-burning shells. During its ascent of the AGB this core mass increases to 1.39 $M_\odot$. We assume that the star engulfs its companion when $M_{core} \simeq 1.0$ $M_\odot$, implying a binary period of about 100 days (see table 2). The system after spiral-in will consist of a 1.0 $M_\odot$ CO white dwarf and a neutron star with a narrow and circular orbit, i.e. closely resembing the PSR 0655+64 system (see table 1). The type of binary evolution considered here is so-called case C (Plavec 1968, Paczynski 1971). Table 2 lists the maximum and minimum orbital periods for case C evolution for companion masses in the range 3 to 7 $M_\odot$. The corresponding CO-core masses are also listed. The table shows that an evolution similar to the one depicted in figure 3 is expected in all wide neutron star binaries in which the mass of the companion is in the range ~3 to ~8 $M_\odot$ as on the AGB all such stars develop degenerate CO cores with a mass in the range 0.51 - 1.39 $M_\odot$ (Paczynski 1970).

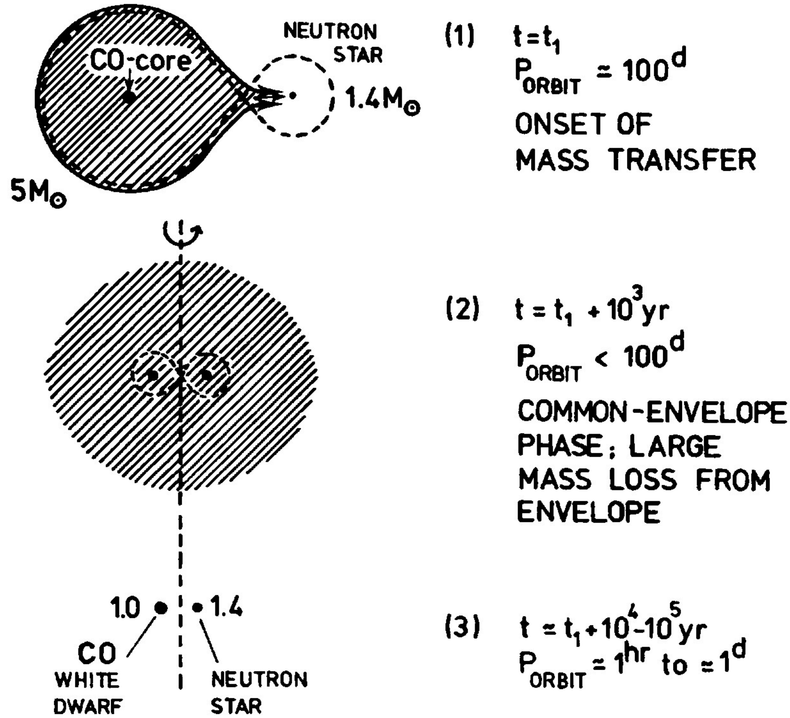


Figure 3. Anticipated evolution of a relatively wide binary consisiting of a 5 $M_\odot$ star with a neutron star companion. At the onset of the mass transfer the 5 $M_\odot$ star is a giant with a 1 $M_\odot$ degenerate CO core and a gradually expanding envelope (1). Rapidly, a common convective envelope forms (2) in which the CO-core and the neutron star spiral-in. During this spiral-in the envelope is ejected due to frictional heating and a very close system remains (3) consisting of a neutron star and a massive CO-white dwarf in a circular orbit. For companions more massive than 8 - 10 $M_\odot$ the evolved core after spiral-in collapses to a neutron star, and a close neutron star binary with an eccentric orbit (or two runaway pulsars) will be formed.

Table 2. Minimum and maximum orbital periods for neutron star binaries in which the companion overflows its critical lobe after it has exhausted helium in its core ("case C" evolution). A neutron star mass of 1.40 $M_\odot$ was assumed and the corresponding masses M_{core} of the degenerate CO-core of the companion are indicated (Paczynski's, 1970, evolutionary tracks were used). The first value of P_{max} corresponds to the moment at which the orbital separation equals the radius of the companion; the value within parentheses corresponds to the moment at which the companion fills its Roche lobe.

Companion mass	P_{min}	M_{core} (He exhaustion)	P_{max}	M_{core}(max)
3 $M_\odot$	32^d	0.51 $M_\odot$	5.5 yr (19 yr)	1.39 $M_\odot$
5 $M_\odot$	76^d	0.95 $M_\odot$	4.5 yr (13 yr)	1.39 $M_\odot$
7 $M_\odot$	173^d	1.02 $M_\odot$	3.6 yr (10 yr)	1.39 $M_\odot$

Companions more massive than ~ 8-10 $M_\odot$ will develop evolved cores too massive to terminate as white dwarfs (Sugimoto and Nomoto 1980, Van den Heuvel 1981, Habets 1983). Following the spiral-in and subsequent nuclear evolution such a core is expected to collapse to a neutron star. The mass ejection in this second supernova in the system may induce a considerable orbital eccentricity or may even disrupt the system. PSR 1913+16 is expected to have been formed in this way.

At the onset of the spiral-in the neutron star will often be older than 10^7 yrs (companion stars of 5 to 15 $M_\odot$ need some (1-5) × 10^7 yrs to leave the main sequence) such that its surface magnetic field strength may have decayed by several orders of magnitude.

During the spiral-in the accretion onto the neutron star will take place near the Eddington-limited rate $\dot{M}_{Edd}$, implying that its rotation may be spun up to a minimum period that according to eq. (3) depends practically only on the surface dipole magnetic field strength B_0.

After the loss of the common envelope these neutron stars will become observable as radio pulsars with a relatively low surface dipole magnetic field strength. For the observed B_s-values of PSR 0655+64 and PSR 1913+16 (table 1), and $R_6 = 1$, $M = 1.4\ M_\odot$, eq. (3) with $\dot{M}_{Edd}$ yields $P = 0.17$ and 0.04 sec, respectively, in fair agreement with their observed pulse periods (allowing for some spin-down since their formation).

The absence of radio pulses from the second (younger) neutron star in the PSR 1913+16 system may either be due to beaming effects, or to the relatively short spindown timescale of a newborn strong-magnetic field neutron star. If the second supernova in the system took place a few million years ago, the new neutron star may already have reached the turn-off period of a few seconds (see figure 1) whereas the "recycled" old one, due to its weaker surface dipole field, will remain observable as a pulsar for a much longer time (van den Heuvel and Taam 1984).

Good progenitor candidates for the above described type of evolution seem to be the B-emission X-ray binaries, which have orbital periods ranging from 15 days to several years (Rappaport and van den Heuvel 1982), and companion masses ranging from ~ 7 $M_\odot$ (spectral type B3Ve) to ~ 20 $M_\odot$ (spectral type O9Ve). The companion of PSR 0655+64 should then have had a mass below the limit for exploding as a supernova, i.e. < 8-10 $M_\odot$ (in case C; in case B: < 10-12 $M_\odot$) whereas that of PSR 1913+16 had a mass above this limit. An alternative progenitor for PSR0655+64 is a symbiotic binary consisting of an $\sim 4\ M_{\odot}$ red giant and a massive white dwarf, in which the white dwarf is driven over the Chandrasekhar limit by accretion from the wind of the red giant when this star describes the helium-burning loop of its evolutionary track (duration $> 10^7$ yrs). The subsequent ascent of the $4\ M_{\odot}$ star along the AGB then leads to the above described spiral-in.

Evolution of a binary consisting of a neutron star and a less massive normal companion: origin of PSR 1953+29 and PSR 0820+02

When in this system the companion has evolved to the giant stage and begins to overflow its Roche lobe, the ensuing mass transfer will be self-stabilizing as it leads to expansion of the orbit. Webbink, Rappaport and Savonije (1983) and Taam (1983) have shown that in this way, starting with companions with $M < 1.2\ M_{\odot}$ and orbital periods upwards from about 1 day, one obtains a long-lasting ($\sim 10^6$ to 10^8 yr) stage of relatively high mass transfer ($\dot{M} > 10^{-8} M_{\odot}$/yr). This explains the existence of several wide low-mass X-ray binaries such as Cygnus X-2 ($P_{orb} = 9.8^d$) and 2S 0921-63 ($P_{orb} = 9\overset{d}{.}0$). During the mass transfer phase the companion ascends the giant branch and has a degenerate helium core with a mass in the range 0.2 to 0.45 $M_{\odot}$, and generates energy by burning hydrogen in a shell around this core. The mass transfer, and the associated expansion of the orbit, are driven by the gradual growth of the core mass. The duration of the mass transfer phase depends mainly on the initial mass of the companion and the initial orbital period. In the end, only the degenerate helium core of the companion is left behind, as a helium white dwarf, and the final orbit will always be wide. Figure 4

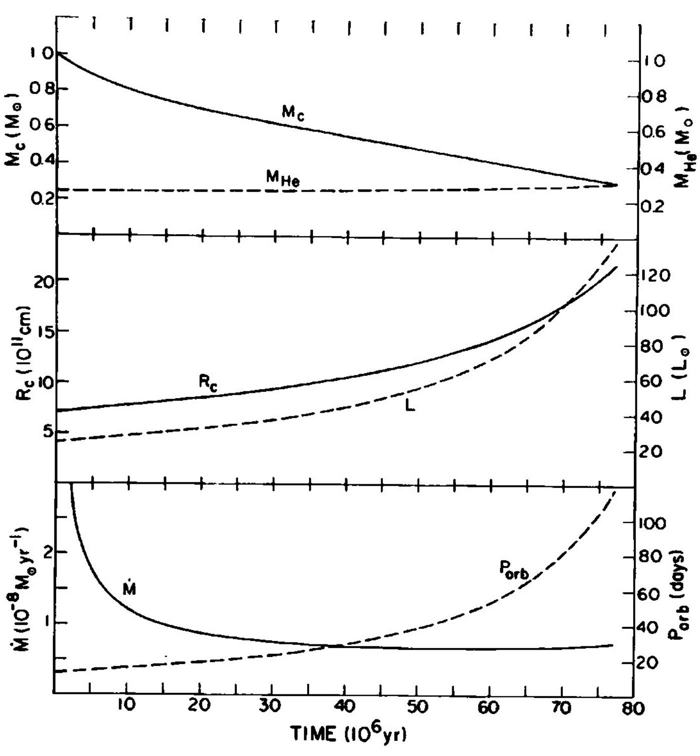


Figure 4. Evolution of a binary with a lower giant branch secondary component of initial mass 1.0 $M_{\odot}$ and surface composition X = 0.70, Z = 0.02, as calculated by Joss and Rappaport (1983). Plots as functions of time: upper, total mass (M_c) and core mass of the secondary; middle, radius and intrinsic bolometric luminosity of the secondary; lower, mass accretion rate $\dot{M}$ onto the neutron star and orbital period. Conservative mass transfer has been assumed. The initial mass of the neutron star was taken to be 1.3 $M_{\odot}$.

depicts as an example, the evolution of a system that started out with a 1.0 $M_\odot$ star together with a 1.3 $M_\odot$ neutron star companion with an initial orbital period P_o = 12.5 d, as calculated by Joss and Rappaport (1983).

Savonije (1983), Paczynski (1983), and Joss and Rappaport (1983) have pointed out that the final systems resulting from this type of evolution show a striking resemblance to that of the 6 msec binary radio pulsar PSR 1953+29, since (i) the final companion mass will be low ($\sim$ 0.3 $M_\odot$), and (ii) the orbit will be (almost) circular as a consequence of the long-lasting preceding mass transfer stage. Figure 4 shows that the most likely initial orbital period of PSR 1953+29 was around 12.5 days; similarly Joss and Rappaport (1983) showed that the initial orbital period of PSR 0820+02 was about 1 year. The duration of the mass-transfer phase in these systems was (3.5-7.7) × 10^7 yrs and 4 × 10^6 yrs, respectively.

Arguments for accretion-induced collapse in wide radio pulsar binaries

In order to explain the low runaway velocity of PSR1953+25 (evidenced by its position close to the galactic plane) Helfand et al. (1983) have suggested that it was formed by the accretion-induced collapse of a massive white dwarf. Blandford and De Campli (1981) and van den Heuvel (1981) suggested a similar history for PSR0820+02, and van den Heuvel and Taam (1984) have pointed out the following additional arguments in favour of the accretion-induced collapse model.

The evolutionary model for these wide systems outlined in the foregoing section implies that the systems must be very old (at least several times 10^9 yrs) since the companion stars should have started out with masses < 1.2 $M_\odot$ and had already completed their main-sequence evolution before the onset of the mass transfer. One would therefore, not expect any detectable surface dipole fields to be left in them. However, PSR 0820+02 and PSR 1953+29 still have a surface dipole magnetic field strength 3.10^{11} G and > 10^9 G, respectively (table 1). The same problem exists in the GX 1+4 system which is an 120 ^{s} X-ray pulsar, and must be a very wide system as the companion star is an M6IIIe red giant (Bradt and McClintock 1983). Such a system seems an excellent progenitor candidate for a system like PSR 0820+02 (van den Heuvel 1981). A lower limit to its magnetic field strength is $\sim$ 3.10^{11} G (Henrichs 1983), similar to that of PSR 0820+02. Its position close to the galactic center and at high z suggests an old disk population old age of (5 - 10). 10^{10} yrs.

The only consistent way in which one may explain why the neutron stars in these old (wide) systems still can have such fairly strong surface mangetic fields seems: if they were formed only recently, i.e.: during the mass-transfer stage itself, by the accretion-induced collapse of a white dwarf. Such a model gives an excellent explanation for the fact that PSR 1953+29 has a 6 msec rotation period and PSR 0820+02 not. Because, in the progenitor of the PSR 1953+29 system the mass transfer lasted 8.10^7 yrs (see figure 4) such that the collapse can have occurred several times 10^7 yrs before the end of the mass-transfer phase.

Consequently, the magnetic field had time to decay to $< 2.10^9$ G and, according to eq. (3) spin-up to ~ 5 msec was possible. On the other hand, in view of the much shorter (4×10^6 yr) mass-transfer time scale in the progenitor of the PSR 0820+02 system, such a field decay and spin up were not possible here.
In addition, the conditions for achieving accretion-induced collapse are expected to be favourable just in systems with a low-mass ($< 1.2\ M_\odot$) giant component (see van den Heuvel 1981, van den Heuvel and Taam 1984, Iben and Tutukov 1984).
Since, at any time during the accretion phase, the envelope mass of the white dwarf is small (more than a few hundredths of a solar mass of hydrogen would not fit inside its Roche lobe) and since the mass loss of the white dwarf during the collapse needs not exceed the equivalent of the binding energy of the neutron star ($\sim 0.1\ M_\odot$), the orbital eccentricity and runaway velocity induced by the mass loss in the collapse need not exceed 0.05 and ~ 10 km/sec, respectively (Flannery and van den Heuvel 1975) and the orbit may be subsequently circularized by the continued mass transfer from the companion and by tidal forces.
Thus the existence of the two binary radio pulsars with wide circular orbits and low mass functions (and of the GX 1+4 system as well), provides strong quantitative evidence that neutron stars can be formed in an old stellar population by the accretion-induced collapse of a white dwarf in a relatively wide binary ("Whelan-Iben model", Whelan and Iben, 1973).

BINARY MODELS FOR THE FORMATION OF THE 1.5 MSEC PULSAR

In binary models, PSR 1937+214 could have lost its companion either by: (i) **disruption** of the system due to the supernova (SN) explosion of its companion, or: (ii) **coalescence** with the companion after spiral in due to orbital angular momentum losses, for example by the emission of gravitational waves.
The first possibility appears to be unlikely for a variety of reasons (see Henrichs and Van den Heuvel 1983; Arons 1983).

We will therefore concentrate only on the second possibilitiy. Coalescence models with three kinds of companions have been proposed. i.e.: (i) a red dwarf or red degenerate star (Alpar et al. 1982; Fabian et al., 1983, Ruderman and Shaham 1983b), (ii) a neutron star (Henrichs and Van den Heuvel 1983) and (iii) a massive white dwarf (Van den Heuvel and Bonsema 1984). Before discussing these we consider some general aspects of the evolution of close mass-transfer binaries with one compact component.

Stability of angular-momentum-loss-driven evolution of close binaries

Consider binaries in which the mass-receiving neutron star is the more massive component. As the mass-losing star is the less massive component mass transfer will lead to the expansion of the orbit and (for $M_2/M_1 <$ 0.85) to expansion of the Roche-lobe radius R_L (M_2).
Whether or not the mass transfer will be self-stabilizing can be examined by comparing the increase of R_L with that of the radius $R_s(M_2)$ of the secondary star when mass is transferred to the neutron star. If

$$\left|\frac{d\ \ln R_L}{d\ \ln M_2}\right| < \left|\frac{d\ \ln R_s}{d\ \ln M_2}\right| \tag{4}$$

8

the radius of the star will increase faster than that of its Roche-lobe. In that case the mass transfer will immediately continue and have a runaway-character, such that coalescence may ensue.
On the other hand, when the left-hand side of inequality (4) is larger than the right-hand side, the mass transfer will be self-stabilizing, because when a small amount of mass is transferred the Roche-lobe radius becomes larger than the stellar radius. In this way, continuous angular momentum loss - for example, by the emission of gravitational waves - drives a continuous and self-stabilizing mass transfer from the secondary to the neutron star. Following Faulkner (1971) calculations for such mass transfer in low-mass X-ray binaries were carried out by Rappaport, Joss and Webbink (1982), to which we refer for details. Stable mass transfer can occur, for example, if the companion is a red dwarf or, alternatively, a degenerate star with a mass $< 0.5\ M_{\odot}$ (see below).

Conservative mass transfer vs. transfer of mass towards a disk

The two extreme possibilities for the change of the Roche-lobe radius during the mass transfer towards a more massive compact companion are: (i) "Conservative" mass transfer, in which the total mass $M_1 + M_2$ and the total orbital angular momentum of the system are assumed to be conserved during the transfer, and (ii) mass transfer into a disk (or ring) surrounding the companion star. In this case the orbital angular momentum is transformed into Keplerian angular momentum of the rotating disk, leading to a much smaller expansion rate of the orbit and the Roche lobe than in case (i).
Expressions for the change of the orbital separation $\underline{a}$ and the Roche-lobe radius of the mass-losing star for cases (i) and (ii) can be found in Paczynski (1971) and Kieboom and Verbunt (1981), respectively, cf. van den Heuvel and Bonsema (1984).

Figure 5 depicts as examples the resulting Roche-lobe radii $R_{L,c}$ and $R_{L,d}$ for the conservative and the disk-transfer case, respectively, as a function of M_2 for three systems, with initial companion masses $M_2^{\circ} = 1.2\ M_{\odot}$, $0.8\ M_{\odot}$ and $0.01\ M_{\odot}$, respectively. In all cases the initial mass of the compact star was assumed to be $M_1 = 1.4\ M_{\odot}$. Also drawn in this figure is the mass-radius relation for electron-degenerate stars that do not contain hydrogen (see next section).

The assumption of "conservative" mass transfer is expected to hold during long-lasting steady stages of mass transfer, also if the mass flows towards the compact star through an accretion disk. This is because in a steady state the total amount of mass and angular momentum in the disk will be constant (the transfer time of matter through a disk is relatively short, of the order of weeks, Pringle 1981). Therefore, the presence of the disk does not contribute to changes in the orbital parameters, and the companion plus disk can be considered as one object which is the companion of the mass-losing star.
On the other hand, in the case that the mass transfer assumes a runaway character, or when it is just starting - such that the disk is just forming - the conservative approximation will not be valid and the Roche-lobe radius will in first instance follow one of the $R_{L,d}$ curves in figure 5.

Intermezzo: Evolution of low-mass X-ray binaries and cataclysmic variables

Red main-sequence dwarfs with masses > 0.1 $M_\odot$ in thermal equilibrium have a mass-radius relation

$$R_s\ (M_2) = k_1\ M_2^n \quad \text{with}\ \ 0.5 < n < 1,\ \text{and}\ k_1 = \text{constant.} \qquad (5)$$

This ensures according to condition (4) and figure 5 that red dwarfs will always be able to achieve stable mass transfer (at a rate ~ 10^{-10} $M_\odot$/yr; Rappaport et al. 1982), while the orbit is shrinking due to GR losses on a timescale

$$\tau_{GR} = \frac{(M_1 + M_2)^{1/3}}{2^{1/3}\ M_1 M_2} \cdot \left(\frac{P}{1.6}\right)^{8/3} \cdot 5 \times 10^7\ \text{yrs} \qquad (6)$$

When the red dwarf reaches a mass < 0.2 $M_\odot$, τ_{GR} becomes shorter than its thermal timescale and the mass transfer drives the star out of thermal equilibrium, causing it to finally follow the mass-radius relation for a convective polytrope:

$$R_s\ (M_2) = k_2\ M_2^{-1/3} \qquad (\text{with}\ k_2 = \text{const.}) \qquad (7)$$

Furthermore, if the companion has a mass < 0.1 $M_\odot$ degeneracy may set in which also gives a mass-radius relation similar to eq. (7). The result is that from here on mass transfer leads to expansion of the orbit while the transfer remains self-stabilizing, as inequality (4) is still not fulfilled (see Paczynski and Sienkiewicz 1981).

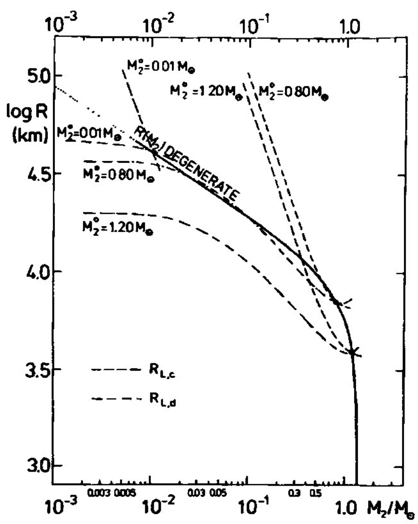


Figure 5. Critical Roche-lobe radii $R_{L,c}$ and $R_{L,d}$ for a secondary star of mass M_2 which is losing mass to a 1.4 $M_\odot$ companion, for three initial values of the secondary mass, M_2^0 = 1.2 $M_\odot$, 0.8 $M_\odot$ and 0.01 $M_\odot$. $R_{L,c}$ corresponds to "conservative" mass transfer, $R_{L,d}$ to mass transfer into a disk around the companion. Also drawn is the mass-radius relation R_s (M_2) for degenerate stars that do not contain hydrogen (R in km).

Figure 6 outlines the above-described evolution of CV binaries and low-mass X-ray binaries which started out with a mass of the red dwarf companion > 0.2 $M_\odot$. After reaching a period minimum of ~ 80 minutes (Paczynski and Sienkiewicz 1981) one would expect the companions to spiral out until finally $\tau_{GR} = \tau_{Hubble}$. At that time the orbital period is ~ 2.2 hr, the companion mass is ~ 0.017 $M_\odot$ and the mass transfer rate is ~ $10^{-12.5}$ $M_\odot$/yr (Henrichs and van den Heuvel 1983). [If additional angular-momentum loss mechanisms are operating the values of the period-minimum and of the final mass may be different, cf. Eggleton 1983].

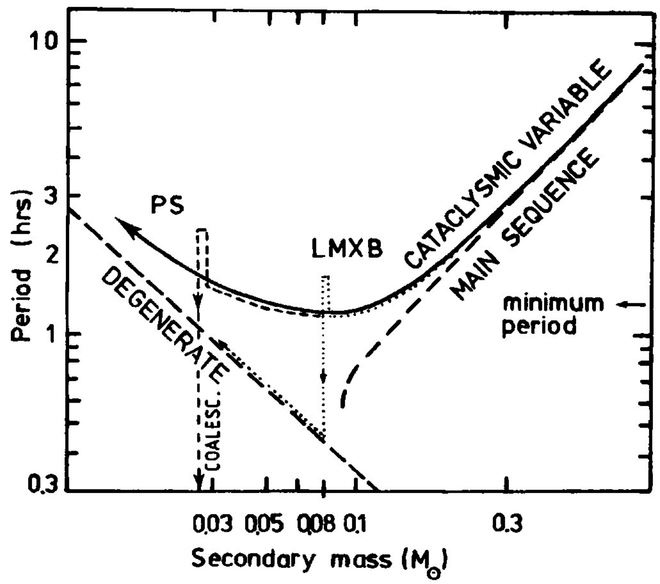


Figure 6. Schematic picture of the secular evolution of cataclysmic variable (CV) binaries. Systems containing degenerate stars (black dwarfs or white dwarfs) would lie along the left-hand dashed line. Systems containing a main-sequence companion in thermal equilibrium would lie along the dashed line on the right-hand side. The fully drawn curve is the model track of Paczynski and Sienkiewicz (1981, see explanation in the text). The dotted curve is the evolutionary track of a system in which the white dwarf collapses to a neutron star when the mass of its red-companion is 0.08 $M_\odot$. This leads to the formation of an ultra-short period low-mass X-ray binary like 4U1626-67. (Joss 1980, priv. commun.)
The dashed track indicates the evolution of a similar system in which at the time of the collapse M_{red} = 0.03 $M_\odot$. When the mass transfer resumes, this companion is disrupted, and a single millisecond pulsar may result (see text).

The fate of low-mass X-ray binaries: coalescence with a red dwarf?

The assumption in the above-described evolutionary picture is that the mass transfer takes place in a steady and continuous fashion, such that in inequality (4) the "conservative" Roche-lobe radius $R_{L,c}$ can be used. However, Ruderman and Shaham (1983b) suggest that when the companion's mass becomes very low, mass and angular momentum will be lost from de disk edge in such a way that the Roche-lobe will hardly expand, leading to runaway mass transfer and disruption of the low-mass star when its mass drops below ~ 0.01 $M_\odot$ (see Shaham and Ruderman, this volume). An alternative possibility is that the mass transfer gets interrupted. When, after such an interruption, the mass transfer resumes, the matter will first form a ring or disk around the neutron star, such that $R_{L,d}$ has to be used in inequal (4). Figure 5 shows that, for example, for M_2 = 0.01 $M_\odot$ the $R_{L,d}$ curve is less steep than the R_s (M_2) curve for degenerate stars (or purely convective stars) such that the mass-transfer will assume a runaway character and the low-mass star will be disrupted on its dynamical timescale (a few minutes). Its matter will then form a disk which subsequently can be accreted, and a single millisecond pulsar may result.

Coalescence with a massive white dwarf

Close binaries consisting of a neutron star and a fairly massive (> 0.7 $M_\odot$) white dwarf do exist in nature, e.g. PSR 0655+64. As pointed out in the previous chapter such systems will result from spiral-in evolution of a neutron star with a companion in the mass range 3-8 $M_\odot$ (figure 3). Their orbital periods are expected to range from ~ 1 hour to ~ 1 day. For M_2 ~ 1 $M_\odot$, M_1 ~ 1.4 $M_\odot$ and P < 16^h will decay on a timescale shorter than τ_{Hubble}. When in such a system the white dwarf begins to overflow its Roche lobe the orbital period is ~ 20 seconds and τ_{GR} ~ 30 yrs. It appears from figure 5 that the further evolution of the system depends on the value of M_2 as follows (for M_1 = 1.40 $M_\odot$):

(1) for M_2° > 0.7 $M_\odot$ both $R_{L,c}$ and $R_{L,d}$ fulfill inequality (4). Hence runaway mass transfer is unavoidable. This is expected to lead to total disruption of the white dwarf on its dynamical timescale of a few seconds (Van den Heuvel and Bonsema 1984).

(2) for 0.5 $M_\odot$ < M_2° < 0.7 $M_\odot$, conservative mass transfer is self-stabilizing, whereas disk mass transfer is unstable and leads to disruption. As the mass transfer begins suddenly, the latter may correspond to the real case.

(3) for ~ 0.035 $M_\odot$ < M_2° < 0.5 $M_\odot$, both conservative transfer and disk transfer are self-stabilizing. Hence, stable mass transfer will ensue.

In case (1) at least ~ 0.1 $M_\odot$ of the mass of the white dwarf is expected to be accreted by the neutron star (this amount of accretion is at least required to provide the kinetic energy for expelling the remaining part of the white-dwarf mass, cf. van den Heuvel and Bonsema 1984).
The progenitor systems were probably relatively wide B-emission X-ray binaries or wide symbiotic binaries with a companion in the mass range 3-8 $M_\odot$ (see figure 3).
The runaway velocities of such systems, imparted by the formation of their neutron stars, are expected to be < 20-30 km/s (Rappaport and van den Heuvel 1982). Indeed, B-emission X-ray binaries are always found close to the galactic plane. At the onset of the spiral-in, the neutron star will have an age > 10^7 yr. With an orbital period after spiral-in of ~ 1h, coalescence will occur ~ 2.10^7 yrs later, which is > 3.10^7 yrs after the birth of the neutron star. At this age its magnetic field will have decayed to a value ~ 10^{8-9} G (see figure 1) and spin-up to a very short period is possible.

Coalescence with a second neutron-star

The orbit of PSR 1913+16 is observed to decay on a timescale of ~ 3.10^8 yrs (Taylor and Weisberg 1982), and coalescence of the two neutron stars in this system is inevidable on this timescale. At the onset of the coalescence the orbital period and the timescale for orbital decay are both equal to about 1 millisecond (Clark and Eardley 1977; Henrichs and van den Heuvel 1983). In the equal-mass case the result will be either a black hole or a massive neutron star - in the latter case with a rotation period slightly below a millisecond. In the case that the neutron stars differ in mass by > 0.2 $M_\odot$, the lower-mass one will have the largest radius and will be the first to overflow its Roche lobe. This leads to a brief spiral out to ~ 100 km followed by total disruption of this star (Clark and Eardley 1977). In this process a considerable fraction of its mass, ~ 0.5 $M_\odot$, may be ejected, and the remaining object is likely to be a rather massive neutron star

($\sim$ 1.9 $M_\odot$), again with a rotation period of slightly less than a millisecond.
At rotation periods < 1.5 msec neutron stars are unstable to the radiation of gravitational waves by non-radial stellar modes (Papaloizou and Pringle 1978) and the period will rapidly increase to P $\approx$ 1.5 msec. The resulting neutron stars are, therefore, always expected to be found with a rotation period > 1.5 msec.

Discussion and Conclusions

The above leads us to the following remarks:
(1) All of the three coalescence models can provide the $\sim$ 0.12 $M_\odot$ accretion required for spin up to a 1.5 msec rotation period.
(2) In the case of a neutron star or a massive white dwarf companion coalescence is certain. For the red-dwarf case coalescence is predicted only if the mass-transfer can be interrupted. This condition should be seen in combination with the condition that the magnetic field strength of 5.10^8 G requires a neutron star age < 10^8 yrs (see figure 1).
This is much shorter than the age of the low-mass X-ray binary progenitor system, as such systems belong to an old disk population with ages > 5.10^9 yrs (cf. Lewin and Joss 1983; van Paradijs 1983). Both the above conditions can be fulfilled simultaneously if one assumes that the neutron star was formed $\sim$ 0.5 $\times$ 10^8 yrs ago by the accretion-induced collapse of a white dwarf. This is because in that case: (i) the progenitor system suddenly became detached due to the sudden increase in orbital separation produced by the supernova mass loss of > 0.1 $M_\odot$ (see Van den Heuvel 1977). Hence the mass transfer became interrupted, and: (ii) If the mass of the red dwarf at that moment was < 0.035 $M_\odot$ - as required for coalescence - the time interval required for it to fill its Roche lobe again (determined by GR losses) is < 10^8 yrs, such that at that time it can still have a magnetic field strength of $\sim$ 10^8 - 10^9 G.
It thus appears that the red-dwarf-coalescence model is viable if the progenitor was a CV binary, in which the red component at the moment of the white-dwarf collapse had a mass < 0.035 $M_\odot$. In a similar white dwarf collapse model with a red companion more massive than 0.035 $M_\odot$, the resulting system after the detached phase presumably will be a low-mass X-ray binary resembling 4U 1626-67 (P_{orb} = 41^m) and 4U 1916-05 (P_{orb} $\simeq$ 50^m), in which the red stars have a mass between 0.01 $M_\odot$ and 0.1 $M_\odot$ (Rappaport and Joss 1984). These two alternatives for the evolution of CV binaries with accretion-induced collapse are represented by the dashed and dotted tracks, respectively, in figure 6.
(3) Neutron stars resulting from the coalescence of a close neutron star binary might be hot and completely melted (Ruderman and Shaham 1983a), in which case a strong magnetic field might be re-generated (Flowers and Ruderman 1977). If this is the case (which seems not yet certain) this coalescence model would not be applicable for the origin of PSR 1937+214.
(4) Coalescence with a red dwarf or a neutron star does not necessarily predict a position close to the galactic plane, as: (i) low-mass X-ray binaries and CV binaries tend to belong to a relatively old stellar population with a spread in z-values of at least 0.5 - 1 kpc;
(ii) neutron star binaries like PSR 1913+16 are expected to have runaway velocities > 100 km/s as a result of the two supernova explosions that took place in them.
We conclude from the above that all three coalescence models are, in principle, viable. Only in the case of coalescence with a white dwarf of

mass > 0.7 $M_\odot$ is the position close to the galactic plane a natural consequence.

Acknowledgements

Part of this work was started at the CECAM workshop on "Late Stages of Close Binary Evolution", Paris, Meudon, summer 1982.

REFERENCES

Alpar, M.A., Cheng, A.F., Ruderman, M.A. and Shaham, J. 1982, Nature 300, 728.

Arons, J. 1983, Nature 302, 301.

Backer, D.C. 1984, Journ. Astroph. & Astronomy (in press).

Backus, P.R., Taylor, J.H. and Damashek, M. 1982, Astrophys. J. 255, L63.

Blandford, R.D. and De Campli, W.M. 1981, in IAU Symp. 95 "Pulsars" (eds. Sieber, W. and Wielebinski, R.), Reidel, Dordrecht 371.

Boriakoff, V., Buccheri, R. and Fanci, F. 1983, Nature 304, 417.

Bradt, H.V.D. and McClintock, J.E.A. 1983, Ann. Rev. Astron. Astrophys. 28, 13.

Clark, J.P. and Eardley, D. 1977, Astrophys. J. 215, 311.

Damashek, M., Backus, P.R., Taylor, J.H. and Burkhardt, R. 1982, Astrophys. J. 253, L57.

Eggleton, P.P. 1983, in: "Cataclysmic Variables and Related Objects" (M. Livio and G. Shahiv, eds.), Reidel, Dordrecht, p. 239.

Fabian, A.C., Pringle, J., Verbunt, F. and Wade, A. 1983, Nature 301, 222.

Faulkner, J. 1971, Astrophys. J. 170, L99.

Flannery, B.P. and van den Heuvel, E.P.J. 1975, Astron. Astrophys. 39, 61.

Flowers, E. and Ruderman, M.A. 1977, Astrophys. J. 215, 302.

Gunn, J.E. and Ostriker, J.P. 1970, Astrophys. J. 160, 979.

Habets, G. 1983, in IAU Symp. No. 105: "Observational Tests of Stellar Evolution" (eds. A. Maeder and A. Renzini), Reidel, Dordrecht (in the press).

Helfand, D.J., Ruderman, M.A. and Shaham, J. 1983, Nature 304, 423.

Henrichs, H.F. and van den Heuvel, E.P.J. 1983, Nature 303, 213.

Henrichs, H.F. 1983 in: "Accretion Driven Stellar X-ray Sources" (eds. W.H.G. Lewin and E.P.J. van den Heuvel), Cambridge University Press, 392.

Iben, I. and Tutukov, V. 1984, Astrophys. J. Suppl. 54, 335.

Joss, P.C. and Rappaport, S.A. 1983, Nature 304, 419.

Kieboom, K.H. and Verbunt, F. 1981, Astron. Astrophys. 95, L 11.

Lewin, W.H.G. and Joss, P.C. 1983, in: "Accretion Driven Stellar X-ray Sources" (eds. W.H.G. Lewin and E.P.J. van den Heuvel), Cambridge University Press, 41.

Lyne, A. 1981, in IAU symp. No. 95 "Pulsars" (eds. Sieber, W. and Wielebinski, R.) Reidel, Dordrecht, 423.

Manchester, R.N., Newton, L.M., Cooke, D.J., Backus, P.R., Damashek, M., Taylor, J.H. and Condon, J.J. 1983, Astrophys. J. 268, 832.

Manchester, R.N. and Taylor, J.H. 1977, "Pulsars", W.H. Freeman & Co., San Fransisco.

Manchester, R.N. and Taylor, J.H. 1981, Astron. J. 86, 1953.

Meyer, F. and Meyer-Hofmeister, E. 1979, Astron. Astrophys. 78, 167.
Paczynski, B. 1970, Acta Astr. 20, 47.
Paczynski, B. 1971, Ann. Rev. Astron. Astrophys. 9, 183.
Paczynski, B. 1976, in IAU Symp. 73, "Structure and Evol. of Close Binaries" (eds. P.P. Eggleton et al.), Reidel, Dordrecht, 75.
Paczynski, B. 1983, Nature 304, 421.
Paczynski, B. and Sienkiewicz, R. 1972, Acta Astron. 21, 73.
Paczynski, B. and Sienkiewicz, R. 1981, Astrophys. J. 248, L27.
Papaloizou, J. and Pringle, J.E. 1978; Mon. Not. Roy. Astr. Soc. 184, 501.
Plavec, M. 1968, Adv. Astron. Astrophys. 6, 201.
Pringle, J.E. 1981, Ann. Rev. Astron. Astrophys. 19, 137.
Rappaport, S.A., Joss, P.C. and Webbink, R.F., Astrophys. J. 254, 616.
Rappaport, S.A. and van den Heuvel, E.P.J. 1982, in IAU Symp. no. 98, "B-emission Stars" (eds. M. Jaschek and H.G. Groth) Reidel, Dordrecht, 327.
Rappaport, S.A. and Joss, P.C. 1983, in "Accretion-Driven Stellar X-ray Sources (eds. W.H.G. Lewin and E.P.J. van den Heuvel), Cambridge University Press., 1.
Rappaport, S.A. and Joss, P.C. 1984, Astrophys. J. (in the press).
Radhakrishnan, V. and Srinivasan, G. 1981, Proc. 2nd Asian-Pacific Regional IAU meeting, Bandung (B. Hidayat, ed.), in the press.
Radhakrishnan, V. and Srinivasan, G. 1982, Curr. Sci. 51, 1096.
Ruderman, M.A. and Shaham, J. 1983a, Comm. Astrophys. 10, 15.
Ruderman, M.A. and Shaham, J. 1983b, Nature 304, 425.
Ruderman, M.A. and Sutherland, P.G. 1975, Astrophys. J. 196, 51
Savonije, G.J. 1983, Nature 304, 422.
Smarr, L.L. and Blandford, R.D. 1976, Astrophys. J. 207, 574.
Srinivasan, G. and van den Heuvel, 1978, paper presented at 9th Texas Symp. on Relativ. Astrophys., München (unpublished).
Srinivasan, G. and van den Heuvel, E.P.J. 1982, Astron. Astrophys. 108, 143.
Sugimoto, D. and Nomoto, K. 1980, Space Sci. Rev. 25, 155.
Sutantyo, W. 1981, Proc. 2nd Asian-Pacific Regional Meeting IAU, Bandung (B. Hidayat, ed.) (in the press).
Taam, R.E. 1983, Astrophys. J. 270, 694.
Taam, R.E. and van den Heuvel, E.P.J. 1984, Astron. Astrophys. (in prepar.).
Taam, R.E., Bodenheimer, P. and Ostriker, J. 1978, Astrophys. J. 222, 269.
Taylor, J.H. 1981, in IAU Symp. No. 95, "Pulsars" (eds. W. Sieber and R. Wielebinski), Reidel, Dordrecht 357.
Taylor, J.H. and Weisberg, J.M. 1982, Astrophys. J. 253, 908.
van den Heuvel, E.P.J. 1977, Annals New Y. Acad. Sci. 302, 14.
van den Heuvel, E.P.J. 1981, in IAU Symp. No. 95 "Pulsars" (eds. W. Sieber and R. Wielebinski), Reidel, Dordrecht, 379.
van den Heuvel, E.P.J. and Bonsema, P. 1984, Astron. Astrophys. (Letters) (in the press).
van den Heuvel, E.P.J. and Taam, R.E. 1984, Nature 309, 235.
van Paradijs, J.A. 1983, in: "Accretion-Driven Stellar X-ray Sources" (eds. W.H.G. Lewin and E.P.J. van den Heuvel) Cambridge University Press, 189.
Webbink, R.F. 1979, in: IAU Colloq. 53, 426.
Webbink, R.F., Rappaport, S.A. and Savonije, G.J. 1983, Astrophys. J. 270, 678.
Whelan, J. and Iben, I. 1973, Astrophys. J. 186, 1007.

DISCUSSION OF VAN DEN HEUVEL'S PAPER

VAN DEN HEUVEL: In reference to an earlier question, the reason why you could see strong fields in old-population sources is that these were formed quite recently by white-dwarf collapse in a binary. So that in Hercules X-1 and 1626-67, the pulsing low-mass X-ray binaries, the neutron stars were formed quite recently by white dwarf collapse in old binaries.

KULKARNI: What I don't understand is that in 1937+21, if it's younger in the same way, why isn't the field 10^{12} gauss? You're saying the heat of the formation is enough to regenerate the field?

VAN DEN HEUVEL: That is only in the case in which you start out with two neutron stars. If you start out with the Hulse-Taylor pulsar 1913+16, you have two neutron stars colliding. The energy which you then release is of the order of supernova energies, and so you probably melt both neutron stars completely. In that case, there seem to be good reasons to assume that the field from the interior comes out.

MANCHESTER: There's no reason why that field couldn't fade.

VAN DEN HEUVEL: Oh, but the thing is formed with a 1.5 millisecond, or one millisecond period. With a 10^{12} or 10^{13} gauss field the luminosity of such a pulsar is a quasar luminosity.

BACKER: In a number of conversations this morning, we've convinced ourselves that the interstellar scintillation results provide strong evidence that the peculiar velocity of the 1937+21 pulsar is of order 100 km/s, so it's curious why it's near the plane.

RUDERMAN: This is a change from the claim that it was differential galactic rotation?

BACKER: Yes.

VAN DEN HEUVEL: It is not differential galactic rotation.

BACKER: Narayan pointed out that differential galactic rotation will not produce interstellar scintillation velocities, because the interstellar medium is not moving anywhere with respect to the line of sight, by anything like 100 km/s. The whole line of sight is twisting but there's no transverse motion.

VAN DEN HEUVEL: This model always gives you a high velocity, because you start as a binary system, with two supernovae. But there you have the problem that the field may not be weak. And I think that this one [1937+21] should also have a high velocity, because it's an old population object, like the low-mass X-ray binaries, which have a space distribution like the novae: an intermediate-age population.

BACKER: It is a fact that the object was pulled out of the radio sky because it was on the galactic plane and showing interplanetary scintillation, so it's a selection effect. While we've not found any others, this strategy has pulled out this one because it was near the plane, and not at $b = 10$ degrees.

VAN DEN HEUVEL: I'd say this model would not give a runaway velocity much above 30 km/s.

RADHAKRISHNAN: At one point you talked about a system of a neutron star and some low mass main sequence star. I'm trying to understand how such a system could form in the first place, because during the explosion more than half of the mass is lost or transferred onto the other star. I haven't been able to imagine how you end up with a neutron star and something less than one solar mass.

VAN DEN HEUVEL: Again, the idea of driving a white dwarf over the Chandrasekhar limit seems the most attractive one. Because if by the transfer you do so, your mass loss can be very small; you lose only the binding energy of the neutron star, about 0.1 solar masses, and the recoil of the system is not much; you would not unbind the system.

RADHAKRISHNAN: Doesn't this almost prove that it has to be that way?

VAN DEN HEUVEL: It seems very attractive for these objects. I think it's probably the only way to do it.

APPLEGATE: Blandford, Hernquist, and I considered mechanisms by which neutron stars can thermally generate their own magnetic fields and don't have to rely on trapped stellar flux. Now, we mainly considered the heat flux due to the cooling of the neutron star after its birth in a supernova explosion. But accretion could also provide quite a bit of heat to a neutron star. The details have not been worked out by any means, except it's possible that accreting X-ray sources could in fact produce magnetic fields in neutron stars, which would provide an explanation for the field of Her X-1, but has some difficulties in that low-mass X-ray sources like the globular cluster sources show no evidence of magnetic fields. All the models for 1937+21 involve accretion and the thing doesn't have a magnetic field, so you'd have to argue that there's a critical luminosity required. But it may be too naive to say that the field is just produced when the thing is born and just decays away. It might be possible to regenerate magnetic fields. If I could make one more comment related to Radhakrishnan's remark, it is precisely the low-mass X-ray sources in globular clusters which are thought to be neutron stars and low-mass main-sequence stars. They are there thought to be produced by stellar-dynamical processes where there's tidal capture between a low-mass star and a neutron star in a globular cluster. Even though this one is not in a globular cluster, these systems can also be ejected from the cluster by collisions and in fact that's a fairly important process in the dynamical evolution of the globular cluster. So if it turns out that 1937+21 has the kinematics of a Pop II object, this is a possible, slightly non-standard, origin.

VAN DEN HEUVEL: I think this is certainly a viable mechanism for making the low-mass X-ray binaries, especially in the bulge of the galaxy.

LYNE: Can I just make a comment about the scintillation velocity? I think, although statistically scintillation velocities do provide quite a good indication of real velocities, you must bear in mind that scintillation might occur in a discrete region near the pulsar, in which case the scintillation velocity observed might be substantially at variance with the pulsar velocity. So I wouldn't be at all surprised if there were an error by a factor of 2 or 3 in the velocity in either direction.

RUDERMAN: But a factor of 3 would still make it young.

ISOLATED AND BINARY MILLISECOND PULSARS

AND ACCRETION SPUN-UP NEUTRON STARS

Jacob Shaham

Physics Department and Columbia Astrophysics Laboratory
Columbia University, New York, New York

This being a short contribution to the workshop, it is really quite impossible to cover all aspects of the accretion spin-up scenario which have, by now, become rather numerous. Some of them have been discussed by Van den Heuvel in his review talk (this volume) and our own views have been published or are being submitted for publication in seveal write-ups (Alpar et al. 1982, Helfand et al. 1983, Ruderman and Shaham 1983a, b, 1984). Assuming, therefore, that the ground rules for this scenario are familiar, namely that the two millisecond pulsars have acquired their ultra-fast spins by accretion from a companion who may either have since completely tidally disrupted (1937+214) or may have remained as a very light dwarf companion (1953+29), I would like to concentrate here on three selected remarks regarding that scenario, which, at least to some of us, seem and seemed to be rather fundamental ingredients to it.

(i) On the Thermal Origin of Neutron Stellar Magnetic Fields and its Relation to 1937+214

Around the time in which the discovery of the 1.5 msec pulsar 1937+214 was announced by Backer et al. (see Backer, this volume), Blandford et al. (1983) suggested a way by which sufficiently hot, cooling, neutron stars, having seed fields of > 10^8 Gauss, could amplify those fields to values up to 10^{13} G in the relatively short time of several hundred years. The process, an astrophysical analogue of the Ettingshausen Effect in physics, essentially takes place when heat conducting electrons are deflected in the seed field by different amounts at different radial distances, so as to create a net electric field which, though small, is curl-free and hence can amplify the seed field or destroy it depending on whether the heat flux is outwards or inwards. There are still several conceptual and numerical details that should be ironed-out regarding this model, but various observational aspects of pulsar physics (Blandford et al. 1983) do seem to suggest that it might be essentially correct.

If one does accept it, this scenario has far reaching consequences regarding the formation of 1937+214. We note that this pulsar is only a factor of 2 or so away from centrifugal break-up, depending on the exact equation-of-state one uses for neutron matter and on the mass of 1937+214. Thus, it could not have been formed spinning much faster than it does today. As its magnetic field today is still in excess of 10^8 Gauss it is reasonable to assume that its field at formation was at least as large and, if its temperature was then > 10^8 °K typical pulsar strong magnetic fields would build up and the pulsar would slow down to far below 1.5 msec long before its field had a chance to decay by any noticeable amount. The unavoidable conclusion is that 1937+214 could not have been formed hot, and - from the Blandford et al. numbers - must have been spun up while staying around or below 10^7 °K.

This kind of large angular momentum needed here must clearly come from a collapse of wide, slowly rotating astrophysical matter; such a process, which has its own thermostat for not exceeding $\sim 10^7$ °K, is the spherical accretion onto a low magnetic field neutron star, which is limited to below the Eddington values, hence to radiation temperatures below $\sim 10^7$ °K.

This is only one way by which one may arrive at the accretion spin-up scenario; but I thought it had some interesting aspects, so I brought it up here.

(ii) The P - $\dot{P}$ Relationship

Perhaps the most attractive feature of the accretion spin-up scenario is the way in which it relates the spun-up period P to its time derivative $\dot{P}$: As the upper bound on P, P_{eq}, depends on the magnetic field (and the accretion rate $\dot{m}$) and as $\dot{P}$ depends on it as well, one finds $\dot{P} \propto P_{eq}^{4/3}$ for typical values of $\dot{m}$ and stellar mass, a relation quite distinct from the $\dot{P} \propto P^{-1}$ relation for ordinary pulsars. Spun up pulsars occupy, therefore, a region in the P - $\dot{P}$ diagram which is quite distinct from that occupied by ordinary pulsars (see, e.g., Ruderman and Shaham 1983b), one in which all hitherto identified binary pulsars lie (the $\dot{P}$ value for 1953+29 is only available as an upper bound so far, but that value is still consistent with $\dot{P}$ lying in that region as well [Boriakoff (this volume)]. It is quite difficult to understand any such P-$\dot{P}$ relation on the basis of any other presently available observations except for the accretion spin-up scenario, even though one may suggest new theoretical scenarios for low P-low $\dot{P}$ pulsars. 1937+214 also lies in that region.

What might seem to weaken this argument for 1937+214 is the fact that no sufficiently sizeable companion has been found orbiting around it (Backer, this volume). And that brings me to my third remark.

(iii) What Ever Happened to the Companion of 1937+214?

On present observational grounds, it seems reasonable that the accretion spin-up ancestor of 1937+214 was a tight galactic bulge source, in which a light main sequence star, companion to a neutron star, overflew its Roche Lobe driven by Gravitational Radiation (or some other mechanism by which Roche Lobe overflow occurs prior to the giant phase of the companion). The neutron star, incidently, was possibly formed by a slow collapse of an accreting white dwarf, so as to keep it in the galactic plane. The evolution of such binaries has been studied extensively, and the main results are the following:

Stable mass transfer with a main sequence companion occurs when the stars indeed approach each other, since only then can the diminishing stellar dimension still fill the (also diminishing) Roche Lobe. However, as the star becomes convective or degenerate, it will begin to expand on losing mass and the binary will therefore have to expand too. Expansion, by the way, is the natural response of a binary when transfer of a massive particle from a low mass companion to the higher mass one occurs while conserving angular momentum. The question is - will the torque on the binary orbit be large enough to allow the binary expansion keep pace with that of the star. Recent estimates that we have made (Ruderman and Shaham

1983a, 1984) and recent numerical estimates by Hut and Paczyncki (1983) show that when the companion mass becomes low enough, $< 10^{-2}$ M , an instability might indeed set in that will result in tidal disruption of the companion. Particulary, if the companion is a helium rather than a hydrogen star, the whole binary evolution will take place at a faster pace since the Roche Lobe needed for given mass is smaller, while disruption will occur at slightly higher mass because of the relative interplay between degenerate and solid state effects inside the star. These two effects can bring about tidal disruption in much less than the Hubble time.

Can a light He star be a natural stage in the evolution of the main sequence companion, as it forms its He core and loses the hydrogen envelope? One should look in more detail into that question, but it may be encouraging to note that the lightest companions that have been found so far in cataclysmic variables do seem to be made of helium (Nather *et al.* 1981; Faulker *et al.* 1972; Patterson *et al.* 1979).

This work was supported by the National Aeronautics and Space Administration under Contract NAS 8-30753. This is Columbia Astrophysics Laboratory Contribution No. 272.

References

Alpar, M.A., Cheng, A.F., Ruderman, M.A., and Shaham, J. 1982, *Nature*, **300**, 728.

Blandford, R.D., Applegate, J.H., and Hernquist, L. 1983, *M.N.R.A.S.*

Faulkner, J., Flannery, B., and Warner, B. 1972, *Ap. J. (Letters)*, **175**, L79.

Helfand, D.J., Ruderman, M.A., and Shaham, J. 1983, *Nature*, **304** 423.

Hut, P., and Paczynski, B. 1983, Princeton University Preprint.

Nather, R., Robinson, E., and Stover, R. 1981, *Ap. J.*, **244**, 269.

Patterson, J., Nather, R., Robinson, E., and Handler, F. 1979, *Ap. J.*, **232**, 819.

Ruderman, M.A., and Shaham, J. 1983a, *Nature*, **304**, 425.

Ruderman, M.A., and Shaham, J. 1983b, *Comm. Astrohys.*, **10**, 15.

Ruderman, M.A., and Shaham, J. 1984, preprint.

DISCUSSION OF SHAHAM'S PAPER

BACKER: What are your current thoughts on the final state of the system [1937+21]? What's left over when it stops accreting?

SHAHAM: You need very well-tuned conditions of the separation and density of the remnant in order for a remnant to even remain. But if you calculate that, by putting in equations of state for solid stars, it's an extremely small planet. It takes very special conditions for that to happen. In most cases the system will be disrupted.

VAN HORN: I have a comment that may or may not support the discussion you've given, Jacob. There are two and possibly three systems in which very low-mass helium stars are known to be accreting onto white dwarfs. These are WZ Sagittae, G61-29, and possibly HZ29. In each case the mass of the low-mass helium companion is of order a few hundredths of a solar mass--.04, .05. And at least for G61-29, the accretion rate is of order 10^{-5} solar masses per year. I'm not sure where that fits into your scenario.

SHAHAM: Those systems spend most of their lifetime in the mass range in which they disrupt. To find systems which are very close to the disruption mass should be the rule. It isn't anything to me that they say the mass accretion rate is 10^{-5} solar masses per year; the only thing I can think of is, maybe the disruption has begun.

NARAYAN: You want a very low accretion rate to prevent heating of the neutron star--correct?

SHAHAM: Not necessarily, because I don't think accretion on such low-field stars generates field. What Jim referred to earlier is for stars in which thermal gradients are not radial, but have an azimuthal component, right?

APPLEGATE: For Her X-1, we actually argued that if you heat the poles, the heat would flow into the inside of the star and then outward radially. But if you accrete such that the heat flow is inward radially, you first of all destroy the magnetic field, and you also tend to expel it.

PINES: It seems to me that that is a pretty good argument against Ed's [van den Heuvel] proposal for Her X-1 because you want to start it with a weak field, in which case you're heating the star roughly spherically. It's an old star with a weak field, you're spinning it up, you're heating it, but you're not heating it in a localized fashion, and that would not tend to generate a field--it would tend to kill the field, or at least not do any big things.

APPLEGATE: The other question I had is, if you have relatively slow accretion onto an essentially unmagnetized object, is it really uniform or do you actually just heat the equator?

PINES: Yes--because you're heating it enough so that it would be hard to have the material diffusion and temperature diffusion on the star go slowly enough under the accretion conditons which would be almost spherical.

NARAYAN: Now we keep hearing about these magnetic fields and heating. That means that you can't have very slow accretion. Because if it's too slow, the neutron star field decays away and you have no magnetic field left to form a pulsar. But does this mean that you really have a very narrow window of $\dot{M}$ in which you can form a millisecond pulsar?

RUDERMAN: There are two places in which magnetic fields have current that affect them. One is in the crust, the other in the core. The only theoretically satisfying understanding of where you expect currents to decay is for crustal currents. If you believe that all the magnetic field is due to crustal currents, then it should die out in a time scale of a million or so years, presumably to zero. If you believe there's a component that is supported by core currents, there is not yet any theoretical estimate of how long that remnant field lasts. So everyone might agree that the magnetic field drops after several million years, but there is no clear understanding of whether it dies to zero or whether it dies to a new level.

VAN DEN HEUVEL: What is the configuration of field in the core? Isn't the core something like a superconductor? How can it have a field at all?

RUDERMAN: The field is in a lot of individual flux tubes, but, if your eyesight is poor, it's topologically similar to an ordinary conductor with toroidal components.

VAN DEN HEUVEL: It cannot shield itself completely? Because then you could finish up with a zero field.

RUDERMAN: Undoubtedly, if you wait long enough, you will.

PINES: Several times the age of the universe.

SHAHAM: You know that for shielding set by currents in the crust, you must get currents in the crust to live more than a million years, and we know that they don't. So I would think that as time goes on, and the field in the crust decays, more and more of the flux from the inside will come out. And the question now is, what happens to the field in the inside?

VAN DEN HEUVEL: And so you cannot say with what field it ends? But at least it does not end with 10^{12} gauss--it ends with something like 10^{8}?

SHAHAM: That seems likely but I think we'd better ask what the millisecond pulsar is telling us rather than try to work it out.

CHENG: About this question of the magnetic field decay. I think the observations suggest that in fact the braking torque on the pulsar is decaying in such a way that either the field is decaying, or the pulsar is aligning. I don't think the observations can tell us which of the two is happening. So that if you're just looking at the evolution in the P-$\dot{P}$ plane, an alternative interpretation is that in fact the magnetic moments and the angular velocities are aligning, but that the field's magnitude stays the same.

VAN DEN HEUVEL: But then there is the question of whether an aligned rotator does not lose energy as efficiently as a perpendicular one.

RUDERMAN: They may disappear as pulsars.

RADHAKRISHNAN: Maybe then you should see correlations between pulse widths and things, for example.

THE PERIOD DISTRIBUTION OF FAST PULSARS

A. K. Harding

NASA Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

Several proposed models for the origin of fast pulsars predict a correlation between period and magnetic field strength, where the shortest period pulsars should have the lowest fields, and therefore the smallest period derivatives. Such a correlation, coupled with a lower limit on pulsar period from rotational stability arguments, could produce a significant clumping in the period distribution near the minimum stable period. The shape of the distribution will depend on the initial magnetic field distribution of fast pulsars and on the strength of the $P,\dot{P}$ correlation.

INTRODUCTION

A number of arguments favor the view that pulsars with millisecond periods represent a separate class having a different origin and evolution from longer period pulsars. If this is the case, then the predicted numbers of millisecond pulsars can not be determined from an extrapolation of the normal pulsar period distribution, raising the question: what should the period distribution of fast pulsars look like? A steady-state period distribution can be determined if one knows something about the source function (the rate of pulsar births) and the period (spin-down) evolution. There are two qualitative features of fast pulsar origin which could influence their period distribution. One is the prediction of several different models that the initial period of the pulsar should depend on its magnetic field strength, B. In the accretion spin-up scenario (Alpar et. al. 1983, Arons 1983) the equilibrium period is that of the Keplerian orbit at the Alfvén radius and thus has a well defined dependence on B. If fast pulsars are born in isolation, then shorter period pulsars are also expected to have smaller fields due to a lower efficiency of angular momentum transfer between the rotating core and the envelope during core collapse in the supernova (Brecher and Chanmugam 1983). The other feature which could affect initial periods is the predicted minimum rotation period of a neutron star which is secularly stable. While the exact value of this critical period depends on our as yet incomplete knowledge of neutron star physics, the existence of a minimum period somewhere around 1 ms will introduce a cutoff in the source function. A third determining factor in predicting the period distribution, and one which is not known but could probably depend in some way on origin, is the magnetic field distribution of neutron stars or progenitor stars which become fast pulsars.

In this paper, I use a method of determining the steady-state distribution of fast pulsar periods from a given source function and spin-down evolution model to predict the shape of the distribution as a function of the P-B correlation and the B distribution. Such predictions can tell us how many pulsars we might expect to find in future searches at short periods and whether the shape of the distribution might depend on the way in which fast pulsars are born.

PREDICTED PERIOD DISTRIBUTIONS

The method used here to calculate the expected period distribution was introduced by Phinney and Blandford (1981) to analyze the observed pulsars in the P-$\dot{P}$ diagram. Vivekanand and Narayan (1981) also used this idea of pulsar "current" to make a determination of the galactic pulsar birthrate. Rather than use an observed distribution in $(P,\dot{P})$ to find the source function, as these previous studies have done, the present calculation will use an assumed source function to predict the distribution in P. If $N(P,\dot{P})dPd\dot{P}$ is the number of pulsars at period P and period derivative $\dot{P}$, and $q(P,\dot{P})dPd\dot{P}$ is the source function of fast pulsars, the number born per second with P and $\dot{P}$, then $N(P,\dot{P})$ is determined by,

$$q\,(P,\dot{P}) = \frac{\partial N(P,\dot{P})}{\partial t} + \frac{\partial}{\partial P}\,[\dot{P}N(P,\dot{P})] + \frac{\partial}{\partial \dot{P}}\,[\ddot{P}N(P,\dot{P})] \qquad (1)$$

which is essentially a pulsar continuity equation. In steady-state ($\partial N/\partial t$ = 0), with the assumption $\ddot{P} \sim 0$,

$$q\,(P,\dot{P}) = \frac{\partial}{\partial P}\,[\dot{P}N(P,\dot{P})] \qquad (2)$$

We therefore have

$$N\,(P,\dot{P}) = \frac{1}{\dot{P}}\int_P^\infty q\,(P',\dot{P})\,dP' \qquad (3)$$

and the period distribution can be obtained by integrating $N(P,\dot{P})$:

$$N\,(P) = \int N\,(P,\dot{P})\,d\dot{P} \qquad (4)$$

To completely determine N(P), an evolutionary model giving $\dot{P}$ as a function of P is needed and we assume magnetic dipole spin-down without field decay, which has the dependence $P\;\dot{P} = C\;B^2$.

To start with the simplest example, suppose all pulsars are born with $P = P_0$ and $B = B_0$, so that the source function is,

$$q\,(P,\dot{P}) = q\,(\dot{P})\;\delta\;(P-P_0) \qquad (5)$$

$$q\,(\dot{P})\;d\dot{P} = q\,(B)\;dB = q_0\;\delta\;(B-B_0).$$

From Eqn (3),

$$N\,(P,\dot{P}) = \frac{q(\dot{P})}{\dot{P}},\; P > P_0 \qquad (6)$$

and the steady-state period distribution is,

$$N\,(P) = \frac{q_0 P}{CB_0^{\,2}},\; P > P_0 \qquad (7)$$

As one might expect by analogy with fluid flows, the density of pulsars in the P-$\dot{P}$ diagram will be largest where the velocity ($\dot{P}$) is smallest, and in the case of dipole spin-down, N(P) increases linearly with P along evolutionary tracks of constant B (see Fig. 1).

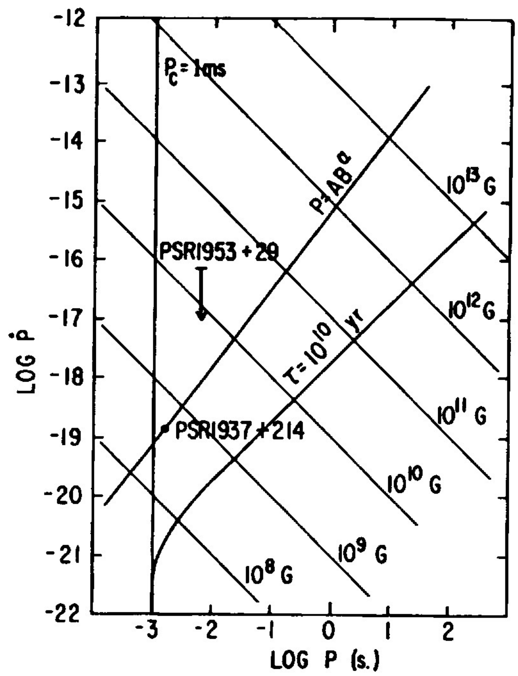


Figure 1 - P-$\dot{P}$ diagram for pulsars showing lines of constant B, the birth line, the critical period P_c, and the maximum spin-down age line.

We now suppose that there is a correlation between initial period, P_0, and B, such that $P_0 = A\,B^{\alpha}$, $\alpha > 0$. If we also assume that there is a minimum stable period, $P = P_c$, then pulsars with low enough fields to be formed or spun-up below P_c will spin-down to P_c by gravitational radiation on short timescales, and will all be "born" at P_c. The source function will therefore be,

$$q\ (P,\dot{P}) = q\ (\dot{P})\ \delta\ (P - AB^{\alpha}),\ P > P_c$$

$$q\ (\dot{P})\ d\dot{P} = q_0\ B^{\beta}\ dB, \qquad (8)$$

where the magnetic field distribution of fast pulsars is assumed to be a power law with index β. As before, N(P, $\dot{P}$) is given by Eqn (3) and integration over B(P) gives:

$$N\ (P) = \frac{P}{C}\frac{q_0}{(\beta-1)}\ [B_{max}^{\beta-1} - B_{min}^{\beta-1}],\ \beta \neq 1 \qquad (9)$$

Figure 1 shows that at each period, B_{max} is determined by the birth line, $P = A\,B^{\alpha}$, and B_{min} is determined, in the most conservative estimate, by the fact that pulsars do not populate the region where the maximum spin-down age,

$$\tau = \frac{P}{2\dot{P}}\ [1 - (\frac{P_0}{P})^2] < \tau_{max} \qquad (10)$$

exceeds the age of the Universe. With these limits of integration,

$$B_{min} \simeq \frac{P}{(2C\tau_{max})^{1/2}} \left[1 - \left(\frac{P_c}{P}\right)^2\right]^{1/2}, \tag{11a}$$

$$B_{max} = \left(\frac{P}{A}\right)^{1/\alpha}, \tag{11b}$$

and the resulting expression for the period distribution is

$$N\,(P) = \frac{q_o}{C(\beta-1)} \left\{ \frac{P^{(\beta-1)/\alpha\, +\, 1}}{A^{(\beta-1)/\alpha}} - \frac{P^{\beta}\left[1- \left(\frac{P_c}{P}\right)^2\right]^{(\beta-1)/2}}{(2C\tau_{max})^{(\beta-1)/2}} \right\} \tag{12}$$

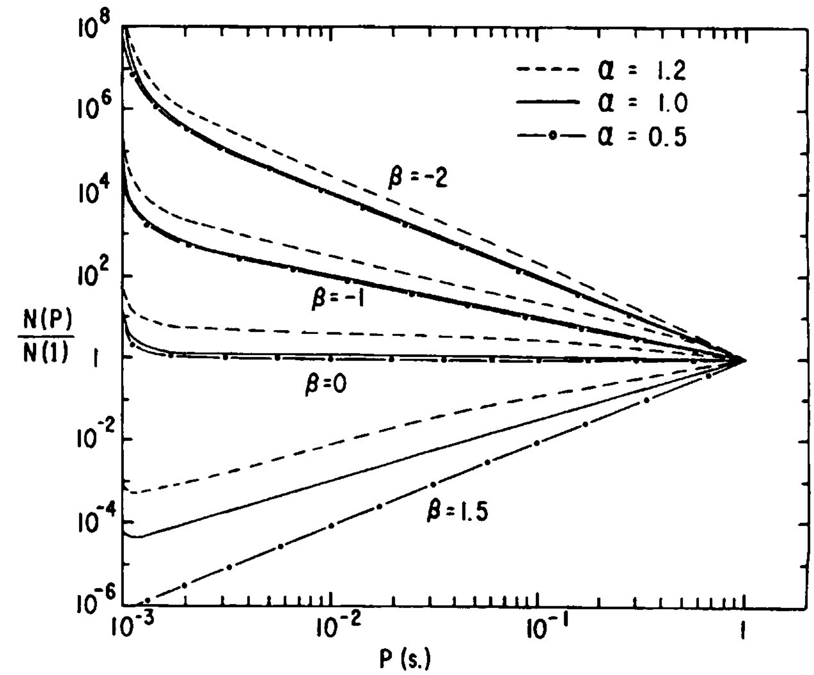


Figure 2 - Predicted period distributions for fast pulsars from eqn (12), normalized to the values at P = 1 s.

In order to evaluate this expression numerically, the constant A from the birth function is determined by normalizing to PSR 1937+214, which has P = 1.56 ms and B = 5 X 10^8 G, and the constant C in the dipole spin-down law is set by taking a neutron star radius, R = 10^6 cm, and moment of inertia, I = 10^{45} g cm^2. The critical period, P_c, depends both on the highest m mode at which neutron stars are unstable (see Imamura 1984) and on the equation of state. If one conservatively assumes that only the m = 2 (Jacobi) mode is unstable (the critical period increases with mode number), then the most reasonable equations of state give $P_c \sim 1$ ms (Harding 1983). Figure 2 shows the ratio of the number of pulsars per period interval normalized to the value at P = 1 s. This plot does not, of course, show the actual numbers of fast pulsars relative to the number of "normal" pulsars, whose period distribution will begin to overlap somewhere around P = 0.1 s. (see Dewey et. al. 1984). For magnetic field distributions with power law indices, $\beta < 0$, the second term in Eqn (12) will dominate, N(P) will decrease as $P^{-\beta}$, and there will be more pulsars at short periods. For $\beta = 0$, the distribution is flat, giving equal numbers at all periods except near P_c, and for $\beta > 0$, the first term of Eqn (12) dominates, causing N(P) to increase with P. Larger values of α cause N(P) to decrease more steeply for $\beta < 0$ and to increase more slowly for $\beta > 0$. For $\beta \leq 0$, the infinite number of pulsars predicted at P_c results from letting the value of B_{min} go to zero. The actual number at P_c will of course be finite and will depend on the lower cutoff in the magnetic field distribution.

In the accretion spin-up models for fast pulsar evolution, the spin-up times are long enough ($\sim 10^8$ yr) that field decay on timescales of several Myr would be expected to produce a population of old neutron stars with very weak magnetic fields. In this case, a steady birthrate of young neutron stars with fields around 10^{12} G undergoing exponential field decay would result in a distribution of weak field neutron stars with $\beta = -1$. If field decay does not occur below a certain field strength, then fast pulsars may themselves have stable fields. The value of α in these models is 6/7. Figure 2 shows that for these parameter values the ratio of pulsars with periods around 1 ms to pulsars around 10 ms is about 100.

CONCLUSIONS

A lower cutoff in the period distribution of fast pulsars is an inevitable consequence of a neutron star instability point. If all neutron stars have the same mass, then this cutoff would be quite sharp, and observational determination of the neutron star critical period might be an intriguing possibility. A measurement of P_c would be a measurement of the mean density of neutron stars, with some uncertainty due to the mode of secular instability. If, however, neutron stars have a range of masses, the cutoff may not be sharp enough to define.

There could also be a "feature" in the observed period distribution near the critical period, where the majority of the fast pulsars may be found. This would result from the fact that periods below P_c are unstable while periods immediately above P_c are very stable, since these pulsars have the lowest $\dot{P}$ values. Whether the number of pulsars decreases or increases above P_c depends primarily in this analysis on the magnetic field distribution. However, prediction of the actual observed period distribution should include selection effects from, for example, a possible dependence of pulsar luminosity on P and $\dot{P}$.

I am very grateful to Jim Felten for some initial suggestions and discussion.

REFERENCES

Alpar, M. A., Cheng, A. F., Ruderman, M. A., and Shaham, J. 1983, Nature, 301, 313.
Arons, J. 1983, Nature, 302, 301.
Brecher, K. and Chanmugam, G. 1983, Nature, 302, 124.
Dewey et. al., these proceedings.
Harding, A. K. 1983, Nature, 303, 683.
Imamura, J. N., Friedman, J. L. and Durisen, R. H., these proceedings.
Phinney, E. S. and Blandford, R. D. 1981, M.N.R.A.S., 194, 137.
Vivekanand, M. and Narayan, R. 1981, J. Astrophys. Astr., 2, 315.

DISCUSSION OF HARDING'S PAPER

CHENG: If you accept the idea that you tend to make ordinary pulsars hot, and as a result they tend to be born with high magnetic fields, wouldn't that be a high positive value of β?

HARDING: β just referred to the field distribution of neutron stars that become fast pulsars.

CHENG: So all pulsars are born with some initial period? You didn't specify what that was, did you?

HARDING: Yes, I did--P_o is the birth function; β is the power-law index of the field distribution.

CHENG: If you tend to make pulsars with large magnetic field, it's a positive value of β.

HARDING: Right.

CHENG: If you accept that, then you would be biased toward a large positive value of β, and that also predicts in your model that most pulsars pile up with large periods.

HARDING: That's right.

NARAYAN: We have seen the plot of recycled pulsars several times today. And every time they have always occurred on this birth line. Never have we seen them on the 10^{10} year line. Would that mean that your assumption of no dipole decay is wrong?

HARDING: Certainly putting in an exponential field decay would change things.

NARAYAN: But on the other hand, after the last talk we decided that we can't have decay in recycled pulsars. I think we have a bit of a conflict here.

VAN DEN HEUVEL: This 10^{10} year line--doesn't it run through the "graveyard?"

HARDING: Your "graveyard" was everything to the right of a pair-production cutoff of some kind. I said that we don't know what the pair-production cutoff is--we can guess something, and it will be a steeper curve. So what I did was a little more conservative. If you think about this, and you say most of the pulsars are in this region, and you take the pair-prouction cutoff which would give you the right cutoff in the normal pulsar distribution, you get something which will not affect fast pulsars. But suppose there is some other pair-production cutoff--then you might begin to affect the fast pulsar distribution. Anything steeper than this will cause even more of an enhancement than I get with this line. So if you steepen this line you're getting relatively more fast pulsars with small $\dot{P}$, and that means you're eliminating these slow $\dot{P}$ ones from the slower-pulsar distribution and therefore you're making the enhancement at the critical periods greater.

ALPAR: I think there is not any problem with assuming the field is constant as you did, because if you look at isochrones like the 10^{10} year one, and the birth line, you will see that they all converge at low periods. So, another way of seeing your results that things pile up at the lowest periods is that things evolve so slowly that you get from the 10^7 year line to the 10^8, 10^9, 10^{10} year line quite slowly and they all live in the short period region of the diagram.

HARDING: That's part of the effect. Also, suppose this line were different and it would cause you to have a very low magnetic field formed below the critical period. Then you wouldn't get the same piling-up effect. Some of the piling-up effect assumes that you're going to have low enough field strengths to form pulsars below the critical period. Or if the critical period were too low, you won't get as much of an effect either.

TAYLOR: Am I right in assuming that all your N(P) predictions were predicting what you would get in a histogram plotted on a linear scale of P, not a logarithmic scale?

HARDING: This is a log-scale here.

TAYLOR: The other question is, these N(P)'s are numbers of pulsars per cubic parsec, and don't have any assumption about luminosity and therefore detectability, right?

HARDING: Right. I'm ignoring selection effects, so what you see will depend on what you put in here for the luminosity dependence on the period.

KULKARNI: The first time I heard all these formation scenarios (and I hope no one's taping this)--I thought, gee, all these guys know what they're talking about. But now it appears after all this discussion that theorists have made several arbitrary assumptions. So I thought I might as well put in another assumption which is somewhat less restrictive and equally black-magic-ish, that is, that depending on the accretion, you get a field anywhere between zero and 10^{12} gauss in a recycled pulsar. If the accretion is really large it could be 10^{12}; if it's really small, you might get 10^8 or 10^6. It's as bad as the assumption about the period not decaying there when accretion starts. At least this assumption has the advantage that you can generate a whole bunch of detectable pulsars this way.

HARDING: Let's take a poll among observers.

On the Nature of the Crablike, Pulsar-powered Supernova Remnant 0540-693: The Pulsar's Initial Period

Stephen P. Reynolds

National Radio Astronomy Observatory[1]
Charlottesville, Virginia

ABSTRACT

While it is generally accepted that most "normal" pulsars are not born rotating near the dynamical limit of about 1 ms, there is almost no direct information on the initial periods of pulsars, except for the Crab pulsar where $P_0 \sim$ 10-20 ms. I use radio, optical and X-ray observations of the Crablike supernova remnant in the Large Magellanic Cloud, 0540-693, to deduce the initial properties of its recently discovered 50 ms X-ray pulsar. Simple evolutionary considerations give the age of the object as 700 -1000 years. Its appearance in all frequency bands can be understood if it is a combination of emission resulting from several solar masses of fast-moving ($\sim 10^4$ km/s) material interacting with the surrounding medium, producing the radio emission, and a solar mass or so of processed material which has been swept into a shell and accelerated by the pulsar. The original luminosity of the pulsar is restricted to the range (5-20) x 10^{38} erg/s, somewhat less luminous than the Crab pulsar at birth. The original rotational energy is inferred to be 2 x 10^{49} erg, depending only insensitively on model details; this implies an initial period for the pulsar of 34 ± 5 ms. Thus this pulsar, the second for which initial parameters can be inferred, joins the Crab in having a relatively slow rotation at birth. I discuss the significance of this finding for theories of pulsars and their supernova remnants.

INTRODUCTION

How fast are pulsars born rotating? While evidence mounts that the two fastest pulsars are recycled (spun up) rather than born with periods of order 1 millisecond, the past history of most currently slower pulsars has been difficult to infer, given typically only the observed period and period derivative. Even if one measures a braking index and assumes it to be constant, a pulsar's true age must be known for an initial period to be derived. Thus the Crab pulsar has been the only one whose initial period can be inferred with some confidence: the observed braking index of 2.5 (Groth 1975), if constant, implies an initial period of 19 milliseconds.

So the study of pulsars themselves, in the absence of a much better theoretical understanding, seems unlikely to lead to better information on their initial periods. However, pulsars in young supernova remnants are susceptible to an entirely different avenue of investigation, through the

[1]National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

study of the dynamics of the remnant. The discovery of the 50 millisecond pulsar in the LMC remnant 0540-693, previously suggested to have Crab-like properties (Clark et al. 1982), promises to provide significant assistance in understanding both Crablike remnants and their young pulsars. The interaction of relatively simple models for the evolution of both classes of object can provide surprisingly good information on the pulsar's physical properties and on the nature of the supernova explosion. In particular, progress is possible on the nagging question: How unusual is the Crab pulsar, and how suitable a prototype for all young pulsars?

The observations of 0540-693 are summarized below. Notable are the spectral indices α ($S_\nu \propto \nu^{-\alpha}$) in the radio (~ 0.4) and optical to X-ray (0.8). The optical emission is a remarkable combination of line emission, almost totally in [OIII] (Mathewson et al. 1980) in a ring structure 8" in diameter, and center-brightened continuum emission, almost certainly synchrotron (Chanan, Helfand, and Reynolds, this volume; henceforth CHR). The lines have velocity widths of ~3000 km s^{-1}, giving a kinematic age of 670 years for a shell radius of 1 pc (corresponding to an assumed distance to the LMC of 55 kpc).

Observations of SNR 0540-693

Band	Frequency	Flux	θ	Reference
Radio	408 MHz	1.5 Jy		1
		2.4 Jy	< 2'	2
	843 MHz	1.1 Jy	<43"	3
	1415 MHz	0.8 Jy		1
	5009 MHz	0.51 Jy		1
	8900 MHz	0.76 Jy		2
	14,700 MHz	0.48 Jy		2
Optical	3.8×10^{14} Hz (= 7900 Å, I band)	0.72 mJy	7".4	4
	[O III] λλ 4959, 5007	2.6×10^{-13} erg cm^{-2} s^{-1}	8"	4,5
	6.8×10^{14} Hz (= 4400 Å, B band)	0.41 mJy	7".4	4
X-ray	10^{18} Hz (≅ 4 keV)	1.3 μJy		6
	~ 2×10^{17} Hz (≃ 1 keV)		<4" (20"-30"?)	7

References: (1) Mills, Turtle and Watkinson 1978. (2) Milne, Caswell, and Haynes 1980. (3) Mills and Turtle 1984. (4) CHR. (5) Mathewson et al. 1980. (6) Clark et al. 1982. (7) SHH.

A MODEL FOR THE SNR 0540-693

This system appears to follow very closely the picture outlined by Reynolds and Chevalier (1984, hereafter RC) for the evolution of a pulsar-driven supernova remnant. In this picture, the pulsar is born pouring a large luminosity in magnetic field (through low-frequency dipole radiation) and relativistic particles into the center of rapidly expanding supernova ejecta, and thereby excavating a bubble of relativistic fluid which is a strong synchrotron source. The bubble expands into the ejecta, accelerating and sweeping up material into a shell. Given the time-dependence of the pulsar energy output and the density and velocity distribution of the ejecta, the rate of expansion of the bubble can be easily calculated. RC consider two recipes for the particle-field mix in the bubble. In the non-equipartition case (case NE), the pulsar injects a fixed ratio of power in electrons and magnetic field into the bubble; radiative losses then depress the particle energy density far below that in field. The total relativistic fluid is then adiabatic, and simple analytic similarity solutions are available for the time-dependence of the bubble radius and magnetic field as a function of time. In the equipartition case (case E), physical processes are invoked to couple electron and field energies in the bubble. Thus radiative losses of the particles are shared with the field; the dynamical equations are much more complicated and a numerical solution is necessary. In either case the bubble is virtually isobaric, since the sound crossing time is a few tens of years (the non-relativistic material in the bubble is taken to be negligible, so the sound speed is $c/\sqrt{3}$). RC assume spherical symmetry and homogeneity for the bubble, though the isobaricity means that the dynamical evolution is not strongly dependent on these assumptions (though the detailed spatial synchrotron brightness structure may be).

The time-dependence of the synchrotron luminosity is critically dependent on the bubble's expansion rate, since adiabatic expansion losses dominate the evolution of low-energy electrons and come to dominate for all particles at late times. Thus the assumption of constant-velocity expansion, made in early work in this field (Pacini and Salvati 1973) and by others (Srinivasan and Bhattacharya 1984) leads to misleading results. Since the relativistic bubble has a different equation of state than the nonrelativistic material forming the ejecta, its expansion rate inside the outer shock marking the interaction of the ejecta with the undisturbed interstellar medium is never the same as that of the outer shock. RC write the time-dependence of the bubble radius R as $R \propto t^r$ and find that before the outer shock decelerates to the Sedov phase, sending a reverse shock to the center of the remnant, r is between 1 and 1.5, that is, the bubble is strongly accelerated. After the reverse shock passes, some 10^4 years for a Type II supernova mass of 8 $M_\odot$, $r = 0.3$. It is never true that $r = 0.4$, as one might naively expect once the outer shock follows this law (Sedov phase).

I assume standard simple pulsar physics, with the pulsar angular velocity evolving according to $\dot{\Omega} \propto \Omega^n$. I assume n to be constant and in a plausible theoretical range of 1.5 to 5; the results turn out to be insensitive to the value of n, so the assumption of its constancy could be relaxed. The solution to the above differential equation can be expressed in terms of the pulsar energy output by $L(t) = I\Omega\dot{\Omega} = L_0/(1 + t/\tau)^{(n+1)/(n-1)}$ where I is the pulsar's moment of inertia. The characteristic time τ is related to the spindown time $t_c \equiv P/2\dot{P}$ by $t_c = (n-1)(t + \tau)/2$; crudely, the pulsar luminosity is constant until τ, decaying as $t^{-(n+1)/(n-1)}$ after that. Note that the spindown time is an upper limit to the true age if $n > 3$, and is unlikely to be much smaller as long as $n > 2$. The initial rotational energy in the pulsar is $E_0 = (n-1)L_0\ \tau/2$; the initial period is $P_0 = (2\pi^2 I/E_0)$. The above equations yield an expression for E_0 in terms of potential observables:

$$E_0 = L(t)\ t_c \left(1 - \left(\frac{n-1}{2}\right)\left(\frac{t}{t_c}\right)\right)^{-2/(n-1)} \quad (1)$$

I assume a power-law distribution of electrons, $N(E) = KE^{-s}$ electrons cm^{-3} erg^{-1}, to be injected into the bubble, with $s < 2$, up to a maximum energy E_m. (As discussed in CHR, the original electron spectrum in 0540-693 is inferred to be $\propto E^{-1.6}$, with the optical and X-ray spectrum steepened by synchrotron losses.)

With these assumptions and the results of RC, the age of 0540-693 can be estimated. If I identify the observed [OIII] shell with the expected shell of swept-up core material, its observed radius and velocity give $t = rR/v = 670\ r\ (R/1\ pc)(v/1500\ km\ s^{-1})^{-1}$ yr. Since $1 < r < 1.5$ for the first few thousand years of the bubble's evolution, the age must lie in the range $700 < t < 1000$ years, quite similar to the age of the Crab Nebula.

The Case E calculation of RC, done numerically, shows a similarly accelerated expansion. However, since in that case the bubble is a very lossy system, it is very much smaller at a given time (the acceleration takes longer to develop). To get the bubble to its observed size in less than the spindown time of 1660 years (SHH), a pulsar luminosity is required that would result in a synchrotron brightness exceeding by many orders of magnitude the observed optical and X-ray fluxes. Thus Case E can be confidently ruled out (a result similar to that found by RC for galactic Crablike remnants). RC calculated models for two different structures of the ejected material. Core-shell models assumed that most of the progenitor's mass is ejected at about 10^4 km s^{-1}, with the processed mantle material, a solar mass or so, expanding uniformly at only ~300 km s^{-1}. Such models have observational and theoretical support (see Chevalier 1977). RC also considered homogeneous models, in which all the ejecta are assumed expanding uniformly. In this case, the observed [OIII] shell would just be that material so far swept up. RC show that r is then between 1.2 and 1, so that the age of 0540-693 is 800 to 1000 years. I consider such models less likely, but they agree in inferred shocked mass and E_0 with the core-shell models described below.

A rough estimate of E_0 can be obtained using the numerical result that models with larger ages, requiring larger r, must have larger τ values in order to have been accelerating for most of their lifetimes. Similarly, models with small ages require small τ values; quantitatively, model calculations show $t \gtrless 800$ yr requires $\tau \gtrless 300$ yr. Equation (1) then restricts allowed values of E_0 to the range $(1.2 - 2.4) \times 10^{49}$ erg s^{-1}

implying P_o = 29-41 ms. This result is independent of the details of the dynamical calculations, which further restrict E_o and P_o.

The results of a range of model calculations are described in more detail in another work (Reynolds 1984); here I note that models spanning the entire range of available (t,n) parameter space yield only a small dispersion in most quantities. In particular, values of E_o (divided by I in units of 10^{45} gm cm^{-1}) lie in the range (1.5 -2.1) x 10^{49} erg, so that P_o = 34 ± 3 milliseconds. A generous allowance for observational uncertainties in the bubble's R and v raises the estimated uncertainty in P_o to 34 ± 5 milliseconds. While different values of n (or values changing in time) have different theoretical adherents, the value of 2.5, that of the Crab (Groth 1975), might be a sentimental favorite; for it, the initial period is 34 ms. The insensitivity to assumed values of n means that even if n is not constant the above conclusions still hold. It should also be noted that the derived value of P_o is independent of the value assumed for the pulsar moment of inertia I.

The observed larger-scale radio emission, and the hint of extended X-ray emission, can be understood in this picture as the interaction of the outermost ejecta with the interstellar medium, producing what should become a normal shell SNR. Mills and Turtle (1984) suggest that the radio size is about 43" or 5 pc; the derived range of ages for the remnant then implies velocities of 4800 -6800 km s^{-1} for the outer ejecta, just what would be expected of largely undecelerated ejecta from a Type II supernova. The flux of about 1 Jy would be 400 Jy at the distance of Cas A, not unreasonable for a young, energetic remnant.

Thus the pulsar in 0540-693 joins the Crab pulsar in not having been born rotating at near breakup angular velocities. If this is typical for pulsars born in Type II supernovae, it supports the contention that much faster pulsars are spun up, and weighs against models powering radio supernovae or the supernova explosions themselves with very fast pulsars.

REFERENCES

Chanan, G. A., Helfand, D. J., and Reynolds, S. P. 1984, preprint (CHR).
Chevalier, R. A. 1977, in Supernovae, ed. D. N. Schramm (Dordrecht: Reidel), p. 53.
Clark, D. H., Tuohy, I. R., Long, K. S., Szymkowiak, A. E., Dopita, M. A., Mathewson, D. S., and Culhane, J. L. 1982, Ap. J., 255, 440.
Groth, E. J. 1975, Ap. J. Suppl., 29, 453.
Mathewson, D. S., Dopita, M. A., Tuohy, I. R., and Ford, V. L. 1980, Ap. J. (Letters) 242, L73.
Mills, B. Y., Turtle, A. J., and Watkinson, A. 1978, MNRAS, 185, 263.
Mills, B. Y., and Turtle, A. J. 1984, in Structure and Evolution of the Magellanic Clouds (IAU Symposium #1081, ed. S. van den Bergh and K. S. de Boer (Dordrecht: Reidel), p. 283.
Milne, J. K., Caswell, J. L., and Haynes, R. F. 1980, MNRAS, 191, 469.
Pacini, F., and Salvati, M. 1973, Ap. J., 186, 249.
Reynolds, S. P. 1984, Ap. J. (Letters), submitted.
Reynolds, S. P., and Chevalier, R. A. 1984, Ap. J., 278, 630 (RC).
Seward, F. D., Harnden, F. R., and Helfand, D. J. 1984, preprint (SHH).
Srinivasan, G., and Bhattacharya, D. 1984, Curr. Sci., 53, 513.

DISCUSSION OF REYNOLDS'S PAPER

APPLEGATE: Is the shock from the actual explosion of the supernova seen in the X-rays?

REYNOLDS: No, in fact.

APPLEGATE: Has this material which has been sped up by the pulsar's braking caught up to the original shock? Is that shock seen?

REYNOLDS: I didn't mention what I would like to use to explain the larger radio size. I would like that to be a normal shell supernova remnant, again as do Srinivasan and Bhattacharya, due to the interaction of the fast-moving hydrogen with the interstellar medium. So there is a forward-facing shock in the ISM which contributes virtually no X-rays (that's not too hard to arrange) but contributes the radio emission, and perhaps I might identify that lowest contour in the HRI picture with that.

PINES: If one wanted to be fanciful, one could try to tie together your scenarios for the Crab and for this pulsar, together with the idea that you have a limit on the rate of rotation of the degenerate core of the star that made the supernova and pulsar, and the magnitude of its magnetic field at that time. For that purpose you would only need to compare the estimates of the magnetic field strengths of the two pulsars with their initial rotation rates. Now how do those work out? The argument which was made earlier by some of the people who are making neutron stars, starting with Roger I guess, was that you won't make a neutron star rotating enormously fast with a high magnetic field because of the coupling of the envelope to the core. You can check that out at least roughly against these two examples.

REYNOLDS: I think they're not far enough apart in period that you learn much. But the magnetic field that you derive for 0540-693, the standard square root of P times $\dot{P}$, is about 5×10^{12} gauss, isn't that right, Gary?

CHANAN: It's slightly higher than the Crab.

PINES: That's roughly the expected anticorrelation.

RUDERMAN: But one has to assume the Ettingshausen effect does not enter in.

PINES: That's what I'm assuming for all such objects.

REYNOLDS: I'd like to make a comment on that effect, by the way. It predicts that pulsars only a few hundred years old should not have strong magnetic fields. Here is a second pulsar which is only a few hundred years old which has a magnetic field, and as I recall, in Blandford, Applegate, and Hernquist an exception had to be made for the Crab, that perhaps there was some rotational effect that induced large fields. Of course that doesn't work for the 1.6 millisecond pulsar. I don't know how hard it is to build up a field in 700-900 years.

APPLEGATE: The answer is that there's a second instability which is a dynamo which operates in a liquid, the 50-100 meters that sit above the solid crust, and probably can account for these fields. The thermo-magnetic instability probably does take somewhat longer.

REYNOLDS: Why doesn't that work for the very fast pulsars?

APPLEGATE: If the very fast pulsar were formed hot, it would work--it would probably have to form cold.

MANCHESTER: I would like to mention another new pulsar in a supernova remnant: 1509-58, with a period of 150 milliseconds and a period derivative three times that of the Crab.

REYNOLDS: Oh, this is MSH 15-5(2).

MANCHESTER: Yes, but I don't like that name. It has an age of 1500 years, and has very strong field. In the tradition of our next speaker I'll do a bit of advertising: We've measured a braking index for this pulsar, and it's 2.8. Unfortunately we can't use that to do what you've just done to get an initial period because we don't know the true age.

APPLEGATE: The age of the remnant was estimated by van den Bergh from the expansion of an optical knot. The interesting thing is of course it comes out quite different from 1500 years.

MANCHESTER: That's right. But I think there is a lot of uncertainty in that.

APPLEGATE: I like it.

REYNOLDS: Where one would like to apply this kind of scenario is where there is definite evidence for a synchrotron nebula. The whole reason this analysis was possible for 0540-693 is that the optical synchrotron nebula was found, and because the beautiful shell of [O III] could be identified with the material that was swept up by the core. That provided a very tight constraint on the models. I don't know what the optical situation is in MSH 15-5(2).

MANCHESTER: I'm not sure I can really answer that. There's a big X-ray nebula, and a big radio nebula too; there's some argument about what part of it is associated. But there's not a small nebula.

CHENG: In the X-rays there is strong evidence for a synchrotron nebula. There is an extended emission region around the central object with a different spectral index from the whole.

REYNOLDS: Yes, but in the radio as I recall the pulsar lies on a pretty low contour of the radio map. If you looked at the radio map and guessed at any of the likely places where you'd put a source of relativistic particles and field, I don't think you'd guess where it actually is.

VAN DEN HEUVEL: I know one different way of making a very fast pulsar, which certainly will happen in the Hulse-Taylor pulsar 1913+16. After 300 million years or so the two neutron stars will collide to form a millisecond pulsar, only we don't know what field it will have. If it has a field like a normal pulsar at that time, it will be quite spectacular: the luminosity would be that of a quasar, 10^{43} or 10^{44} erg/s.

APPLEGATE: It might be a black hole, though, with a mass of 2.8 solar masses.

VAN DEN HEUVEL: Well, I don't know what the upper mass limit for a neutron star is; it could be as high as this.

PINES: Very unlikely. In fact, two recent sets of arguments state that the maximum mass could be as low as 1.4 solar masses. Two is a conservative number.

REYNOLDS: Let me just quit by pushing for the idea of looking at the nebulae around pulsars not in supernova remnants as excellent diagnostics of the properties of the pulsar. For instance the brightness of such an object would probably be much less than you would expect for an object in a supernova remnant, because there's no material around it to confine this enormous luminosity in field and relativistic particles in some fashion. It would be very difficult to predict what that would look like. On the other hand, there's some possibility that such a luminous pulsar would be spectacular, so that it would be impossible to miss anywhere in the galaxy.

VAN DEN HEUVEL: It probably does not happen very often.

THE ORIGIN OF PULSAR VELOCITIES

V. Radhakrishnan

Raman Research Institute, Bangalore - 560 080, India.

ABSTRACT

Ever since pulsars were found to have significant proper motions, the origin of the velocities has been an intriguing question. The more recent finding that the velocities display a significant correlation with the derived magnetic moments of the pulsars has made the origin of the velocities appear even more mysterious. We advance arguments to show that the above correlation is not 'causal', but 'accidental'. Pulsar velocities are determined by their binary histories and not governed in any way by their magnetic fields.

Anderson and Lyne (1983) have found an interesting correlation between the velocities of 26 pulsars, accurately measured by Lyne et al., (1982), and their magnetic dipole moments derived from P and $\dot{P}$. Although they come to no firm conclusion on the origin of pulsar velocities, they end their paper by suggesting that the velocities are probably due to asymmetric explosions, and that the asymmetry could be influenced by the magnetic dipole moment.

The attractiveness of the asymmetric hypothesis is due to the fact that the kinetic energy of the pulsar is about five orders of magnitude smaller than that of the ejecta of the supernova shell. But it is equally true that the energy stored in the dipole magnetic field is about as many orders down from the kinetic energy of the pulsar. It is therefore physically inconceivable that the magnetic field can be responsible for more matter being pushed out on one side than on the other, which would lead from the conservation of momentum to a kick being imparted to the pulsar.

Quite apart from this, no pure dipole field or indeed any single multipole component can cause an asymmetry of the kind required, but only a combination of two or more multipole fields. Assuming that this did exist, the energy contained in this "asymmetric" part of the field would be a minute fraction of the energy in the dipole component, making it even more difficult to take seriously. If there are any who feel that multipole components much much larger than the dipole component may exist in pulsars, then my final argument for dismissing the idea would be that the correlation of the velocities should not be with the dipole components, which are the ones derived from the slowdown of the pulsars. It seems clear therefore that the observed correlation is not "causal" but "accidental" in that both the velocities and the fields are the result of some other 'cause'.

Figures 1a and 1b taken from Anderson and Lyne show the observed correlation. 1a is a plot of the derived magnetic moment (assuming constant moment of inertia) against velocity, and there seems little doubt about the existence of the correlation. However, if the

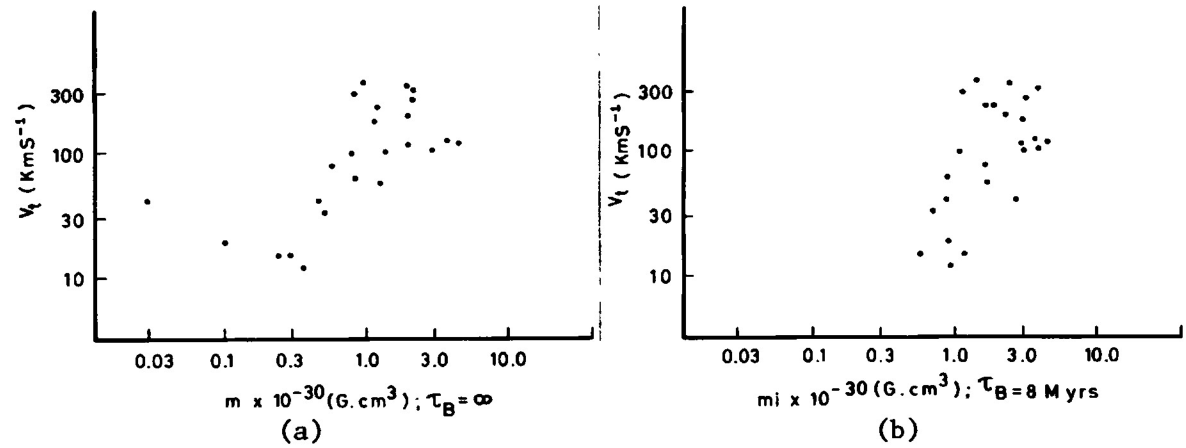
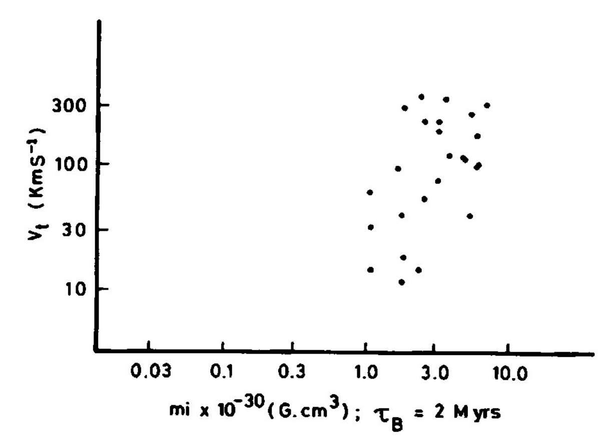


Fig. 1 : Transverse velocities of 25 pulsars plotted against initial magnetic dipole moment, from Anderson and Lyne (1983). (a) assuming no field decay, (b) assuming exponential decay with characteristic time of 8 Myrs.

magnetic field did influence the velocity, then one must allow for the fact that the field would have decayed since the birth of the pulsar, whereas the velocity (barring unlikely collisions) would have remained unchanged; the amount of interstellar matter encountered in the pulsar's travel is far too small to have any effect. Since many of the pulsars in the sample are reasonably old, Anderson and Lyne have attempted to allow for this and have calculated the expected initial fields of these pulsars assuming an exponential decay time of 8 Myrs (Fig. 1b). They note that there is a substantial steepening of the relationship and discuss the possibility that this might be due to a selection effect. If one assumes a characteristic decay of 2 Myrs, which I feel is a much better estimate from all available pulsar data, the corresponding plot is shown in figure 2. The steepening here is even greater, but the correlation is still significant and must be accepted as real. But

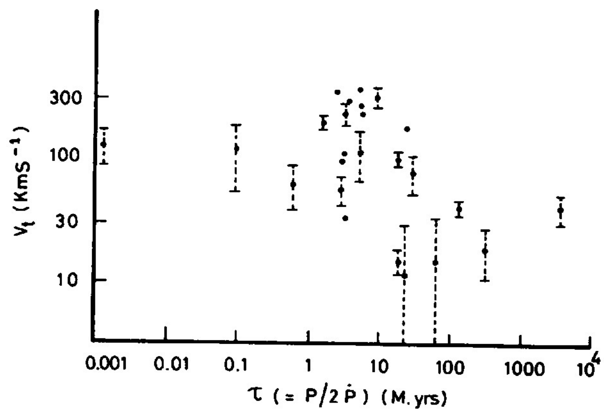
Fig. 2 : Same as in Fig. 1 but assuming a characteristic decay time of 2 Myrs.



what is remarkable is that the correlation is definitely better for "observed" fields rather than "initial" fields. Any satisfactory explanation of the correlation must also account for this extraordinary fact.

Having considered various possibilities, I feel that the observed correlation can find an explanation on the basis that the sample of pulsars contains a mixture of two populations, one being normal young high-field pulsars, and others which have been recycled in binaries. Figure 3 shows a plot of velocity vs. characteristic age which is very suggestive of a division into two groups, with the younger having high

Fig. 3 : Transverse velocities plotted against the characteristic age $\tau(\frac{1}{2}P/\dot{P})$. Small error bars for some of the pulsars have been omitted from the figure for clarity.



velocities and those with large $P/2\dot{P}$ having low velocities. It should be mentioned that Lyne et al., clearly noted that the distribution of velocities did not seem to be Maxwellian, there being excesses of both high and low velocity objects. Anderson and Lyne refer to the suggestion of Helfand and Tademaru (1977) that there might be two classes of pulsars, and in fact note that having two classes of pulsars could explain the correlation. But as we saw above, this correlation has the strange property of becoming worse when 'initial' (rather than 'observed') fields are considered. The important point I wish to make is that "initial" fields cannot be calculated for recycled pulsars in the way Anderson and Lyne have done, for the simple reason that the angular momentum transfer during accretion changes the evolutionary track. As pointed out by Radhakrishnan and Srinivasan (1981) when proposing a class of recycled pulsars, this can be estimated only by taking into account the spin-up to an equilibrium period during accretion (see also Radhakrishnan, 1982).

An interesting and important characteristic about recycled pulsars is that they should all have characteristic ages of $\gtrsim 10^7$ yrs. The reason for this can be seen in figure 4 where the field period equilibrium line (Srinivasan and van den Heuvel, 1982) has almost the same slope as the characteristic age lines, and coincides in position with that for 10^7 yrs. Note that this is independent of the decay time scale for the magnetic fields, and is therefore an excellent diagnostic

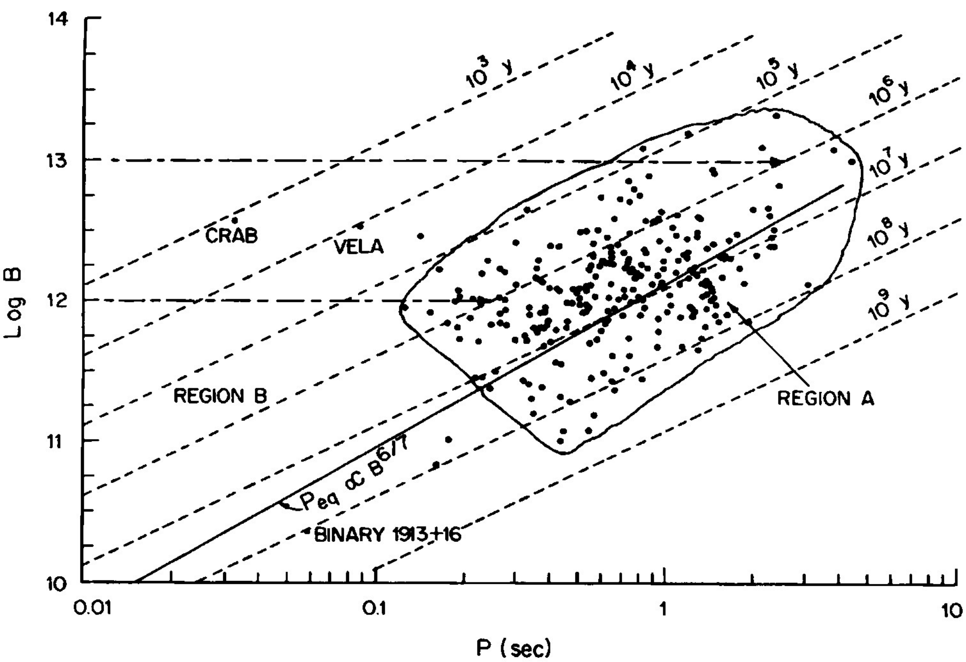


Fig. 4 : Plot of derived magnetic field vs. period for pulsars showing characteristic ages and the field-period equilibrium condition for spin-up (solid line) derived by Srinivasan and van den Heuvel (1982). Figure taken from Radhakrishnan (1982).

for recycled pulsars in providing a necessary although not sufficient condition. If we go back to Fig. 3 now, we see that most of the low velocity pulsars satisfy this condition, and that the apparent correlation with magnetic field is a result of the "correlation" with characteristic age. The fact that the decrease in correlation with "initial" fields is only partial, and not total, is also understandable now as due to incorrect extrapolation backwards for the recycled pulsars, which gives them apparent lower initial fields.

If the above hypothesis is correct, one surprising conclusion is that an appreciable fraction (6 to 7 out of 25 in Fig. 3) of known pulsars must be recycled ones, i.e., had a binary history in which the first explosion did not disrupt the system. This fits in with the idea that most stars are born in binary systems, and as emphasised by van den Heuvel (1982), that the majority of radio pulsars were formed in binaries. Even more surprising is their low velocity ($\sim$ 30 km/s); it is easy to show that the velocity of the first born neutron star after the second SN explosion in a massive close binary system is expected to be greater than 100 km/s. Both these surprises may find a natural explanation if there are enough binaries consisting of a neutron star and a low mass secondary which does not explode as a supernova, but disappears in other ways after spinning up the neutron star (see e.g. Ruderman and Shaham, 1983 and van den Heuvel, 1984). If this is indeed so, the velocity of the recycled pulsar will be simply the 'runaway' velocity of the binary system after the first explosion, which, for such systems, is estimated to be only $\sim$ 20-30 km/s (van den Heuvel and Bonsema, 1984).

ACKNOWLEDGEMENTS

I would like to acknowledge numerous discussions with my colleagues M. Vivekanand and C.S. Shukre as also much help with computations and the preparation of figures.

REFERENCES

Anderson, B. and Lyne, A.G. 1983, Nature, 303, 597.
Helfand, D.J. and Tademaru, E. 1977, Astrophys. J., 216, 842.
Lyne, A.G., Anderson, B. and Salter, M.J. 1982, Mon. Not. R. astr. Soc., 201, 503.
Radhakrishnan, V. 1982, Contemp. Phys., 23, 207.
Radhakrishnan, V. and Srinivasan, G. 1981, in Proceedings of the Second Asian-Pacific Regional Meeting of the IAU held in Bandung, Indonesia, Aug. 24-29, 1981.
Ruderman, M.A. and Shaham, J. 1983, Nature, 304, 425.
Srinivasan, G. and van den Heuvel, E.P.J. 1982, Astron. Astrophys., 108, 143.
van den Heuvel, E.P.J. 1982, in Proceedings of IAU Symp. 95, Pulsars, eds. W. Sieber and R. Wielebinski, Reidel, Dordrecht, p.379.
van den Heuvel, E.P.J. 1984, J. Astrophys. Astron. (in press).
van den Heuvel, E.P.J. and Bonsema, P. 1984, Astron. Astrophys. (in press).

DISCUSSION OF RADHAKRISHNAN'S PAPER

ALPAR: What is the space distribution of your recycled class (the low-velocity ones)--is there a correlation with the galactic plane?

LYNE: Mostly very close to the galactic plane. There is a selection effect you have to be careful of here, and that is that on the whole the sources which would have large characteristic ages and high velocities are likely to disappear when they get well away from the galactic plane, and we're likely not to see them. This effect could explain the gap up at the top in your diagram of velocity against characteristic age. The difficulty is explaining the bottom left-hand corner.

RADHAKRISHNAN: As I was saying to someone in another connection, we just have to wait for 500 observations which will finally establish it, but I think it's better to come up with what one thinks is the way it works now.

LYNE: Can I just remark that I think we really just ran out of ideas in proposing the asymmetric explosion--it didn't seem very satisfying, but nothing really did.

KULKARNI: This selection effect: It seems to me that if a pulsar formed with a velocity of a few hundred km/s, in 10 million years it won't be more than 3 kpc away from the plane, and you have an advantage because the surveys are complete, essentially all sky, and you are not confused with synchrotron radiation at low frequencies which is always a big contribution to noise. So there's one selection effect which will help you find pulsars away from the plane, and another which is operating in the opposite way. I'm not sure whether quantitatively the selection effect is important.

TAYLOR: I think the point is, Shri, that 3 kpc away from the plane is 3 kpc away from the Sun, and that's a large distance. Most observed pulsars are closer than that. The ones that are seen that far away have to be unusually luminous ones. There are quite a lot of those, to be sure, but vastly fewer of those than there are of the lower-luminosity ones that we can see within one or two kiloparsecs.

RADHAKRISHNAN: If you just run a histogram of pulsars whose distances are known, you'll find that in every respect it looks the same.

KULKARNI: But, Joe, in the plane, at 400 MHz or 327 or whatever your frequency, there is a tremendous amount of synchrotron radiation that won't go away. So the fact of 4 or whatever that you lose in distance is more than made up.

TAYLOR: I don't think so.

ALPAR: In this connection, I think there is another selection effect: If recycled pulsars are descendants of a galactic bulge population, then you are looking at the intersection of the survey sphere centered at the Sun, and the galactic bulge population centered at the galactic center. That intersection will confine you to part of the sky.

RADHAKRISHNAN: These sources as I understood were picked because there was a good extragalactic source in the beam. In that sense I think of it as an unbiased sample; am I wrong?

LYNE: And also because they were reasonably close to us. Nearly all these pulsars are within 3 kpc, most of them within 1 kpc.

ALPAR: I'm not talking about this particular sample. In general, if you think that the population that has been spun up in close binaries has descended from galactic-bulge type X-ray sources, then that comes from a population that's centered about the galactic center. You are looking from the Sun down to a certain depth, so you are looking at the intersection of those two spheres--it should be symmetric about the galactic plane.

VAN DEN HEUVEL: How far away from the plane are they, at most?--these low velocity ones.

LYNE: In general they're within 100 pc of the plane.

VAN DEN HEUVEL: That's really bad then. So that would suggest that it has to do with Population I. So maybe you need more massive binaries to make them from.

APPLEGATE: Is it true that all O stars are in binaries?

VAN DEN HEUVEL: Practically all stars are in binaries. Actually Helmut Abt showed that 130% of all G stars were in binaries--which means that a large fraction is in triple and quadruple systems. I wonder whether there really are any single stars.

RADHAKRISHNAN: There's a remark I was going to make that in general one is being led toward thinking that all stars are born in binaries, and that all motions come from them. I think this concerns this angular momentum question which has been with us for a long time: how do you make stars--how do you get rid of the angular momentum of single stars?

KULKARNI: One thing that bothers me about your recycling hypothesis is, why is there a sharp cutoff in recycled pulsars? I can understand a sharp cutoff in the ones which had only one birth. That is, if there are two classes of pulsars in what we earlier thought of as one class, why is it that they have the same cutoff in P?

TAYLOR: The question is, why can't recycled pulsars have been spun up even faster, farther to the left.

VAN DEN HEUVEL: The Eddington limit limits the accretion.

PULSAR SPACE VELOCITIES FROM INTERSTELLAR SCINTILLATIONS

J. M. Cordes

Astronomy Department, Cornell University and NAIC

J.M. Weisberg

Physics Department, Princeton University

ABSTRACT

Interstellar scintillation observations have been used to determine transverse velocities of the underlying diffraction patterns which, in turn, seem to be determined mostly by the pulsar space velocities. The distribution of transverse speeds for 70 objects shows large departures from a Maxwellain distribution both at large and at small speeds, in agreement with interferometer results on 26 objects. Velocities show a correlation with magnetic moment (or with period derivative or with spindown age) that suggests a common link between space velocity and surface magnetic field. We suggest that continued scintillation observations will 1) independently determine the orbital inclination for the 8-hour binary pulsar 1913+16 and will determine the space velocity of the binary from which the presupernova mass of the system can be deduced; and 2) will rule out certain scenarios for the production of the other binary radio pulsars and for the isolated millisecond pulsar 1937+214.

INTRODUCTION

Electron density variations in the interstellar plasma cause the formation of a random diffraction pattern from the spatially coherent pulsar signal. Motion of the pattern across a radio telescope by the combined velocities of the pulsar, interstellar medium, and observer produces intensity variations on a time scale that is related to the spatial scale of the intensity. At a given radio frequency f, the interstellar scintillations (ISS) can be characterized by a bandwidth Δf and time scale Δt from which a pattern speed can be estimated as

$$V_{ISS} = 10^{4.1} \, (L \, \Delta f)^{1/2} \, / \, f \, \Delta t \quad \text{km/s} \tag{1}$$

where L is the distance in kpc, Δf is in MHz, and f is in GHz. Lyne and Smith (1982) showed that the ISS speed is 60% correlated with the speed deduced from interferometric proper motions for 20 objects. The importance of this result lies in the fact that ISS measurements can be made on a much larger sample of objects than can interferometry. We report here the results of two ISS surveys made at the Arecibo Observatory and with the 300' telescope of the NRAO.

ISS Speeds for 70 Objects

We obtained pulsar dynamic spectra at ~10 sec intervals over total bandwidths of 0.1 to 10 MHz at frequencies from 0.32 to 1.4 GHz. The dynamic spectra were subjected to a two-dimensional correlation analysis from which Δf and Δt were obtained. The random error in V_{ISS} associated with measuring a finite number of bright ISS features is small, 10% or so. Larger sources of error arise from uncertainties in the pulsar distance scale, the geometry of scattering material along the line of sight, contributions to V_{ISS} from Earth orbital motion and differential transverse Galactic rotation (small); and the influence of refraction (due to large scale irregularities) on the diffraction quantities. Without further information, one must accept at least a factor of two uncertainty in relating the ISS speed to the pulsar transverse speed. For some objects, the distance is more well known than by scaling the dispersion measure and for some lines of sight we can determine if extra scattering material is present, since scattering material seems to consist of a fairly uniform diffuse component with embedded clumps with very large levels of turbulence (Cordes, Weisberg, and Boriakoff 1984; Cordes, Ananthakrishnan, and Dennison 1984).

Figure 1 shows the correlation of ISS speed with interferometer speed. These results confirm those of Lyne and Smith (1982). We have used the interferometer measurements of Lyne, Salter, and Anderson (1982) and our own ISS values. The correlation coefficient is 70% (calculated between logarithms for the two speeds and also for the rank correlation).

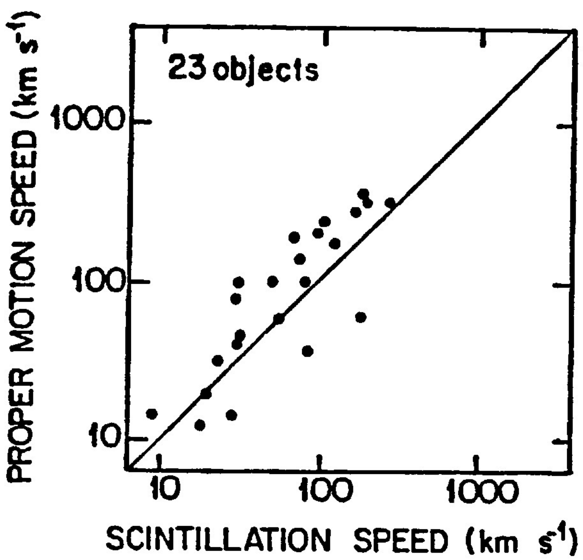


Figure 1. Scintillation speed vs. speed derived from interferometric proper motion measurements from Lyne et al. (1982) for 23 pulsars.

For some objects we have ISS measurements at several epochs over a two year period and we find that the ISS bandwidth and time scale vary (probably due to refractive modulation effects) but the ISS speed is nearly constant. Figure 2 shows a histogram of the ISS speeds compared with those from an isotropic Maxwellian which gives the same mean transverse speed. The excess of large and small speeds is obvious and we interpret this as evidence that the distribution probably has two components, perhaps corresponding to two classes of objects with different formation histories. The ISS speed from eqn (1) seems to underestimate the inteferometric speed by a factor of 1.4, due to the choice of the numerical coefficient in eqn (1), which has assumed that spherical waves from a pulsar are scattered from a honogeneously turbulent medium. The coefficient must be viewed as an approximate quantity because a rigorous scattering theory for the situation does not exist. Nonetheless, in our judgement, the form of the distribution in Figure 2 is sound and must be taken as strong evidence for a dual component pulsar population.

In Figure 3 we show the transverse speed plotted against $P\dot{P}$, which is proportional to the square of the surface magnetic field for idealized magnetic dipole spindown theory. The positive correlation noted by Helfand and Tademaru (1977) and Anderson and Lyne (1983) from much smaller samples of objects (12 and 26, respectively) persists. The results do not allow two discrete classes of pulsars to be isolated from just the transverse speed and $P\dot{P}$. Rather, it appears that the classes have overlapping distributions, as suggested by Helfand and Tademaru.

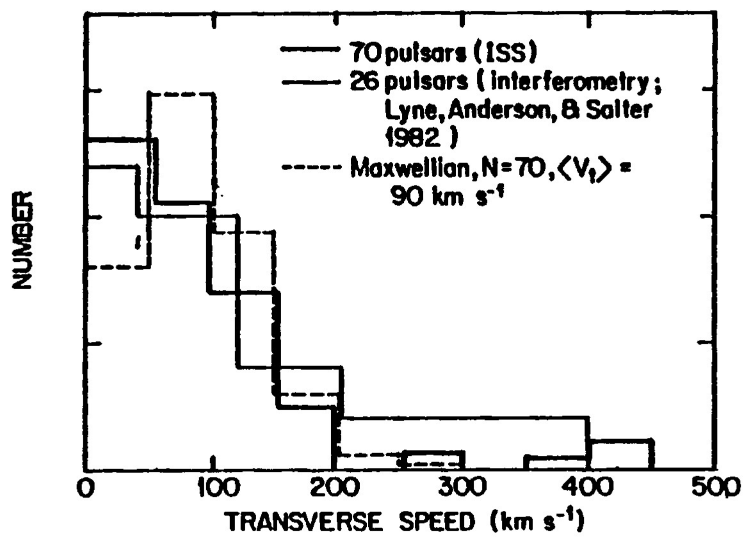


Figure 2.

Histograms of transverse speeds

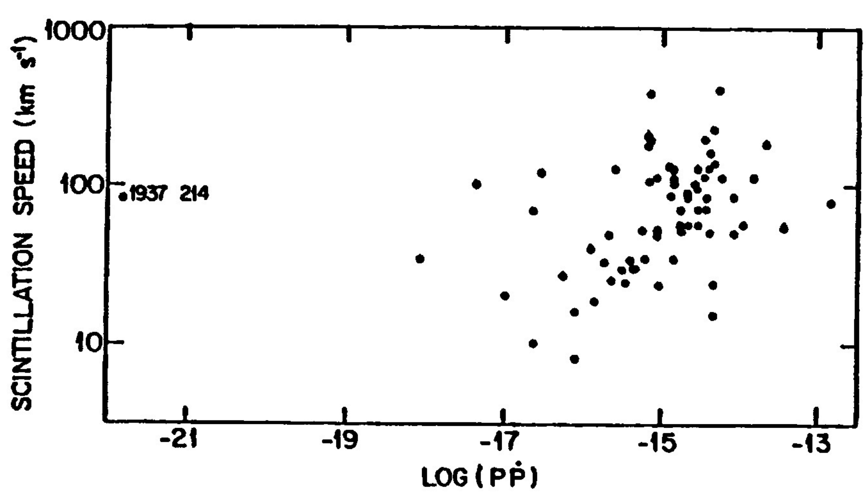


Figure 3.

Scintillation speed vs. $P\dot{P}$

Although the ISS technique in general gives only a statistical value for the speed, in specific cases it can be used to derive very accurate results. For binary pulsars, for example, the known orbital motion combined with ISS measurements as a function of orbit phase can be used to 'calibrate' the coefficient in eqn (1) and the translational motion of the binary can, in principle, be determined.

In the case of the 8-hour binary pulsar, PSR 1913+16, the results of ISS measurements (now in progress) will be very exciting because they should allow an independent determination of the orbital inclination, and the determination of the translational motion can be used to constrain the mass of the system before the last supernova explosion (whether it produced the observed pulsar or the unobserved companion). This conclusion follows because it can be argued (Cordes and Wasserman 1984) that the pre-supernova system must have been circularized and the orbital and spin angular momenta must have been aligned by tidal effects; that the present-day system also probably has aligned momenta, and has not changed its size significantly (due to orbital decay) since the supernova. Consequently, the present-day translational motion is a direct measure of the amount of mass lost in the explosion, and the degree of asymmetry of the explosion and/or magnetic dipole radiation. In the absence of any asymmetries, the binary should be moving at 171 km/s plus the contribution from the first explosion in the system plus any peculiar galactic motion, both of which are probably much smaller than 100 km/s.

Of the four known binary radio pulsars, van den Heuvel (this volume) has argued that two (0820+02 and 1953+29) should have been produced in low mass progenitor systems, 1913+16 from a high mass system, and 0655+64 from a medium to high mass system. ISS observations yield a very low speed (~16 km/s) for 0820+02 which is consistent with it arising from a low mass system with small mass loss during its evolution. Lyne (1984) has shown that 0655+64 has a translational speed of 10 or 40 km/s which supports formation in a low to intermediate mass system. Results on 1913+16 must await observations now in progress at Arecibo, but it is expected that a large (>100 km/s) speed will be measured, consistent with its formation in a once massive binary. The fourth object (1953+29) may be too weak to ever measure the ISS or to determine a timing proper motion.

We argue now that the fairly large speed determined for the 1.6 ms pulsar (1937+214) of 80-100 km/s (unpublished data; Backer et al. 1983) supports the idea that this object was formed in a massive system with considerable mass loss. The dominant error in this speed arises from the assumed distance of 5 kpc (Heiles et al. 1983), based on HI absorption measurements. The distance could be as low as 3 kpc in which case the speed would be 60-80 km/s. Although excess scattering material close to the pulsar could geometrically amplify the true space velocity, the level of scattering along this line of sight is consistent with that expected from a fairly uniform component of the scattering medium (Cordes, Weisberg, and Boriakoff 1984). Therefore, such amplification probably does not occur.

This research was supported by NSF grant AST-8311844. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under contract with the NSF. The NRAO is operated by Associated Universities, Inc. under contract with the NSF.

REFERENCES

Anderson, B. and Lyne, A. G. 1983, Nature, 303, 597.
Backer, D. C., Kulkarni, S.R., and Taylor, J.H. 1983, Nature, 301, 314.
Cordes, J.M. Weisberg, J.M., and Boriakoff, V. 1984, Ap.J., in press.
Cordes, J.M. and Wasserman, I. 1984, Ap.J. 279, 798.
Cordes, J.M. Ananthakrishnan, S., and Dennsion, B. 1984, Nature, in press.
Heiles, C., Kulkarni, S.R., Stevens, M., Backer, D.C., and Davis, M.M. 1983, Ap.J. (Letts.).
Helfand, D.J. and Tademaru, E. 1977, Ap. J., 216, 842.
Lyne, A.G. 1984, preprint and these proceedings.
Lyne, A.G. and Smith, F.G. 1982, Nature, 298, 825.
Lyne, A.G., Anderson, B., and Salter, M.J. 1982, M.N.R.A.S., 201, 53.
van den Heuvel, E.P.J. 1984, these proceedings.

DISCUSSION OF CORDES'S PAPER

VAN DEN HEUVEL: I'm not completely sure that 0655+64 should have a high velocity, because there was only one supernova in the system and it may have happened when the system was still wide. And if it was a wide system with a fairly massive companion, the recoil is not much.

CORDES: I think these kinds of measurements can answer those questions.

HARDING: I'm not sure I'm convinced that just a low electron density along that line of sight, and low levels of turbulence, would preclude your still having a distribution of clumps of stuff near the pulsar.

CORDES: It's always possible but we've done a survey on a total of 76 pulsars—we have a fairly good idea what the galactic distribution of scattering material is. Basically the amount of scattering along that line of sight is at the base level for that distribution. That says that you've got just a garden variety of scattering. If you had any extra it would have enhanced the number we got for the level of turbulence.

TAYLOR: I think it's worth pointing out that the 5 kpc distance may be on the large side—you could probably bring it in to 3.5 or something like that without violating anything and the numbers go down a little bit. It seems to me having a velocity as large as 80 km/s or so makes it hard to understand how it's still so close to the plane.

CORDES: But it's a sample of one.

TAYLOR: Yes. It doesn't prove anything; it just makes it a little bit uncomfortable.

The Orbital Inclination of PSR 0655+64

A.G. Lyne

University of Manchester
Nuffield Radio Astronomy Laboratories
Jodrell Bank
Macclesfield
Cheshire
SK11 9DL

For most binary stellar systems spectroscopic observations provide information only on the size and shape of the orbit normal to the plane of the sky. Usually it is not possible to determine the inclination of the orbit to the plane of the sky so that little is known about the size of the orbit and the masses of the stars required to keep it bound. Such has been the case with the pulsar PSR 0655+64 which is in a closely circular orbit and which has an orbital period of about 24 hours. (Damachek et al. 1982).

However it has been demonstrated that the speed of interstellar scintillation of pulsar radiation is related directly to the transverse velocity of a pulsar (Lyne and Smith 1982). In a recent experiment at Jodrell Bank, the rate of scintillation of the radiation from PSR 0655+64 has been found to vary by about a factor of two around its orbit (Lyne 1984). The observations allow a direct measurement of the inclination of the orbit, the transverse velocity of the whole binary system and the scale size of the scintillation pattern. The single observation made so far allows two degenerate solutions with inclination and transverse velocity being either $62^{o} \pm 4^{o}$ and $10 + 5$ km s^{-1} or $84^{o} \pm 3^{o}$ and 46 ± 6 km s^{-1}. A further observation at a different time of year when the Earth's velocity vector around the Sun is different should allow a single solution.

As it is, the orbit is clearly highly inclined to the plane of the sky and a study of the mass function of the orbit shows that the masses of the pulsar m_p and companion star m_c are related by

$$\frac{m_c^{\ 3}}{(m_c+m_p)^2} = 0.103 M_o \text{ or } 0.072\ M_o$$

Thus if the pulsar has a mass of 1.4 M_o the mass of the companion must be small and only 0.8 or 0.7 M_o.

I note that it is possible that the masses could be determined directly in the future by measurement of the general relativistic time delay as the line of sight to the pulsar passes through the gravitational field of the companion.

Lyne, A.G., 1984, Nature. In the Press.
Damashek, M., Backus, P.R., Taylor, J.H. and Burkhardt, R.K., 1982, Astrophys.J., 253, L57.
Lyne, A.G. and Smith, F.G., 1982, Nature, 298, 825.

DISCUSSION OF LYNE'S PAPER

VAN HORN: You said that a white dwarf would be visible. What were you assuming for the parameters of the white dwarf?

LYNE: Maybe Joe can tell you better than I can.

TAYLOR: If the distance is 300 pc, the distance modulus is small, so anything with an absolute magnitude of 15 or so would be visible on normal deep plates. There's nothing there that's brighter than around 23d magnitude. There is in fact a faint smudge there at roughly the plate limit on the Sky Survey. Our statement had been (and I see no reason to change it now) that if that's a white dwarf, it's a very cold one--5000 K, I think.

VAN HORN: If the age is of the order of 3 billion years, that is if the spindown time actually indicates the age, then you're getting in that range.

TAYLOR: Yes, but for ages of 10^9 years, with any kind of velocites it's hard to understand why it's within 300 pc of the plane still--or 200 pc.

VAN DEN HEUVEL: How good is the distance?

TAYLOR: How good are dispersion distances in general? I think pretty good, probably within a factor of two, anyway.

A model of radio emission of the millisecond pulsar PSR 1937+214

by

Janusz A. Gil

National Radio Astronomy Observatory*, Charlottesville, VA 22903

N. Copernicus Astronomical Centre, Warsaw, Poland

ABSTRACT

A model of radio emission of millisecond pulsar PSR 1937+214 is proposed. The emission region is expected to lie very close to the polar cap surface, where the contribution of the quadrupole component to the actual magnetic field may be significant. It is argued that the interpulse as well as the main pulse are emitted from the same magnetic pole.

INTRODUCTION

The millisecond pulsar PSR 1937+214 differs considerably from a typical pulsar. The value of its period, P = 1.55 msec, and the rate of change of period, $\dot{P} = 10^{-19}$ s/s, correspond to the light-cylinder radius R_{LC} = 76 km, a characteristic age of about 10^8 years, and a surface magnetic field of $B_o = 10^8$ G. The pulse-width $\Delta\phi$ is about 10° at 1.4 GHz; it is strongly frequency dependent at low frequencies, $\Delta\phi \propto \nu^{-1.5}$. The lack of detectable non-dispersive time delays in pulse arrival suggests that all emission from 0.3 to 1.4 GHz must arise from the range of radii $\Delta r = \pm$ 2 km (Cordes and Stinebring 1983).

In some respects, however, the millisecond pulsar behaves like many others. It exhibits interpulse emission as do many short period pulsars. The separation between the main pulse and interpulse is independent of frequency (Cordes and Stinebring 1983) which is also typical. The main pulse consists of two closely spaced components.

In this paper I propose a model that explains almost all of the observed properties of PSR 1937+214. This model is based on the magnetic-pole model in which the pulsar radio-emission is produced by relativistic charged particles moving along curved magnetic field lines (Radhakrishnan and Cooke 1969, Ruderman and Sutherland 1975).

*National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

THE EMISSION REGION

The magnetic field within the light-cylinder with R_{LC} = 76 km may be approximately dipolar at the radii r = (5-6) R, where R ≈ 10^6 cm is the neutron star radius. In this region coherent curvature radiation should not be produced for at least two reasons: (1) the radius of curvature $\rho \propto r/\sin\theta$ of dipolar field lines may be too small to give curvature emission in the frequency range $\nu = 10^{(8\div 9)}$ s^{-1} and (2) the number density of charged particles $n \propto B \cdot (R/r)^3/P$ may be too small for the bunching mechanism to be effective in producing the observed brightness.

Therefore, if coherent curvature radiation is responsible for the observed radio emission of PSR 1937+214 it should arise very close to the polar cap surface. In this region the higher multipole components may give significant contributions to the magnetic field.

A MODEL

Let us assume that the observed emission of the millisecond pulsar arises in a region where the geometry of the magnetic field is determined mainly by a quadrupole component. The symmetry of the main pulse profile suggests that the field has axial symmetry. In the spherical coordinates this field has the form

$$B_r = (3/4) \cdot (q/r^4) \cdot (3\cos^2\theta - 1)$$

$$B_\theta = (3/2) \cdot (q/r^4) \cdot \sin\theta \cdot \cos\theta \qquad (1)$$

$$B_\phi = 0 ;$$

where r is the radius, ϕ is the azimuthal angle, and θ is the polar angle measured from the quadrupole moment axis q. The equation of field lines is

$$r = C \cdot \sin\theta \cdot \cos^{1/2}\theta . \qquad (2)$$

Note that $r \leq r(\theta_o)$ where $\theta_o = \mathrm{atan}((2)^{1/2}) \approx 55°$. Thus, for particular field line the labelling parameter C is approximately equal to 1.6 times the maximum radius $r_{max} = r(55°)$.

One can show that for small θ the radius of curvature of quadrupole field lines, (Eq. (2)), is approximately given by

$$\rho \approx C . \qquad (3)$$

If one assumes that the observed frequency $\nu < 10^{10}$ s^{-1} lies close to the critical frequency of curvature radiation $\nu_c = (3/4)\,\gamma^3\,c/\rho$ then for $\gamma > 100$ one obtains $\rho > 5 \cdot 10^7$ cm. Thus the radio emission can be produced at lines for which $C > 5 \cdot 10^7$ cm or $r_{max} > 6$ R. These field lines originate at distances $d < 2 \cdot 10^4$ cm from the magnetic axis on the polar cap.

THE RADIUS-TO-FREQUENCY MAPPING

In the force-free magnetospheric model (Goldreich and Julian 1969) the number density of particles $n \propto B$, where B is the magnetic field. One can assume the frequency of the observed radiation $\nu \propto \nu_p$, where $\nu_p \propto n^{1/2}$ is the plasma frequency. Thus for a quadrupole field $B \propto 1/r^4$ and $\nu \propto r^{-2}$. Therefore, the radius-to-frequency mapping has a form

$$r(\nu) \propto \nu^{-0.5} . \tag{4}$$

To compare this result with the data of the millisecond pulsar let us put $r_1 = r(1.4\ \mathrm{GHz}) \approx R$. Then it follows that $r_2 = r(0.3\ \mathrm{GHz}) \approx 2\ R$. The corresponding range of radii is $\Delta r \approx 10$ km. The observational limit for Δr is about 4 km (Cordes and Stinebring 1983). However, the actual radius-to-frequency dependence operating in the millisecond pulsar may be stronger than that following from the plasma frequency (Eq. (4)). For example, if the gyroresonance $\nu \propto B \propto r^{-4}$ is taken into account then $r_2 \approx 1.5$ R and $\Delta r \approx 5$ km. Also, a contribution from higher multipole components can decrease Δr.

THE FREQUENCY DEPENDENCE OF PULSE-WIDTH

The curvature radiation is emitted mainly in the direction of source motion. In the magnetic-pole model the emitting particles move along magnetic field lines. The opening angle α between the tangent to the quadrupole field line and the magnetic axis is $\alpha = \mathrm{asin}\ (\vec{B} \cdot \vec{e}_z/B)$, where B is described by Eq. (1). In the approximation $\theta \ll 1$

$$\alpha \approx r/C . \tag{5}$$

Taking the radius-to-frequency mapping, (Eq. (4)), one obtains

$$\alpha \propto \nu^{-p_1} \tag{6}$$

where $p_1 = 0.5$.

The pulse-width of a symmetrical pulsar profile can be written in the form (Gil 1981)

$$\Delta\phi = 2\phi \tag{7}$$

where $\phi = 2 \cdot \mathrm{asin}\ (x/y)^{1/2}$

and $x = \sin\left(\frac{\alpha}{2} - \frac{\xi-\Theta}{2}\right) \cdot \sin\left(\frac{\alpha}{2} + \frac{\xi-\Theta}{2}\right)$, $\quad y = \sin\Theta \cdot \cos\Theta$.

Here ϕ is the pulse longitude, Θ is the angle between the rotation and magnetic axes, and ξ is the angle between the rotation axis and the line-of-sight. Hence $\xi-\Theta$ is the angle of closest approach of the observer's line-of-sight to the magnetic axis ($\alpha > |\xi-\Theta|$). Note that if $\Theta = \xi$ the pulse width $\Delta\phi \approx 2\alpha/\sin\Theta$. In general, one can write

$$\Delta\phi \propto \alpha^{p_2 [\alpha(\nu);\, \Theta,\xi)]} \tag{8}$$

where $p_2 = 1$ for $|\xi-\Theta| = 0$. The coefficient p_2 (α) can be calculated under the initial condition that $p_2 = 1$ for $\alpha >> |\xi-\Theta|$.

Combining the Eqs. (6) and (8) one obtains the pulse width in the form

$$\Delta\phi \propto \nu^{-p} , \tag{9}$$

where $p = p_1 \cdot p_2 > 0.5$. For typical pulsars $p < 0.5$ while for the millisecond pulsar $p = 1.5$ at low frequencies (Cordes and Stinebring 1983). This value corresponds to $p_2 \approx 3$. Detailed calculations show that this can occur when $\Theta \approx 20°$, $\xi \approx 25°$ and $5.5° < \alpha < 6.5°$ in the emission region. If this is the case then the pulse width calculated from Equation (7) is about 18°, in good agreement with the observed value. At the same time, the maximum gradient of the position angle curve (at the main pulse center) is about 3, close to the observed value (Stinebring et al. 1984).

INTERPULSE EMISSION

The millisecond pulsar has an interpulse that is separated from the main pulse by 174° (Stinebring and Cordes 1983). This separation appears to be independent of frequency, just like in pulsars 0531+21, 0950+08, 1822-09. The frequency independence of the main pulse to interpulse separation is consistent with the single-pole model of interpulse origin (Gil 1983, Narayan and Vivekanand 1983). Within this model the interpulse will be present if the following condition is satisfied:

$$1.5(2\pi r(\nu)/cP)^{1/2} > \xi+\Theta , \tag{10}$$

(Gil 1983). If $r(\nu_{min}) \approx 2$ R then one obtains for the millisecond pulsar $\Theta + \xi \leq 45°$. This means that PSR 1937+214 does not have to be a nearly aligned rotator. Note that the estimate from the previous section $\Theta \approx 20°$, $\xi \approx 25°$ is consistent with this result.

In general, the deviation, $\delta\phi$ from a 180° separation between the main-pulse and interpulse increases with decreasing pulsar period. This may be interpreted in terms of rotational deformations of the planes of field lines (Gil 1983). For the millisecond pulsar $\delta\phi$ is only 6 degrees. This may be a reflection of the fact that the emission arise very close to the stellar surface where rotational deformations are not significant.

The single-pole model of PSR 1937+214 seems to be confirmed by recently discovered emission components between the main pulse and the interpulse, (Stinebring et al. 1984). On the other hand, the position angle curve has almost the same gradient at the interpulse and mainpulse (Stinebring et al. 1984). This fact favors a double-pole interpretation. However, for $\Theta \approx 90°$ and $(d\psi/d\phi)max \approx 3$ one obtains $\xi-\Theta = 30°$. This implies an opening angle $\alpha > 30°$ and large pulse-width, in conflict with the observations. Thus, although the two-pole interpretation cannot be excluded, the single-pole model seems to be more plausible for the millisecond pulsar. However, the behavior of the position angle curve must be reconciled with it.

REFERENCES

Cheng, A., Ruderman, M. A., 1977, Astrophys. J. 214, 598.

Cordes, J. M., Stinebring, D. R. 1983, Astrophys. J., 277, L53.

Gil, J. 1981, Acta Phys. Pol. B11, 1081.

Gil, J. 1983, Astron. Astrophys. 127, 267.

Goldreich, P., Julian, W. H. 1969, Astrophys. J. 157, 869.

Narayan, R., Vivekanand, M. 1983, Astrophys. J. 274, 771.

Radhakrishnan, V., Cooke, D. J. 1960, Astrophys. Letters 3, 225.

Ruderman, M. A., Sutherland, P. G. 1975, Astrophys. J. 196, 51.

Stinebring, D. R., Boriakoff, V., Cordes J. M., Wolszczan, A., Deich, W.T.S., these proceedings.

PULSAR STATISTICS: A STUDY OF PULSAR LUMINOSITIES

M. Prószyński[1,2] and D. Przybycień[2]

[1] Space Telescope Science Institute, Baltimore
[2] N. Copernicus Astronomical Center, Warsaw

ABSTRACT

We find a statistically significant correlation between pulsar luminosity at 400 MHz and both pulsar period and period derivative. Fitting a phenomenological power-law model $L_{model}(P, \dot{P}) \sim P^{\alpha}\dot{P}^{\beta}$ (where P is pulsar period, $\dot{P}$ - period derivative and L - radio luminosity) to the pulsar luminosity data, we obtain $\alpha = -1.04 \pm 0.15$ and $\beta = 0.35 \pm 0.06$. The above values suggest that pulsar radio luminosity varies roughly as the cube root of the total loss of rotational energy.

INTRODUCTION

Lyne, Ritchings and Smith (1975) found that pulsar radio luminosity correlates with period and period derivative—the pulsars with a short period and a large period derivative are likely to be brighter than those with a longer period and a smaller period derivative. They summarized this dependence in the form of a power-law model $L_{400} \sim P^{-1.8}\dot{P}^{0.88}$, where the pulsar luminosity at 400 MHz is given by $L_{400} = S_{400}\, d^2$, with S_{400} being the mean spectral energy density of incoming radiation at this frequency and d being the distance to the pulsar. As the pulsars with a short period and a large period derivative are believed to be young, their conclusion was that the younger pulsars are brighter.

Vivekananad and Narayan (1981) used the model of the same type and obtained values of the free parameters by a least-squares fit in logarithms* to the then available sample of 242 pulsars with known both $\dot{P}$ and L_{400}. They obtained $L_{400} \sim P^{-0.86\pm0.20}\dot{P}^{0.38\pm0.08}$ for all the 242 pulsars, and $L_{400} \sim P^{-0.79\pm0.30}\dot{P}^{0.36\pm0.11}$ for the 84 pulsars that were earlier used by Lyne, Ritchings and Smith.

Here we present an independent analysis of the correlations between pulsar radio luminosity and both pulsar period and period derivative.

THE DATA

Our analysis is based on the pulsar data taken from the most recent catalogue of Manchester and Taylor (1981). We add to the catalogue two recently discovered

* As the luminosities span almost five orders of magnitude, the only reasonable least-squares approach is to fit the model to the data in logarithms.

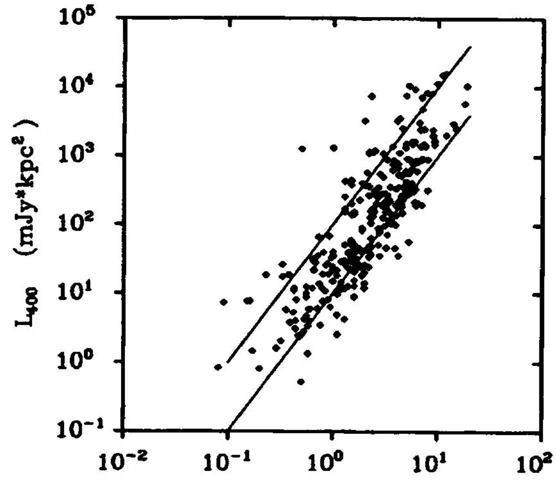


Figure 1 The distribution of pulsar radio luminosity with respect to the pulsar distance. The two lines correspond to the spectral energy density of 10 and 100 mJy, respectively.

pulsars for which the period derivative has already been determined: PSR1509-58 with $P = 0.1502$ s, $\dot{P} = (1.520 \pm 0.013) \times 10^{-12}$, $S_{400} = 2.0$ mJy and $d =$ 4.2 kpc (Seward and Harden 1982; Manchester, Tuohy, and D'Amico 1982), and PSR1937+21 with $P = 0.001558$ s, $\dot{P} = (1.058 \pm 0.009) \times 10^{-19}$, $S_{400} = 300$ mJy and $d = 5$ kpc (Smith, 1983; Stinebring and Cordes 1983; Heiles *et al.* 1983). Following Lyne, Anderson and Salter (1982) we adopt the distance $d = 0.160$ kpc (instead of 1.3 kpc) for PSR1642-03. We choose only those pulsars from the catalogue for which the mean spectral energy density is available and the quoted uncertainty in the value of the period derivative is less than 20 percent of the nominal value. As a result we obtain a sample of 275 pulsars. We define radio luminosity to be simply $L_{400} = S_{400}\, d^2$.*

RESULTS

Figure 1 presents a distribution of the radio luminosity with respect to the distance. The strong correlation between the two parameters is a direct consequence

* Manchester and Taylor in their 1981 catalogue quote the 'radio luminosity' which they calculate from the observed spectral energy density and the width of inegrated profile under assumptions that pulsars emit coherent radio emission in a band 400 MHz wide, and that the emission beam is conical in crossection and of a width equal to the equivalent width of the integrated profile. (They claim to use for this purpose a half-power width, but they apparently use it only in cases when equivalent width is not available.) Such an approach is model dependent. The beam of pulsar emission is not necessarily a conical one (Prószyński 1984), and even if it were, the non-perpendicular inclination of the magnetic axis with respect to the rotation axis would lead to an apparent broadening of observed profiles; the angular extent of the beam may be much smaller than suggested by the profile width (*e.g.*, Prószyński 1979). In consequence, the luminosity calculated in this way may be significantly overestimated for some pulsars, especially for those that are nearly parallel rotators. We feel much safer defining radio luminosity in a model independent way.

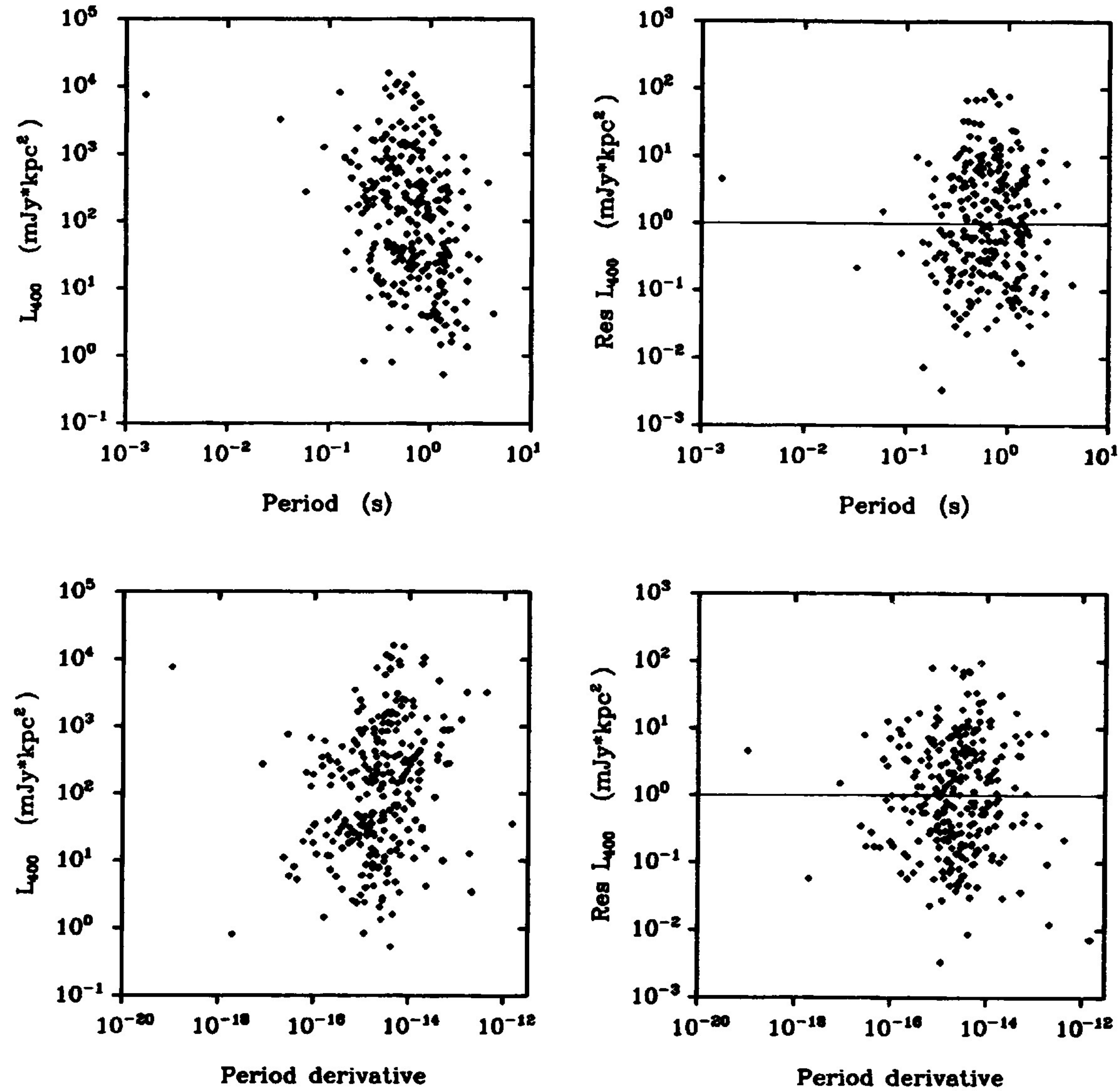


Figure 2 The distribution of pulsar radio luminosity with respect to period and period derivative (left) and the distribution of radio luminosity residual after subtraction of the best-fitting power-law model (right).

of a well known fact that the mean spectral energy density, S_{400}, is almost independent of the distance (or of the dispersion measure). The lack of points in the lower-right hand corner is obviously due to the observational selection effects. The lack of points in the upper-left hand corner in Figure 1 reflects the fact that very luminous pulsars are rare objects and, as the volume of galactic disk searched is increased, there is a higher probability of discovering some (Lyne 1981).

The left-hand side diagrams in Figure 2 show the distribution of radio luminosity with respect to period and period derivative. The presence of correlations is clear. As there is no *à priori* reason for pulsar luminosities, periods and period derivatives to be all distributed normally, we decide to use a nonparametric (distribution-free) method to estimate correlations between these quantities. For this purpose we choose the Kendall correlation coefficient (Kendall and Stuart 1973; Siegel 1956). The main advantage of using a nonparametric correlation coefficient based on ranks is that its value is not affected by the population distribution (*i.e.*, the values of the correlation coefficient and of the significance level corresponding to it are the same, independently of whether they are calculated for quantities of interest or for logarithms of them). The Kendall correlation coefficient for the data in the left-hand side diagrams in Figure 2 is $\tau(L_{400}, P) = -0.202$ and $\tau(L_{400}, \dot{P}) = 0.198$, respectively. The level of significance, *i.e.*, the probability of obtaining by chance the value of $|\tau|$ greater than or equal to that observed, is 6.1×10^{-7} and 9.7×10^{-7}, respectively. Needless to say, the correlation of L_{400} with both P and $\dot{P}$ is statistically significant.

As a second step we use the same type of the power-law model that was used in both previous studies, and we fit it to the logarithms of the luminosity data, *i.e.*, we minimize a sum

$$S = \sum_{n=1}^{N} \left(\log L_{model}(P, \dot{P}) - \log L_{400}\right)^2,$$

where N is the number of pulsars in our sample. The best-fitting model is given by

$$L_{model}(P, \dot{P}) = 10^{7.01\pm0.93}\, P^{-1.04\pm0.15}\, \dot{P}^{0.35\pm0.06},$$

where quoted uncertainties correspond to the 68.3 percent confidence intervals obtained for each parameter separately via the standard ratio-of-variances method. These uncertainties correspond to increasing S by $S/(N - M)$ from the minimal value, with $M = 3$ being the number of fitted parameters (Eadie *et al.* 1971; Lampton, Margon, and Bowyer 1976).

The right-hand side diagrams in Figure 2 show the residual luminosity after subtraction of the model best-fitting all the 275 data points. As the model is fitted in logarithms, the residual is here defined in a quite unusual way:

$$Res\ L_{400} = 10^{\log L_{400} - \log L_{model}(P,\dot{P})} = L_{400}/L_{model}(P, \dot{P}).$$

A comparison of the scatter of points in left and right diagrams in Figure 2 leads to an initially rather surprising conclusion that the subtraction of the best-fitting model does not reduce the scatter of points along the luminosity axis in a noticeable manner. However, it removes the correlation from the data.

It is not difficult to notice that $P^{-1.04}\dot{P}^{0.35} \approx (P^{-3}\dot{P})^{0.35}$, and that $P^{-3}\dot{P}$ is proportional to the total loss of rotational energy per unit of the neutron star's moment of inertia. As the moments of inertia of pulsars are expected to be similar (or, at least, to be of the same order of magnitude), one can say that pulsar radio luminosity at 400 MHz varies roughly as a cube root of the total energy loss. The correlation between L_{400} and $P^{-3}\dot{P}$ is much stronger than between L_{400} and P or

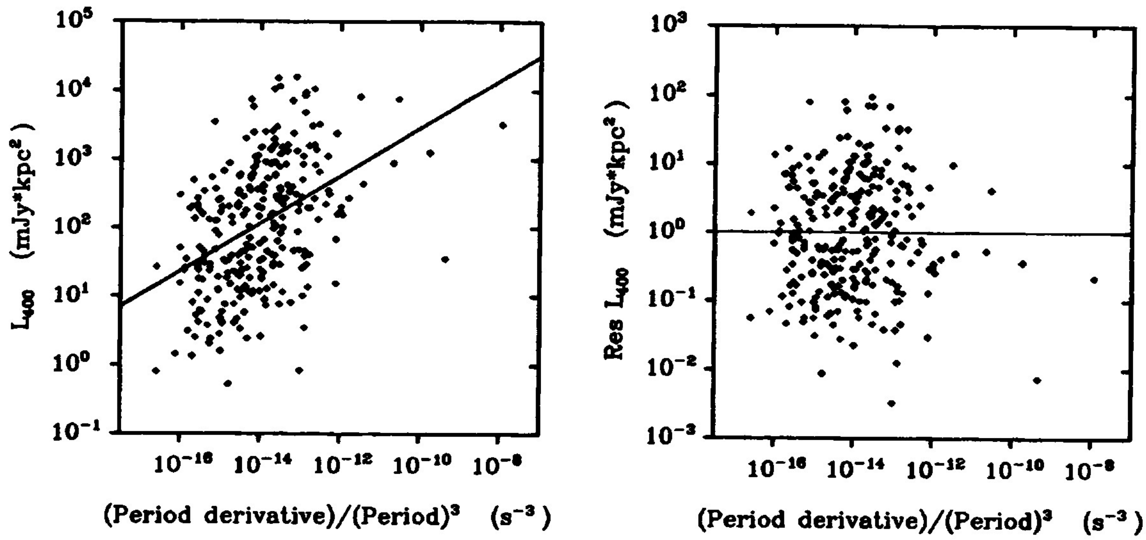


Figure 3 The distribution of pulsar radio luminosity with respect to total loss of rotational energy per unit of momentum of inertia (left) and the distribution of radio luminosity residual after subtraction of the best-fitting power-law model (right).

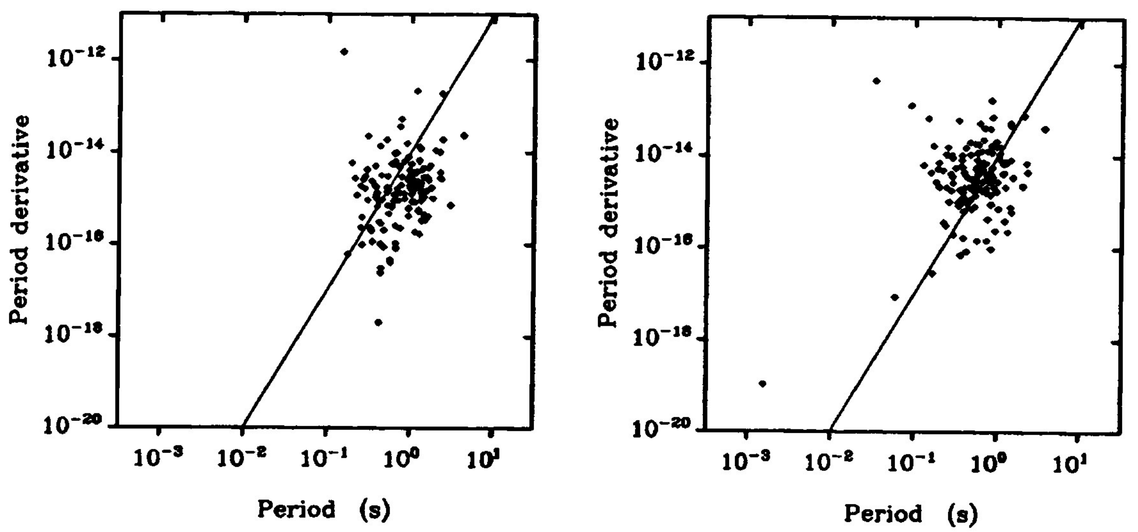


Figure 4 The distribution of pulsars with respect to period and period derivative. Left - pulsars with L_{400} smaller than the median luminosity of the whole sample, right - pulsars with L_{400} larger than the median. The sloping line corresponds to $P^{-3}\dot{P} = const.$

$\dot{P}$ alone, $\tau(L_{400}, P^{-3}\dot{P}) = 0.313$ with the corresponding level of significance being 5×10^{-15}. The least-squares fit (again in logarithms) yields:

$$L_{model}(P^{-3}\dot{P}) = 10^{6.94\pm0.61}(P^{-3}\dot{P})^{0.348\pm0.043},$$

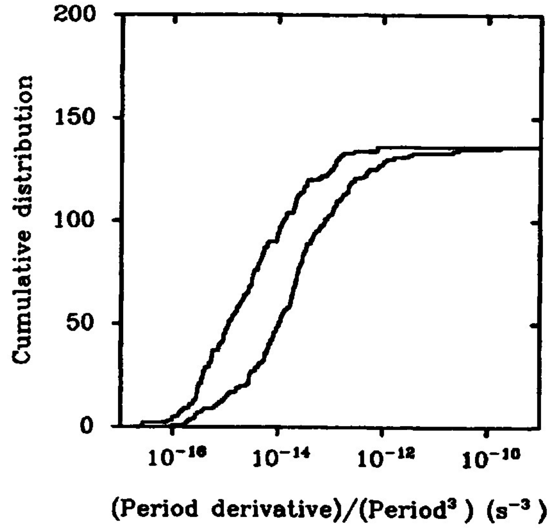


Figure 5 The cumulative distribution function with respect to $P^{-3}\dot{P}$. Upper curve - pulsars with L_{400} smaller than the median luminosity of the whole sample; lower curve - pulsars with luminosity larger than the median.

where uncertainties are calculated in the manner described above. Figure 3 shows the distribution of L_{400} with respect to $P^{-3}\dot{P}$ and the residuals after subtraction of the best-fitting model.

The volume of the galactic disk searched for pulsars depends on the pulsar luminosity. It is of interest, therefore, to check whether the correlation of pulsar radio luminosity with period and period derivative influences the coverage of the $(P, \dot{P})$-space in a noticeable manner. One can expect that a part of the $(P, \dot{P})$-space may be under-populated with respect to the rest because of observational selection; pulsars with small $P^{-3}\dot{P}$ are, in average, weaker and so they are more difficult to detect. To check if this is the case, we divide our sample of pulsars into two halves with respect to the luminosity. The left-hand side diagram in Figure 4 shows the distribution of pulsars less luminous than the median luminosity in our sample, while the right-hand side diagram shows pulsars more luminous. Figure 5 presents cumulative distribution functions of both sub-samples with respect to $P^{-3}\dot{P}$. Even such a simple analysis shows that selection effects in the filling of the $(P, \dot{P})$-space are important. They should be taken into account in statistical studies of the pulsar evolution.

REFERENCES

Eadie, W.T., Drijard, D., James, F.E., Ross, M., and Sadoulet, B. 1971, *Statistical Methods in Experimental Physics* (Amsterdam: North-Holland).

Heiles, C., Kulkarni, S.R., Stevens, M.A., Backer, D.C., Davis, M.M., and Goss, W.M. 1983, *Ap. J.*, **273**, L75-L79.

Kendall, M.G., and Stuart, A. 1973, *Advanced theory of statistics, Vol. 2* (London: Griffin).
Lampton, M., Margon, B., Bowyer, S. 1976, *Ap. J.*, **208**, 177-190.
Lyne, A.G. 1981, in *IAU Symposium 95, Pulsars*, ed. W. Sieber and R. Wielebinski (Dordrecht: Reidel), pp. 423-436.
Lyne, A.G., Anderson, B., and Salter, M.J. 1982, *M.N.R.A.S.*, **201**, 503-520.
Lyne, A.G., Ritchings, R.T., and Smith, F.G. 1975, *M.N.R.A.S.*, **171**, 579-597.
Manchester, R.N., and Taylor, J.H. 1981, *Astr. J.*, **86**, 1953-1973.
Manchester, R.N., Tuohy, I.R., and D'Amico, N. 1982, *Ap. J.*, **262**, L31-L33.
Prószyński, M. 1979, *Astr. Ap.*, **79**, 8-13.
Prószyński, M. 1984, *Pulsar multi-component profiles: a phenomenological model*, this volume.
Seward, F.D., and Harden, F.R., Jr. 1982, *Ap. J.*, **256**, L45-L47.
Siegel, S. 1956, *Nonparametric Statistics for the Behavioral Sciences* (New York: McGraw-Hill).
Smith, D.H. 1983, *Sky and Telescope*, **66**, 311-313.
Stinebring, D.R., and Cordes, J.M. 1983, *Nature*, **306**, 349-351.
Vivekanand, M., and Narayan, R. 1981, *J. Astr. Ap.*, **2**, 315.

III. PHYSICS OF RAPIDLY ROTATING NEUTRON STARS

Superfluidity in Millisecond Pulsars

David Pines and M. Ali Alpar
Department of Physics
University of Illinois at Urbana-Champaign
Urbana, Il 61801

We review the evidence for superfluidity in the Vela pulsar, the Crab pulsar and PSR 0525+21, and examine the prospects for observing similar consequences of superfluidity in the already-discovered millisec pulsars. We consider, inter alia, the likelihood of observing glitches, the expected postglitch behavior, and pulsar heating by energy dissipation due to the creep of neutron vortex lines in pinned superfluid regions of the crust.

Introductory Remarks

Neutron stars are expected to be superfluid on quite general grounds [Baym, Pethick, and Pines (1969)]. The direct observational evidence for the existence of superfluids inside neutron stars comes from the observed relaxation of the rotation rate, $\Omega_c(t)$, and the spindown rate, $\dot{\Omega}_c(t)$, after sudden jumps (glitches) in these quantities detected in the Vela [Radhakrishnan and Manchester 1969; Downs 1981] and Crab pulsars [Boynton et al. 1969; Lohsen, 1981] and in PSR 0525+21 (Downs 1982). Initial work on explaining postglitch behavior focussed on the coupling of the core proton and neutron superfluids to the crust (Baym et al. 1969). Subsequent observational and theoretical developments have led us to investigate whether the postglitch behavior of these pulsars might find an alternative explanation in the coupling between crustal nuclei and those vortex lines in the rotating neutron superfluid which tend to pin to them [Alpar et al. 1984a and references contained therein]. More specifically, on the one hand the simple two-component model proved inadequate to explain the full details of the postglitch behavior of these three pulsars, and was likewise in conflict with the analysis of the timing noise from the Crab pulsar; on the other hand, recent calculations of the crust-core coupling show that because neutron vortices in the stellar interior carry magnetic flux, the electron-magnetic neutron vortex scattering equilibrates the core superfluid to the crust on time scales ~ seconds (Alpar, Langer and Sauls, 1984).

In collaboration with P. W. Anderson, J. Shaham, and R. Nandkumar, we have considered a number of observational consequences of the pinned crustal neutron superfluid in conventional pulsars. We have been able to obtain an excellent fit to the timing observations of Downs (198) for the Vela pulsar, which span the decade 1969-79, and include four giant glitches (Alpar et al. 1984b), and to the observed postglitch behavior of the Crab pulsar and PSR 0525+21 (Alpar, Nandkumar and Pines, 1984), while preliminary calculations indicate that vortex unpinning and creep provides a natural explanation for pulsar timing noise (Alpar, Nandkumar, and Pines, in preparation). In this talk we shall review briefly this work and consider its applicability to the recently discovered millisecond pulsars.

Millisecond Pulsar Superfluids

Millisecond pulsars differ from "ordinary" pulsars in two essential ways: a much larger superfluid angular velocity, Ω, and a much lower inferred dipolar field, B_s. Neither of these changes affects the superfluid physics of the neutron star. To be sure the distance between the quantized vortex lines of the rotating neutron superfluid, $d_v = (2\Omega/\kappa)^{-1/2}$, where κ is the quantum of vorticity, h/2m, is reduced by an order of magnitude, while the spacing between the quantized flux lines of the proton superfluid in the core, $d_F = (B_s/\Phi_o)^{-1/2}$, where Φ_o is flux quantum, hc/2e, increases by two orders of magnitude. Because these changes do not affect any of the basic superfluid scales (the coherence lengths, ξ and ξ_p of the two superfluids and the London length Λ for the proton superfluid remain small compared to d_v and d_F), the crust-core coupling continues to be quite rapid; for the 1.5 ms pulsar, we find

$$\tau_v \sim 1.3 \times 10^{-4} \text{ s} \quad \text{(neutron vortex-charge coupling)} \tag{1a}$$

$$\tau_{EK} \sim 4\, T_8 \text{ s} \quad \text{(Ekman coupling of crust to interior electrons)} \tag{1b}$$

where T_8 is the interior temperature in units of 10^8 K. Hence, as is the case with ordinary pulsars, the dynamic time scales for crust-core coupling are so fast that the core may be assumed rigidly tied to the crust for time scales of observational interest.

The properties of the pinned crustal superfluid are likewise essentially unchanged. The distance between vortex lines is large compared to the lattice spacing, while the spin down rates, $\dot{\Omega}_c$, which determine the relevant coupling times for vortex creep, are comparable to those of ordinary pulsars. The search for observational consequences of superfluidity in millisec and pulsars thus becomes a search for pinned crustal superfluid phenomena which are the same as those already proposed for ordinary pulsars. We here consider three such phenomena:

(1) The internal generation of heat by vortex creep.
(2) Macroglitches, such as those observed in the Vela pulsar, produced by the simultaneous unpinning of a large group of vortex lines.
(3) Postglitch timing behavior associated with the gradual recoupling of the pinned superfluid.

As we shall see, all three phenomena scale with $\dot{\Omega}_c$.

Energy Dissipation by Vortex Creep: The Surface Temperature and Creep Relaxation Times of Old Pulsars

Pulsars which have radiated away their original heat content will continue to be heated by the internal dissipation of the stored rotational energy of the star. The dominant dissipative mechanism is the creep of vortex lines in the pinning layers of the crust (Alpar et al. 1984a). [An elementary calculation shows that this phenomenon is some hundred times more effective than its principle competitor, the logarithmic creep of dislocations (Baym and Pines 1971).] The continuous energy dissipation due to vortex creep, which will then be equal to the surface luminosity, L_s, is given by

$$\dot{E}_{diss} \approx |\dot{\Omega}| I_p \bar{\omega}_{cr} = L_s \tag{2}$$

where I_p is the moment of inertia of the entire set of crustal pinning layers, and $\bar{\omega}_{cr}$ is an average through the pinning layers of the maximum angular velocity difference which can be supported by pinning forces,

$$\omega_{cr} \equiv (\Omega - \Omega_c)_{max} = \frac{E_p(\Delta,\rho)}{\rho\kappa r\xi b} \quad , \tag{3}$$

where E_p, the pinning energy, is a function of the neutron superfluid energy gap, Δ, and the density ρ, and b is the spacing between pinning sites along the vortex line. The corresponding limiting blackbody surface temperature is

$$T_s \simeq 1.1 \times 10^5 [I_{p,43} \bar{\omega}_{cr} \dot{\Omega}_{-14}/R_6^2]^{1/4} \quad . \tag{4}$$

From the upper limit to the surface luminosity of the Vela pulsar in the soft x-ray region (Harnden et al. 1979), and the Einstein detection of PSR 1929-10 (Helford 1982), we estimate

$$I_{p,43} \bar{\omega}_{cr} \sim 1 \quad . \tag{5}$$

For such a pulsar, the internal temperature will be close to the surface temperature. On the other hand, the average thermal creep relaxation time associated with a physically distinct pinning layer is given by

$$\tau^i = \frac{k_B T \, \omega^i_{cr}}{E^i_p \, |\dot{\Omega}_c|} \equiv \alpha_i \frac{T}{|\dot{\Omega}_c|} \tag{6}$$

where the supercript i refers to the layer in question. Alpar, Nandkumar, and Pines (1984) find that a good fit to the postglitch behavior of the Crab pulsar and PSR 0525+21 can be obtained if one assumes that the vortex pinning layers in these pulsars are essentially the same as those hypothesized previously (Alpar et al. 1984b) for the Vela pulsar. On taking the internal temperature of PSR 0525+21 to be given by Eqs. (4) and (5), they find for the superweak pinning region (which relaxes some twenty times more rapidly than the weak pinning region) a relaxation time ~ 140^d in excellent agreement with their fit to the postglitch timing data. The latter yields a "fast" relaxation time ~ 150^d and is consistent with the presence of a much slower 3000^d relaxation process.

We assume that all old pulsars possess essentially the same pinning layers as PSR 0525+21 and the Crab and Vela pulsars. We thus expect that all old pulsars will have temperatures determined by internal dissipation according to Eqs. (4) and (5), and will possess pinning relaxation times which depend only on their spin-down rate, and are

$$\tau_{sw}^{old} \sim 220|\dot{\Omega}_{-14}|^{-3/4} \text{ d} \tag{7a}$$

$$\tau_{w}^{old} \sim 4.4 \times 10^{3}|\dot{\Omega}_{-14}|^{-3/4} \text{ d} \tag{7b}$$

for the superweak and weak pinning layers respectively.

If we make the physically plausible assumption that the millisecond pulsars are old pulsars, from Eqs. (2) and (5) it follows that their surface luminosity is given by

$$L_s \sim 10^{29}|\dot{\Omega}_{-14}| \text{erg s}^{-1} . \tag{8}$$

For the millisecond pulsars one finds (see Table 2) that the values of $\dot{\Omega}$ are typically comparable to those of comparatively slow old pulsars, i.e., $|\dot{\Omega}_{-14}| \sim 1$. Hence with present satellite capacities one will only be able to detect the surface luminosity of a millisecond pulsar which lies at a distance of $\lesssim 50$ pc.

Glitches and Postglitch Behavior

Substantial glitches $(\Delta\Omega/\Omega \gtrsim 10^{-7})$ have thus far been observed in four pulsars: six in the Vela pulsar; one each in PSR 1325-43, 1641-45, and 2224+65 (Manchester *et al.* 1978, Newton, Manchester and Cooke 1981, Backus *et al.* 1982). In addition smaller glitches $(|\Delta\Omega/\Omega| \lesssim 10^{-8})$ have been observed in both the Crab pulsar and PSR 0525+21, while detailed studies of the post-glitch behavior have been carried out for the four Vela glitches which took place in the decade, 1969-79, for two of the Crab glitches, and for that in PSR 0525+21. As we have noted, since a detailed fit to the observed post-glitch behavior of the latter two pulsars can be made with the "Occam's razor" hypothesis that these stars possess essentially the same vortex pinning layers as the Vela pulsar, it is tempting to pursue the hypothesis that the millisecond pulsars possess similar vortex pinning layers, and hence to apply directly prior results for all three conventional pulsars to the millisecond pulsars.

In what follows we shall take the point of view that all old pulsars, including the millisecond pulsars, will exhibit substantial glitches, $\Delta\Omega/\Omega \gtrsim 10^{-7}$, with a glitch expectancy which is related to $\dot{\Omega}$. In estimating the likelihood of observing a glitch in the millisecond pulsars we consider two alternative hypotheses for the interval between successive glitches:

- That a glitch occurs when, as a result of pulsar spindown, vortices which have been unpinned in the previous glitch are replaced. The number of such vortices is proportional to the reduction in the superfluid angular velocity in that glitch, $\delta\Omega$; the time to the next glitch is therefore

$$t_g = |\delta\Omega/\dot{\Omega}| \equiv (I_c/I_p)|\Delta\Omega_c/\dot{\Omega}| \tag{9}$$

where I_p is the moment of inertia of the pinning layers involved in the glitch, and I_c is the "crustal" inertial moment, which effectively includes the rest of the star.

- That a glitch occurs when, again as a result of pulsar spindown, a critical angular velocity difference, $[\delta\omega]_{cr}$, is reached at the pinning layer responsible for major glitches. The time to the next glitch is therefore

$$t_g = |\delta\omega_{cr}/\dot{\Omega}| \tag{10}$$

One can test each of these hypotheses against the observed glitch intervals for the Vela pulsar, and against the total number of glitches observed for the entire pulsar sample.

At present neither hypothesis can be ruled out. The first explains in a natural way the typical interval (~ 2y) between Vela glitches. For a given glitch, I_p/I_c is given directly by:

$$\frac{I_p}{I_c} \simeq \left|\frac{\Delta\dot{\Omega}}{\dot{\Omega}}\right| \tag{11}$$

so that Eq. (9) becomes

$$t_g^A = |\Delta\Omega_c/\Delta\dot{\Omega}_c| \; . \tag{12}$$

In Table 1 we give glitch parameters and t_g^A for a typical Vela glitch and for PSR 1641-45. Observations of $|\Delta\dot{\Omega}_c|$ have not been made for the other two pulsars which have glitched; for these, we may estimate the glitch interval by setting $(I_p/I_c) \sim 10^{-2}$, in which case we find

$$t_g^B = 10^2|\Delta\Omega_c/\Omega_c|T_s \tag{13}$$

where $T_s \equiv |\Omega_c/\dot{\Omega}_c|$ is the pulsar spindown time. The resulting glitch intervals are likewise given in Table 1.

On the second possibility, the glitch interval is obviously sensitive to one's choice of $(\delta\omega)_{cr}$. For the Vela pulsar one finds $(\delta\omega)_{cr} \sim 10^{-2}$; on the other hand, from their statistical survey, Alpar and Ho (1983) estimate $(\delta\omega)_{cr} \sim 2\times10^{-3}$; on adopting the latter value, we find

$$t_g^C \simeq 2 \times 10^{-3}|\dot{\Omega}|^{-1} \tag{14}$$

and these values are likewise given in Table 1.

Also included in this Table is PSR 1930+22 which, on either of the above criteria, is the pulsar which, among the sample of pulsars not yet seen to

Table 1. Observed and Predicted Macroglitches for Five Pulsars

Pulsar	Vela	1641-45	1325-43	2224+65	1930+22
P_{-3}	89	455	533	683	144
$\dot{P}_{-15}$	125	20.1	3.01	9.67	57.8
$\lvert\dot{\Omega}_{-14}\rvert$	10^4	61.1	6.67	13.	1.7×10^3
B_{12}	3.4	3.1	1.3	2.6	2.9
$(\Delta\Omega_c/\Omega)_{-7}$	~ 25	1.9	1.16	17.1	1^*
$(\Delta\dot{\Omega}_c/\dot{\Omega}_c)_{-2}$	~ 1	.16±.12	-	-	-
$t_g^A(y)$	~ 2	90^{+250}_{-40}	-	-	-
$t_g^B(y)$	~ 2	14	65	380	0.8
$t_g^C(y)$	~ 2	100	950	490	4
$\tau^{sw}(d)$	3	10	60	40	1

Notes: $B = \left[(3/8\,\pi^2)IR^{-6}c^3P\dot{P}\right]^{1/2}$; $B_{12} \simeq I_{45}^{1/2}R_6^{-3}(P\dot{P}_{15})^{1/2}$

$$t_g^A = \left|\frac{\Delta\Omega_c}{\Delta\dot{\Omega}_o}\right| \; ; \quad t_g^B = 10^{-5}(P/\dot{P})\left(\frac{\Delta\Omega}{\Omega}\right)_{c\,-7} \; ; \quad t_g^C \sim 2\times10^{-3}/|\dot{\Omega}|$$

* Assumed value

Table 2. Properties of Millisecond and Binary Pulsars

Pulsar	1937+21	1953+29 *	1913+16	0655+64	0820+02
P(ms)	1.5	6.1	59	196	865
$\dot{P}_{-19}$	1.2	7.8	86.4	< 49	1000
$\dot{\Omega}_{-14}$	33	13	1.55	$< 8\times10^{-2}$	8.4×10^{-2}
B_8	4.3	22	230	< 310	3000
$t_g^B(y)=10^{-5}T_s$	4000	2500	2200	> 13000	2750
$t_g^C(y)$	190	480	4100	> 79000	76000
$\tau^{SW}(d)$	17	34	170	> 1600	1500
$\tau^{W}(d)$	340	680	3400	> 3100	30000

* Using $\dot{P}$ scaled as $P^{4/3}$ from the observed $\dot{P}$ value for PSR 1937+21

glitch, is the most likely to glitch.

We turn now to the two millisecond pulsars, and to the three binary pulsars which are also candidates for neutron stars which have been spun up by accretion. For these pulsars we calculate both t_g^B (assuming a previous glitch magnitude of $|\Delta\Omega_c/\Omega_c| \sim 10^{-7}$) and t_g^C (assuming $\delta\omega_{cr}^g \sim 2 \times 10^{-3}$). As may be seen in Table 2, the results are not especially encouraging for would-be observers of glitches in millisecond pulsars; although the glitch intervals, t_g^C, are comparable to those found in the conventional pulsar sample, the number of pulsars in the present sample is too small to make it likely that a substantial glitch will be observed in the near future. Matters would change should a millisecond pulsar with an $\dot{\Omega} \gtrsim 10^{-12}$ be discovered.

We also give in Table 2 our estimated relaxation times, τ_{sw}, based on Eq. (7a). While it would take a glitch for these times to be observed directly, it is possible that these might give rise to features in the noise spectrum which could in principle be observed.

Timing Noise

While preliminary indications suggest that vortex creep and unpinning may provide an explanation for timing noise in conventional pulsars, one does not yet have the kind of detailed analysis and comparison of theory and observation which would permit us to make predictions about the level of timing noise anticipated for millisecond pulsars. Power spectra of the timing noise in these pulsars would be extremely valuable for on many models for that noise one expects structures for frequencies such that $\omega\tau \sim 1$, where τ refers to either the weak or superweak pinning regions. It would be interesting, too, to learn whether the millisecond pulsar timing noise strength correlates with $\dot{\Omega}$ in a fashion similar to that which has been found for conventional pulsars by Cordes and Helfand: their observations suggest that the noise strength might be proportional to $|\dot{\Omega}|$.

Acknowledgements

This research was supported in part by NSF Grant PHY 80-25605, NASA Grant NSG-7653 and NATO Research Grant RG 816-81.

REFERENCES

Alpar, M. A., Anderson, P. W., Pines, D. and Shaham, J. 1984a, Ap. J., 276, 325.

Alpar, M. A., Anderson, P. W., Pines, D. and Shaham, J. 1984b, Ap. J., 278, 791.

Alpar, M. A. and Ho, Cheng 1983, M.N.R.A.S., 204, 655.

Alpar, M. A., Langer, S. and Sauls, J. A. 1984, Ap. J., to be published.

Alpar, M. A., Nandkumar, R. and Pines, D. 1984, submitted to Ap. J. Letters.

Bachus, P. R., Taylor, J. H. and Dameshek, M. 1982, Ap. J., (Lett.), 225, L63.

Baym, G., Pethick, C., Pines, D. and Ruderman, M. 1969, Nature, 224, 872

Baym, G., Pethick, C. and Pines, D. 1969, Nature, 224, 673.

Baym, G. and Pines, D. 1971, Ann. Phys. 66, 816.

Boynton, P. E., Groth, E. J., Hutchinson, D. P. Nanos, G. P. Partridge, R. B. and Wilkinson, D. T. 1972 Ap. J., 175, 217.

Cordes, J. M. and Helfand, D. J. 1980, Ap. J., 239, 640.

Downs, G. S. 1981, Ap. J., 249, 687.

Downs, G. S. 1982, Ap. J. (Lett.), 257 L67.

Harnden, F. R., Hertz, P., Gorenstein, P., Grindlay, J., Schreier, E. and Seward, F. D. 1979, Bull. AAS, 11, 424.

Helfand, D. 1983 - private communication.

Lohsen, E. 1981, Astr. Ap. Suppl. 44, 1.

Manchester, R. N., Newton, L. N., Goss, W. M. and Hamilton, P. A. 1978, M.N.R.A.S., 184, 35P.

Newton, L. N., Manchester, R. N. and Cooke, D. J. 1981, M.N.R.A.S. 194, 841.

Radhakrishnan, V. and Manchester, R. N. 1969, Nature, 222 228.

DISCUSSION OF PINES'S PAPER

SHAHAM: There is a major difference between pulsars that were born fast and slowed down, and neutron stars that are spinning up as in X-ray sources, as far as the superfluid behavior is concerned. When you have a neutron star that you form very hot, and then freeze, it's easy to see how you form the vortex lines. Then as it slows down, the vortex lines simply migrate out, and get lost somewhere at the edges. When you speed up a pulsar, you must create vortex lines somewhere (which is a process that a priori seems to be more complicated than destroying them) and then have them migrate inward. The millisecond pulsars really offer a laboratory in which you have both processes.

PINES: The problem there in X-ray sources is that the accretion noise overwhelms any possible timing noise associated with the interior superfluid, by about three orders of magnitude. So that what you see is the noise associated with the jumps in the frequency associated with the accretion process. So the millisecond pulsar is a beautiful example to see whether neutron stars are as good at creating vortices that move in as buckets of helium are. I think the answer is, no doubt.

CHANMUGAM: What can you say about the masses of the neutron stars, Vela and the Crab?

PINES: It's tempting to simply say that all neutron stars have the mass Joe Taylor has determined--they're all 1.4 solar masses.

CHANMUGAM: No, from the superfluidity results: your relaxation calculations. How do they depend on the masses of the stars?

PINES: Only in a very rough way. They depend much more sensitively on the equation of state. You need a fairly stiff equation of state to get enough crust. If you take a really soft equation of state, you're in trouble because you can't get a large enough crust to support a large enough pinning moment of inertia--the pinning moments of inertia must be of order 1% to explain Vela, the Crab, PSR 0525+21. So that makes it more sensitive to the equation of state than the mass. But you'd be in trouble with a half solar mass.--No, you'd be all right with a half solar mass.

MANCHESTER: Have you tried to apply your model to the 1641-45 glitch?

PINES: The postglitch behavior hasn't been studied; we did apply it in that table, and I could show that again. That is, one doesn't have enough information after the glitch to make a detailed fit; at least, we have not seen it in the literature in terms of tables of phase arrival time. Do you have those fits?

MANCHESTER: We haven't published the arrival times--we've published the residuals.

PINES: What we've found is that there's no substitute for having your hands on the real data. You need at the very least to have a go at deciding what the residuals are and to see either the phase arrival times or the plot of Ω or $\dot{\Omega}$. Our favorite plot is of $\dot{\Omega}$, actually. It's the one that's easiest to start making good fits to. We'd be very interested in trying to do it; we have a clear statement of what we would expect.

MANCHESTER: It seemed to have no $\Delta\dot{\Omega}$.

PINES: You did have a measured $\Delta\dot{\Omega}$, which we used to estimate the time to the next glitch for that pulsar. It was 1.6 ± 1.2.

TAYLOR: That's zero.

RUDERMAN: You mentioned that in the older pulsars, the heat that would be generated from the vortex creep is more important than the residual radiation from its cooling. In almost everybody's models for pulsar emission (perhaps in everybody's), it's heating at the polar caps which is a more substantial source; and therefore I think that you can embarrass theorists by looking even at a higher level of X-ray emission, that is to say, one would expect to see more X-ray emission in old pulsars.

PINES: We tried to estimate that very roughly. We did look at the question of thermal creep of dislocations in the crust, which is about 1% of the vortex creep. A very rough estimate of the heating of the polar cap led us to conclude that vortex creep is more effective. You've got all that rotational energy stored in there, if you can get rid of it at a reasonable rate.

RUDERMAN: In some of the older ones, $I\Omega\dot{\Omega}$ is not all that much bigger than the radio emission.

PINES: In answer to your question about 1641-45, Dick, [Manchester] we would anticipate a superweak coupling time of the order of ten days, and a weak coupling time which would be 200 days. So that if you've got data covering the first year after the glitch, and with fairly good coverage, we can check and see whether these ideas are right.

MANCHESTER: The coverage is not very good.

PINES: We can certainly try--we can construct one of our classic curves and see whether it will go through the observed points. We'd like to very much; indeed, we feel quite frustrated that we've been unable to persuade the people who observed the fifth and sixth Vela glitches to send us the data or to analyze it using our theory. So we don't know yet if, having worked for four, it will work for five and six. I will take bets, however.

Neutron Star Seismology: Understanding the Oscillation Modes

P. N. McDermott[1], C. J. Hansen[2], R. Buland[3] and H. M. Van Horn[1]

ABSTRACT

Spherical, non-rotating, non-magnetic neutron stars can sustain nonradial oscillations over periods ranging from tenths of milliseconds to tens of seconds. We are seeking an understanding of the nature of these modes in order to provide a foundation for investigations of the more complex situation that prevails in pulsars. The models that we have studied consist of three components: a fluid core, a solid crust, and at the surface a fluid ocean. This three component structure leads to a complex mode spectrum. In the absence of rotation there are two general classes of oscillation modes, the torsional and the spheroidal. The torsional oscillations are completely nonradial and have periods of $\sim$ 20 ms and shorter. The spheroidal modes consist of a number of subclasses: the p-modes, g-modes, and a new class of modes familiar to geophysicists that are dominated by the non-zero shear modulus in the neutron star crust. This new class of shear modes has periods of $\lesssim$ 5 ms. The p-modes have periods of $\lesssim$0.5 ms and are only slightly affected by the presence of the crust. In addition, there are two distinct g-mode spectra, one associated with the fluid core and the other associated with the fluid ocean. The ocean g-modes have periods of $\gtrsim$ 50 ms (depending sensitively on temperature) and are essentially confined to the fluid layer above the crust. The core g-modes are largely confined to the region below the crust and have periods of $\gtrsim$ 30 seconds for one specific model that we have studied.

I. Introduction

The complex structure of neutron stars produces a rich variety of possible normal modes of oscillation. The mode periods range from tenths of milliseconds to tens of seconds. Different modes are sensitive to the mean density (and hence the equation of state), to the internal temperature and temperature distribution, to the shear strength of the crust, and to the crust thickness. This suggests the interesting possibility of using the oscillation modes as probes of the interiors of neutron stars.

For a spherically symmetric, non-rotating, non-magnetic neutron star with a solid crust there are two general classes of oscillation modes: the torsional and the spheroidal. The torsional oscillations are completely nonradial and have periods of about 20 ms and shorter (Hansen and Cioffi 1980; Schumaker and Thorne 1983). The spheroidal modes consist of a number of subclasses: the p-modes, g-modes, and a new class of modes familiar to geophysicists that we call the S modes. The p-modes have periods of

[1]Department of Physics and Astronomy and C. E. Kenneth Mees Observatory, University of Rochester, Rochester, NY 14627.
[2]Department of Astrogeophysics, Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder, CO 80309.
[3]Department of Interior, United States Geological Survey, Box 25046, Mail Stop 967, Denver Federal Center, Denver, CO 80225.

$\gtrsim 0.5$ ms (Thorne 1969; Lindblom and Detweiler 1983) and are only slightly affected by the presence of the crust. There are two distinct g-mode spectra, one associated with the fluid core and the other associated with the fluid ocean. The ocean g-modes have periods of $\gtrsim 50$ ms (for central temperature $T_c \lesssim 10^8$ K) depending sensitively on temperature (McDermott et al. 1983) and are highly trapped in the thin fluid layer above the crust. The core g-modes are entirely confined to the fluid core and have periods of $\gtrsim 30$ seconds for one specific model that we have studied. The S modes owe their existence to the non-zero shear modulus of the crust and are essentially normal modes of shear waves.

A number of observations in radio pulsars and in X-ray burst sources are suggestive of neutron star oscillations. Van Horn (1980) has proposed that pulsar microstructure and drifting subpulses might be due to neutron star oscillations. Some X-ray burst sources are observed to have periodicities ranging from 12 ms to 70 ms. It has been suggested by Livio and Bath (1982) that these periodicities might be due to surface g-modes.

The purpose of this paper is to summarize our growing understanding of the properties of nonradial oscillation modes of neutron stars. In the following sections we first sketch the properties of the equilibrium model used in our study and outline a local analysis of the pulsations. Current results from our continuing numerical calculations of neutron star oscillations are given in § III.

II. Equilibrium Models and Local Analysis

The equilibrium model used in our pulsation calculations is one taken from the evolutionary sequences computed by Richardson et al. (1982). The stellar mass is $0.5\ M_\odot$, the star has a radius of 10.1 km, a central temperature of 1.0×10^8 K, and the local effective temperature at the surface is 2×10^5 K. The equation of state (EOS) is relatively soft; specifically the EOS C for hyperonic matter of Pandharipande (Baym, Pethick and Sutherland 1971) is used in the core, and the EOS developed by Baym, Pethick and Sutherland (1971) is used in the crust. The crust is 2.45 km thick and terminates at a density of 1.84×10^{14} gm/cm^3. The ocean is assumed to be 1.8 meters deep.

Although the equilibrium models are fully consistent with general relativity, we have analyzed the pulsations using Newtonian hydrodynamics augmented by the addition of the shear modulus μ, in the stress tensor, to account for the solid crust (Van Horn and Savedoff 1976, Hansen and Van Horn 1979). We assume the oscillations to be adiabatic, and we use the Cowling approximation, in which perturbations to the gravitational potentials are neglected. These simplifying assumptions are sufficient to enable us to map out the oscillation spectrum of the neutron star. The resulting pulsation equations, together with appropriate boundary conditions, form an eigenvalue problem for the period and resulting motion of the neutron star matter.

To obtain an approximate idea of the physical properties of the oscillations we first solve these equations in the limit in which the effective wavelength of the perturbations is much smaller than any scale height that enters the problem. This is accomplished by assuming that the spatial dependence of all perturbation quantities is proportional to e^{ikr} where k is the wavenumber and kr>>1. For the spheroidal modes this results in two classes of solutions for the frequency σ. One class corresponds to the p-modes and the other to the S-modes. The p-modes have frequencies given by (to highest order in k)

$$\sigma_p^{\,2} \approx k^2 c_\ell^{\,2} \tag{1}$$

where $c_\ell^{\,2} = (\Gamma_1 p + 4\mu/3)/\rho$ is the longitudinal wave speed (sound speed), and Γ_1 is the adiabatic exponent; ($\Gamma_1 \equiv (\partial \ln p/\partial \ln \rho)s$). The S-modes have frequencies given by

$$\sigma_s^{\,2} \approx k^2 c_s^{\,2} \tag{2}$$

where $c_s^{\,2} = \mu/\rho$ is the transverse wave speed. In the limit in which $\mu \to 0$ we recover the standard fluid results: $\sigma_p^{\,2} \to k^2 \Gamma_1 p/\rho$, and the character of the other frequency completely changes to give g-modes (i.e. $\sigma_s^{\,2} \to \ell(\ell+1)N^2/(kr)^2$ where N is the Brunt-Väisälä frequency).

This analysis thus provides some idea of what to expect from the global calculations and assists in the interpretation of these calculations.

III. Results of Global Mode Calculations

A sampling of the results of the global mode calculations is contained in Table 1 and Figures 1-3. All modes in the table and figures correspond to $\ell=2$ (quadrupole) oscillations. Displayed in Table 1 are mode periods, pulsation energies and amplitude damping times due to emission of gravitational radiation. The energies are scaled to the relative radial amplitude at the surface squared (e.g. $(U/r)^2_{r=R_*}$). As an example this means that if the relative surface amplitude is $(U/r)_{r=R_*} = 10^{-3}$ then the energies in Table 1 must be multiplied by $(10^{-3})^2$.

TABLE 1

MODE	PERIOD	$E/(U/R)^2$ (ergs)	τ_g
⋮	⋮	⋮	⋮
g_2^c	69.89 s	4.32+57	1.84+15 y
g_1^c	30.85 s	2.40+54	1.95+13 y
⋮	⋮	⋮	⋮
g_3^s	840.7 ms	7.08+43	4.21+21 y
g_2^s	622.4 ms	1.23+43	1.33+20 y
g_1^s	355.3 ms	1.78+42	1.37+19 y
$_0S_2$	6.528 ms	2.65+52	3.92-2 y
$_1S_2$	2.262 ms	1.77+52	1.55-1 y
⋮	⋮	⋮	⋮
$_9S_2$	0.4232 ms	5.70+50	1.40+3 sec
f	0.3979 ms	9.79+50	1.38-1 sec
$_{10}S_2$	0.3835 ms	5.06+50	3.56+2 sec
⋮	⋮	⋮	⋮
$_{19}S_2$	0.1951 ms	1.09+51	9.83+1 sec
p_1	0.1858 ms	1.84+48	1.57-1 sec
⋮	⋮	⋮	⋮
p_2	0.1585 ms	2.07+47	2.60-1 sec
⋮	⋮	⋮	⋮
p_3	0.1240 ms	1.27+47	1.37-1 sec

The lowest period core g-mode, labeled g_1^c (nomenclature: g_n^c where n represents the overtone number), has a period of about 31 seconds. The radial dependence of the eigenfunctions for this mode is depicted in Figure 1 note that both components of the motion (U is the radial component, V the horizontal component) have negligible amplitude in the crust ($r/R_* \geq 0.76$). Higher order core g-modes have increasingly longer periods than the g_1^c.

At shorter periods lie the surface g-modes (g_n^s). The lowest period of these corresponds to the g_1^s mode with a period of 355 ms. Again, the overtones have longer periods. The g_1^s eigenfunctions are shown in Figure 2. There are two features to be especially noted; the motion is confined almost totally to the fluid ocean ($\log(1-r/R_*) \leq -3.7$), and the horizontal amplitude completely dominates the vertical (e.g. $V \sim 10^5 U$). The reason for the confinement is that the crust acts like a wall at which the fluid is free to slip horizontally, and therefore the coupling of the horizontal motion across this wall is weak. The gravitational radiation damping times for both core and surface g-modes is very long and these modes are undoubtedly damped by other mechanisms.

The S-modes have periods of about 6.5 ms, for the ${}_0S_2$ (nomenclature: ${}_nS_\ell$, where n=overtone number and ℓ=2 for quadrupole modes), and shorter for the overtones. Shown in Fig. 3 is the radial dependence of the eigenfunctions for the ${}_0S_2$ mode. The radial amplitude U, peaks at the core-crust interface ($r/R_*=0.76$). Also note the sharp discontinuity in the horizontal amplitude V at the interface. The ${}_0S_2$ mode is somewhat atypical of the other S-modes in that it has a significant core amplitude; the overtones are almost totally confined to the crust. The S-modes have large energies and relatively long gravitational radiation damping timescales.

The f-mode has a period of 0.398 ms, which is virtually the same as the period derived from a calculation assuming an inviscid fluid. The p_1-mode has a period of 0.186 ms which is to be compared to the pure fluid period of 0.189 ms. The f-mode and the p-modes are only very slightly affected by the shear in the crust because $\Gamma_1 p \gg \mu$ (see equation 1) throughout the crust. Note that these modes are interspersed among the higher order S modes. The f-mode and the p-modes have relatively large energies and

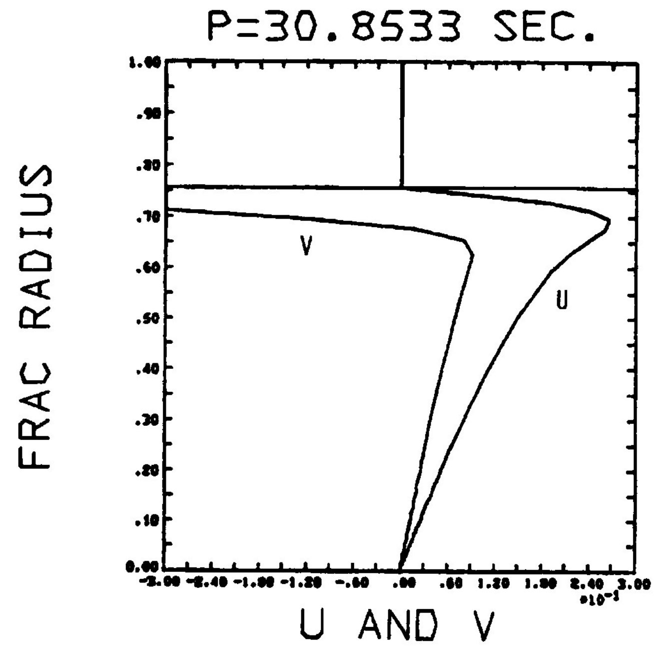


Fig. 1-The radial dependence of the horizontal (V) and radial (U) eigenfunctions is shown for the $g_1{}^c$(lowest period core g-mode) mode. The motion is confined almost totally to the fluid core ($r/R_* \lesssim 0.76$).

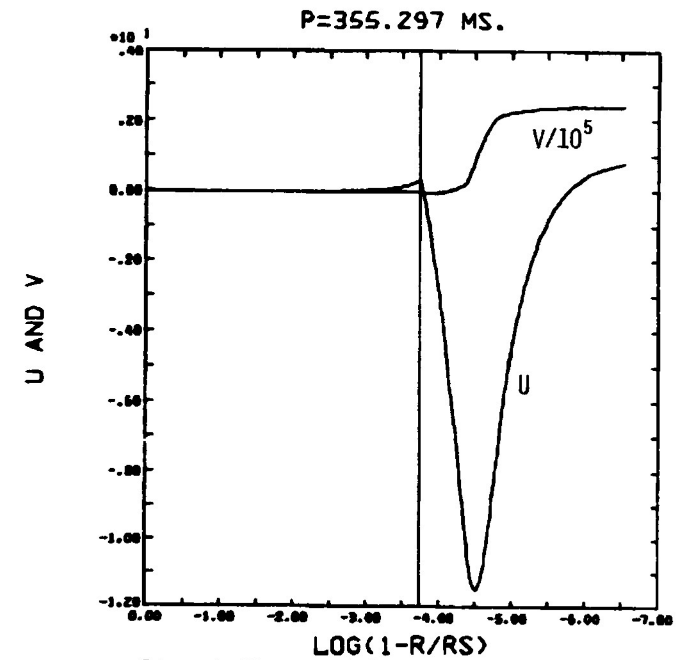


Fig. 2-The radial dependence of the eigenfunctions is shown for the $g_1{}^s$(lowest period surface g-mode) mode. Note the logarithmic scale necessary to display this mode. The motion is almost totally confined to the thin fluid ocean overlying the crust. The crust/ocean interface is at $\log(1-r/R_*) = -3.75$. Note that the horizontal eigenfunction V has been divided by a factor of 10^5.

very short gravitational radiation damping times. In fact gravitational radiation is so efficient in damping these modes that it is almost certainly the dominant energy loss mechanism.

We have performed numerical experiments to test our understanding of the effects of the shear on the S-modes. The shear modulus has been artificially reduced by a series of constant factors (e.g. 2, 4, 6, 8, 10, etc.). The effect of this is to cause the ${}_nS_\ell$ modes to migrate upward in period, as expected on the basis of equation (2). This confirms the physical description of these modes given above. Not surprisingly, the ${}_0S_2$ and ${}_1S_2$ modes do not obey equation (2) which is only strictly valid for very high order overtones (kr>>1). The overtones however conform quite well to equation (2).

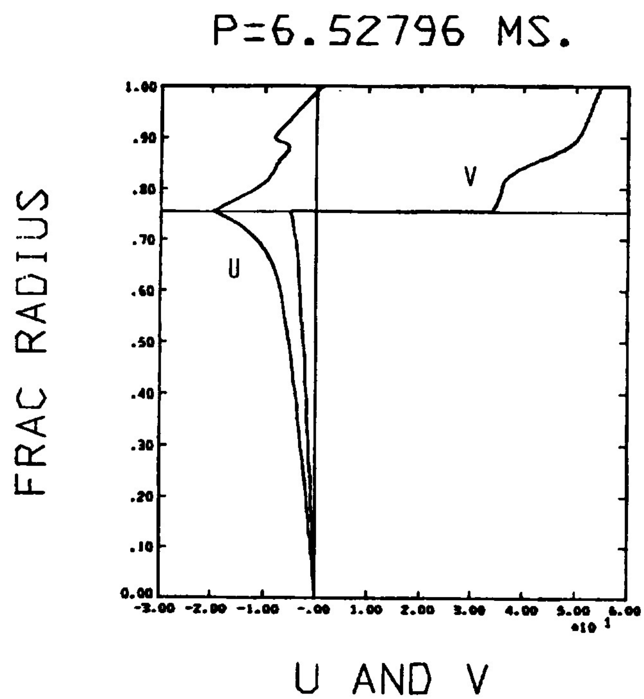


Fig. 3-The radial dependence of the eigenfunctions is shown for the ${}_0S_2$ mode. Note the large amplitude of the radial motion, U, at the core/crust interface ($r/R_* = 0.76$), and the large discontinuity in the horizontal motion, V, there.

V. Conclusions

Neutron stars are capable of sustaining a rich variety of oscillation modes ranging from core g-modes with periods of tens of seconds to p-modes with periods of tenths of milliseconds. The surface g-modes have relatively low energies and might be easily excited in a pulsar macroglitch or in an X-ray burst event. Even for unit horizontal amplitude at the surface ($V \sim R_*$) the pulsation energy of the surface g-modes is 10^{33}ergs. This is only a small fraction of the amount of energy released in a glitch ($\Delta E \sim \frac{1}{2} I\Omega^2 (\frac{\Delta\Omega}{\Omega}) \sim 10^{41}$ergs) or in an X-ray burst event ($\Delta E \sim 10^{39}$ergs, van Paradijs 1978). Considering the energetics of either a pulsar macroglitch or an X-ray burst event and the impulsive nature of such events it is difficult to imagine how surface g-modes could not be excited!

We wish to gratefully acknowledge the partial support of National Science Foundation grant AST 83-07214 (U. Rochester) and AST 83-15698 (U. Colorado).

References

Baym, G., Pethick, C., and Sutherland, P. 1971, Ap. J., 170, 299.

Hansen, C. J. and Van Horn, H. M. 1979, Ap. J., 233, 253.

Hansen, C. J., and Cioffi, D. F. 1980, Ap. J., 238, 740.

Lindblom, L., and Detweiler, S. L. 1983, Ap. J. Suppl., 53, 73.

Livio, M., and Bath, G. T., 1982, Astr. Ap., 116, 286.

McDermott, P. N., Van Horn, H. M., and Scholl, J. F. 1983, Ap. J., 268, 837.

Richardson, M. B., Van Horn, H. M., Ratcliff, K. F., and Malone, R. C. 1982, Ap. J., 255, 624.

Schumaker, B. L., and Thorne, K. S. 1983, M. N. R. A. S., 203, 457.

Thorne, K. S. 1969, Ap. J., 158, 1.

Van Horn, H. M., and Savedoff, M. P. 1976 in Proceedings of Los Alamos Conference on Solar and Stellar Pulsation, ed. A. N. Cox and R. G. Deupree (LA-6544-C).

Van Horn, H. M., 1980, Ap. J., 236, 899.

van Paradijs, J. 1978, Nature, 274, 17.

DISCUSSION OF McDERMOTT'S PAPER

PINES: I have a question and a comment. The question is, how do you think things will scale to a somewhat more realistic neutron star--with a real equation of state, and 1.4 solar masses?

McDERMOTT: That's a good question. We have planned to try to extend that calculation to more realistic stars.

PINES: Do you have any estimates of this?

McDERMOTT: It depends very much on what sort of mode you're talking about.

PINES: The comment is, that in unpublished work, Uomoto has pointed out that the spin up of the millisecond pulsar might be very interesting as a probe of what is going on; because if you look at the periods of oscillation modes, you pass through many of those periods as you're spinning up the neutron star. If you couple strongly to these modes in the spin-up process, you could couple sufficiently efficiently that you might even stop the spin-up at one of the modes. It raises problems for quite a few more thesis students--one, to do a realistic star; two, then to sort out what happens with the spinning-up neutron star and the coupling to the internal modes. It's not a problem that's been addressed for the Earth, as far as I know--if you spin up the Earth, do you excite modes and so forth.

SHAHAM: I want to indicate two possible problems. One is that since we sort of know that there is superfluidity in neutron stars, and since we know that each vortex has an angular momentum associated with it, many of your modes involve a real change in angular momentum. Since the vortices are dragged with the nuclei, and they might resist a change in angular momentum, offhand the solution to this question may seem to be that those nuclei to which vortices are pinned simply don't participate in the motion. But I don't know whether that's possible. It may or may not affect some of the modes in a major way. That's one problem. The other is, the surface magnetic field as we know does create havoc on the surface--especially when you want to apply those things to real pulsars with strong magnetic fields. Wouldn't that change a lot of your results?

McDERMOTT: Yes, it would. In fact, we expect that the surface g-modes are probably strongly affected by typical pulsar magnetic fields. I can't say much more than that at this point.

SHAHAM: Did you have a chance to think about the pinning?

McDERMOTT: That is something that we have not considered.

CHANMUGAM: Do you have any idea of the damping time scales for these modes?

McDERMOTT: Yes. We've considered various damping mechanisms, and it depends again on what mode you're talking about. Let's talk about the surface g-modes, for example. We've computed gravitational radiation and found time scales. Those are enormously large--on the order of 10^{15}, 10^{17} years, assuming no rotation, just a quadrupole oscillation--emission of quadrupole radiation. We have tried to make some estimates of the non-adiabatic effects. Those seem to indicate that the damping time scale might be on the order of 100 seconds or so. Another calculation that we've done is, we know that if you do have a magnetic field, the matter will push the field around; the field will oscillate and will cause emission of electromagnetic radiation. We've tried to do admittedly a somewhat inconsistent calculation (because we haven't accounted for the magnetic field in computing the oscillations themselves) but after the fact we've put in a field and tried to compute the radiation that might result. We find that the damping is very rapid. In fact, the damping time is roughly comparable to the oscillation time. So if you have strong magnetic fields, the surface oscillations for example might not hang around. It's a different story for the other modes.

STOLLMAN: You were saying something about the X-ray burst process--the g-modes--when are they seen? Is that in the burst itself?

McDERMOTT: During the burst, in the tail. They seem to last for on the order of 10 - 100 seconds.

HANKINS: In the microstructure oscillations, periodic microstructure, sometimes I see long trains of periodic micropulses whose period increases over the burst, by a factor of two. Is there any way that you could get that kind of behavior?

VAN HORN: The one thing that comes to mind, Tim, is that as Pat [McDermott] pointed out, the surface g-modes are extremely temperature-sensitive. If you have something that causes the temperature to change, over the time scale that you're observing, if it cools, for example, over that period--then you would in fact expect some changes. Anothr possibility: Several of these different overlapping spectra are quite complex. You might be able to find a situation in which you get the oscillations effectively transferring from mode to mode. I don't know how likely that is; I don't know whether the observations are smooth or relatively discontinuous; so I don't know which of those would be more likely.

BORIAKOFF: There is the discontinuous mode as well. As Tim pointed out, there are cases in which you have a high-Q oscillation, and then a phase shift and the same high Q. So you have a variety of modes which could be explained by mode coupling or some other mechanism.

GRAVITATIONAL RADIATION FROM A SOLID CRUST NEUTRON STAR

M. Ali Alpar

and

David Pines

Department of Physics
University of Illinois at Urbana-Champaign
1110 W. Green Street
Urbana, IL 61801

ABSTRACT

A rapidly rotating neutron star with a solid crust will have a rotationally induced oblateness that is constrained by the rigidity of the solid. It is shown that the effective triaxiality and the gravitational radiation output are small, in agreement with the very small $\dot{P}$ of PSR 1937+21.

I. INTRODUCTION

The discovery of the first millisecond pulsar PSR 1937+21 (Backer et al., 1982) presented a puzzle, since such a rapidly rotating pulsar would be expected to be very young and energetic while PSR 1937+21 showed none of the signs of activity associated with a conventional young pulsar. This suggested that the pulsar possessed a magnetic field that is substantially lower than the canonical 10^{12} Gauss magnetic fields inferred for the "ordinary" pulsars (Alpar et al., 1982, Radhakrishnan and Srinivasan, 1982). Scenarios for the formation of millisecond pulsars therefore sought to provide intrinsic associations of high rotation rates with magnetic fields low enough to compensate for these rapid rotation rates and give a low rate of energy loss to electromagnetic radiation. The subsequent measurement of $\dot{P} \simeq 1.05 \times 10^{-19}$ ss^{-1}, (Ashworth, Lyne and Smith, 1983, Backer, Kulkarni and Taylor, 1983, Backer, 1984) was in basic agreement with the theoretical predictions. This small value of $\dot{P}$, in conjunction with the rapid rotation rate, poses the analogous question for gravitational radiation: balancing the rate of energy loss to gravitational radiation against the rate of decrease of the rotational energy, one has, naively

$$I\Omega\dot{\Omega} = \frac{32}{5}\frac{G}{c^5} I^2 \varepsilon_{eff}^2 \Omega^6 \tag{1}$$

where I is the moment of inertia of the star, Ω its angular velocity and ε_{eff} is an effective triaxiality. Substituting the observed P and $\dot{P}$ in Eq. (1), one obtains an exceedingly small value for the maximum permissible value of ε_{eff}:

$$\varepsilon_{max} = 1.9\times10^{-9}\left(\frac{\dot{P}_{-19}}{I_{45}}\right)^{1/2} P(ms)^{3/2} \quad . \tag{2}$$

If ε_{eff} exceeded this limit, gravitational radiation alone would spin a millisecond pulsar down at a faster rate than the observed $\dot{P}$.

At first sight this constraint on the "gravitational" triaxiality of millisecond pulsars would seem to imply that gravitational radiation imposes a major constraint on their possible evolutionary scenarios, since as may be seen in Table I, the rotational oblateness $\varepsilon_\Omega \equiv I\Omega^2/4A$ of these pulsars is some 10^7 times larger than ε_{max}. In this talk we show that this is in fact not the case. More specifically, we demonstrate that the effective oblateness, ε_{eff}, which determines the gravitational radiation of a neutron star depends on three factors: its reference oblateness ε_o, the angle θ_o which measures the misalignment of its reference and rotational axes, and the ratio of the elastic energy coefficient to the gravitational energy coefficient associated with oblateness. When reasonable estimates of these quantities are made, $\varepsilon_{eff} << \varepsilon_{max}$. We therefore conclude that gravitational radiation is not likely to play a major role in the evolution of millisecond pulsars.

Table 1

Pulsar	1937+21	1953+29	1913+16	0820+02	0655+64	"Ordinary"
P(ms)	1.6	6.1	59	865	196	200
$\dot{P}(10^{-19} ss^{-1})$	1.05*	7.8†	86	10^3	< 10‡	10^5
$\varepsilon_{ff}(I_{45}^{-1/2})$	3.8×10^{-9}	8×10^{-8}	8×10^{-6}	1.5×10^{-3}	$< 1.6\times10^{-5}$	1.7×10^{-3}
$\varepsilon_o(I_{45}/A_{53})$	4.1×10^{-2}	2.7×10^{-3}	2.8×10^{-5}	1.3×10^{-7}	2.5×10^{-6}	2.5×10^{-6}

* Backer (1984).
† Scaling as $P^{4/3}$ from the observed value for PSR 1937+21. The current observational upper limit is $\dot{P} < 4.2 \times 10^{-17}$ ss^{-1} (Boriakoff, 1984).
‡ Current upper limit (Lyne, 1984).

II. EFFECTIVE TRIAXIALITY FOR GRAVITATIONAL RADIATION FROM A SOLID CRUST NEUTRON STAR

We make the plausible assumption that a neutron star's shape is determined by the shape of its solid crust, any outermost fluid layers having a negligible effect. The moment of inertia tensor of a neutron star with a solid crust is:

$$\overleftrightarrow{I} = I_o\left[\left(1 - \frac{\varepsilon_\Omega}{2} - \frac{b\varepsilon_o}{2}\right)\overleftrightarrow{e} + \frac{3}{2}\varepsilon_\Omega\hat{n}_\Omega\hat{n}_\Omega + \frac{3}{2}b\varepsilon_o\hat{n}_o\hat{n}_o\right] \tag{3}$$

where I_o is the moment of inertia in the spherical case (no rotation), ε_Ω the "rotational oblateness" and ε_o the reference oblateness of the solid crust. b is a coefficient describing the rigidity of the solid. $\hat{n}_o$ and $\hat{n}_\Omega$ are unit vectors along the reference axis and the instantaneous angular velocity vector $\vec{\Omega}$ and $\overleftrightarrow{e}$ the unit tensor (Pines and Shaham, 1972a). We defer a discussion of the values of b, ε_Ω and ε_o to Section III. Here we note only that the triaxiality of $\overleftrightarrow{I}$ stems from b, the rigidity of the solid. The corresponding fluid star (b=0) would have an axially symmetric equilibrium shape.[1]

First note that the $\hat{n}_\Omega \hat{n}_\Omega$ term in $\overleftrightarrow{I}$ acts like the unit tensor $\overleftrightarrow{e}$ on the $\vec{\Omega}$ vector. The kinetic energy T then has the same form as that of a symmetric top with symmetry axis $\hat{n}_o$:

$$T = \frac{1}{2} I_o\left[(1+\varepsilon_\Omega+b\varepsilon_o)\Omega_3^2 + (1+\varepsilon_\Omega - \frac{b\varepsilon_o}{2})\Omega_1^2 + (1+\varepsilon_\Omega - \frac{b\varepsilon_o}{2})\Omega_2^2\right] \qquad (4)$$

where Ω_3 is the component of $\vec{\Omega}$ along $\hat{n}_o$. Then $\hat{n}_o$, $\vec{\Omega}$ and the angular momentum $\vec{L}$ all lie in a plane, which precesses about the fixed $\vec{L}$ axis, with a precession frequency in the non-rotating frame given by

$$\Omega_{pr} = \frac{L}{I_1} = \frac{L}{I_o}\left(1 - \varepsilon_\Omega + \frac{b\varepsilon_o}{2}\right) \approx \Omega\left(1 + \frac{3b\varepsilon_o}{2}\cos^2\theta_o\right) , \qquad (5)$$

on expanding to lowest order in the last equality. Thus we have a truly triaxial body, which acts dynamically like a symmetric top because the rotationally induced contribution to the non-sphericity of $\overleftrightarrow{I}$ has $\vec{\Omega}$ itself as a symmetry axis. To diagonalize $\overleftrightarrow{I}$, a rotation in the $\vec{L},\vec{\Omega}$ plane is required. Since the two independent vectors $\hat{n}_o$ and $\hat{n}_\Omega$ lie in this plane, so do two principal axes, $\hat{n}_1$ and $\hat{m}_1$, of the moment of inertia. Thus, the $\vec{L},\vec{\Omega}$ plane is a symmetry plane of the triaxial neutron star, which therefore precesses about $\vec{L}$ at the frequency Ω_{pr}.

The gravitational radiation power in a frequency ω is (Weinberg 1973):

$$P(\omega) = \frac{2G\omega^6}{5c^5}\left\{D^*_{ij}(\omega)D_{ij}(\omega) - \frac{1}{3}\left|D_{ii}(\omega)\right|^2\right\} \qquad (6)$$

where

$$D_{ij}(t) = \sum_{\omega>0} e^{-i\omega t}D_{ij}(\omega) + \text{complex conjugate} \qquad (7)$$

is the moment

$$\begin{aligned} D_{ij}(t) &= M(t)_{ia}M(t)_{jb}\int d^3x'x'_a x'_b\rho(x') \\ &= M(t)_{ia}M(t)_{jb}\left(\frac{TrI}{2}\,\delta_{ab}-I_{ab}\right) . \end{aligned} \qquad (8)$$

Here $\rho(x')$ is the mass density, $\vec{x}'$ is the position vector in the body frame which we take as the principal axes of $\overleftrightarrow{I}$, and M(t) is the instantaneous trans-

1 Wagoner (1984) finds that non-axially symmetric perturbations of a fluid neutron star can grow only at angular velocities 1.5–2 times faster than that of PSR 1937+21. Friedman (1983) finds that nonaxial perturbations are stable at P ≈ 1.5 ms for some equations of state; this result, however, rests on the assumption that the viscosity is that appropriate to a temperature $T \sim 10^{9}$ °K, a temperature far too high for the quite old millisecond pulsars. We thus conclude that the underlying fluid equilibrium shape is axially symmetric.

formation matrix from the body frame $\hat{m}_1(t), \hat{n}_1(t), \hat{m}_1(t) x \hat{n}_1(t)$ to a fixed frame, whose $\hat{x}_3$ axis we choose to be parallel to $\vec{L}$. The geometry is shown in the figure. The gravitational radiation comes out in the frequencies Ω_{pr} and $2\Omega_{pr}$. Note that for a beam fixed in the triaxial body of the star, the observed pulsar frequency is also Ω_{pr}, since the $\vec{L}\vec{\Omega}$ plane which precesses about $\vec{L}$ is a symmetry plane of the star. First diagonalizing $\overleftrightarrow{I}$ to find $\hat{m}_1(t), \hat{n}_1(t), \hat{m}_1(t) x \hat{n}_1(t)$ and thus the matrix M(t), we find from Eqs. (3)-(8), the output power, to lowest order in $b\varepsilon_o$ and $b\varepsilon_o/\varepsilon_\Omega$:

$$P(2\Omega_{pr}) \simeq \frac{72}{5} \frac{GI_o^2}{c^5} \Omega_{pr}^6 \; b^2 \varepsilon_o^2 \sin^4\theta_o \tag{9}$$

$$P(\Omega_{pr}) \simeq \frac{9}{10} \frac{GI_o^2}{c^5} \Omega_{pr}^6 \left(1 - \frac{3}{2}\varepsilon_\Omega\right)^2 b^2 \varepsilon_o^2 \cos^2\theta_o \sin^2\theta_o \quad . \tag{10}$$

Returning now to Eq. (1), we find that

$$\varepsilon_{eff}^2 = \left(\frac{3}{2} b\varepsilon_o \sin^2\theta_o\right)^2 + \left(\frac{3}{8} b\varepsilon_o\left(1 - \frac{3}{2}\varepsilon_\Omega\right) \cos\theta_o \sin\theta_o\right)^2 \tag{11}$$

III. ε_{eff} FOR MILLISECOND PULSARS

We now turn to consider the values of b, ε_o and θ_o for a millisecond pulsar that has been spun up by accretion, and has been spinning down as a pulsar since the end of the accretion phase.

The Rigidity b

The coefficient b in Eq. (3) is a ratio of an elastic energy coefficient, B, and a gravitational energy coefficient A for an oblate neutron star with a solid component:

$$b \equiv \frac{B}{A+B} \quad . \tag{12}$$

More precisely, a solid with oblateness ε and reference oblateness ε_o has an elastic energy $B(\varepsilon-\varepsilon_o)^2$ while the oblateness increases the gravitational potential energy by an amount $A\varepsilon^2$ above the gravitational energy of a spherical star of the same mass. Pandharipande, Pines and Smith (1976) have calculated A and B for a variety of neutron star models of different mass, and employing several different equations of state. Typical values of B and A imply

$$b \sim 10^{-5} \quad . \tag{13}$$

The Reference Oblateness ε_o

The quantity ε_Ω in Eq. (3) is the equilibrium oblateness of a fluid body rotating at angular velocity Ω:

$$\varepsilon_\Omega \equiv \frac{I_o \Omega^2}{4A} \quad . \tag{14}$$

The reference oblateness ε_o is defined as the oblateness of the star at the time of formation of its solid crust, modified subsequently according to its seismic history, through plastic flow or starquakes (Ruderman, 1969, Baym and Pines, 1971). If we make the conservative assumption that a typical neutron star spun up by accretion has, at the time of crust solidification, a period $\sim$ 1 sec, the initial value of the reference oblateness is:

$$\varepsilon_o(0) \approx \frac{I_o \Omega_o^2}{4A} \sim 10^{-6} \quad . \tag{15}$$

If we neglect plastic flow associated with the logarithmic creep of dislocations in the crust (Baym and Pines, 1971), ε_o will change only through starquakes, which take place when

$$|\varepsilon_\Omega - \varepsilon_o| \approx \theta_m \tag{16}$$

where θ_m is the critical strain angle of the solid crust. $\theta_m \sim 10^{-4}$-10^{-5} for typical terrestrial metals, while for a pure Coulomb lattice, which may be a better approximation to the neutron star crust, $\theta_m \sim 10^{-1}$-10^{-2} (Smoluchowski, 1970). We consider various possibilities for the evolution of ε_o:

(i) $\theta_m \sim 10^{-4}$

In this case, ε_o follows the accretion spin-up and the subsequent pulsar spin down by a series of quakes, starting at a time when $\varepsilon_\Omega \sim 10^{-4}$, $\varepsilon_o \sim 10^{-6}$, to its current value

$$\varepsilon_o \cong \varepsilon_\Omega \approx 10^{-1} \qquad \text{(PSR 1937+21, currently)} \tag{17}$$

within $\theta_m \sim 10^{-4}$ of ε_Ω. Even if the reference oblateness ε_o was also effected by solidification of accreted material, the conclusion (17) would not change, since the smallness of the critical angle θ_m and the consequent large number of quakes during the $\sim 10^8$ yr. accretion era, and the comparably long pulsar era that follows it, will bring the final ε_o close to ε_Ω.

(ii) $\theta_m \sim 10^{-1}$

In this case, the reference oblateness ε_o may keep its initial value of $\sim 10^{-6}$ through the entire spin-up era, without reaching the condition (16) for quakes. The subsequent decrease of ε_Ω during spin-down as a pulsar will decrease the difference $\varepsilon_\Omega - \varepsilon_o$; hence the current reference oblateness is:

$$\varepsilon_o \approx \varepsilon_o(0) \sim 10^{-6} \quad . \tag{18}$$

For large critical angle, $\theta_m \sim 10^{-1}$, one might consider the possibility that ε_o grows by solidification of accreted material in a way that does not follow the evolution of ε_Ω. We note, however, that the magnetic field that channels the distribution of accreted material plays a negligible role in the equilibrium energy balance on the star's surface in comparison to rotation:

$$\eta \equiv \frac{B^2}{8\pi} \frac{\frac{4\pi}{3} R^3}{I_o \Omega^2} \simeq \begin{cases} 4 \times 10^{-6} & (B = 10^{12} G, \ P=1s) \\ 10^{-19} & (B = 10^{8} G, \ P=1.5ms) \end{cases} \tag{19}$$

Furthermore, although the total amount of matter accreted is $\sim 0.1\ M_\odot$, , it is unlikely that this can adhere, in a metastable way, to the magnetic-field-accretion geometry and solidify to change ε_o on timescales as long as the accretion time $\sim 10^8$ yrs: The temperature of the accreted matter is in the x-ray range through this era, so diffusion and plastic flow timescales are likely to be much shorter than 10^8 years.

<u>The Angle θ_o Between $\hat{n}_o$ and $\hat{n}_\Omega$</u>

The angle between $\hat{n}_o$ and $\hat{n}_\Omega$ can also change through quakes. Pines and Shaham (1972b) have shown that the critical value of θ_o for such a "θ-quake" is reached when:

$$3\varepsilon_\Omega \varepsilon_o \ \theta_o^2 \simeq \theta_m^2 \tag{20}$$

(note that our θ_o is $(\theta-\theta_o)$ in the notation of Pines and Shaham, 1972b). Again, we consider the different possibilities, depending on θ_m:

(i) $\theta_m \sim 10^{-4}$, $\varepsilon_o \simeq \varepsilon_\Omega \sim 10^{-1}$

In this case, the critical value of θ_o given by Eq. (21) is $\sim 10^{-3}$. Thus, a crust with a small critical angle cannot sustain any misalignment between $\hat{n}_o$ and $\hat{n}_\Omega$ greater than about 10^{-3} radians. $\theta_o \simeq 0$ at initial solidification, and cannot exceed $\sim 10^{-3}$ through the star's history.

(ii) $\theta_m \sim 10^{-1}$, $\varepsilon_\Omega \simeq 10^{-1}$, $\varepsilon_o \simeq 10^{-6}$

In this case, Eq. (21) imposes no bounds on θ_o: starting at $\theta_o \simeq 0$ at solidification, θ_o could in principle grow arbitrarily without inducing a "θ-quake" in such a strong crust. However, one needs an evolutionary reason for a secular increase of θ_o, and the only candidate, solidification of accreted material persisting through the 10^8 year accretion phase, is ruled out by the considerations outlined above in connection with the related question of the evolution of ε_o for a $\theta_m \sim 0.1$ crust.

<u>The Expected Value of ε_{eff}</u>

We thus conclude that the effective triaxiality ε_{eff} in Eq. (11) is:

(i) $\varepsilon_{eff} \simeq \frac{3}{8} b\varepsilon_o\theta_o \simeq \frac{3}{8} \times 10^{-5} \times 10^{-1} \times 10^{-3} \simeq 4 \times 10^{-10}$, if $\theta_m \sim 10^{-4}$

(21)

(ii) $\varepsilon_{eff} \simeq b\varepsilon_o \simeq 10^{-5} \times 10^{-6} \simeq 10^{-11}$, if $\theta_m \sim 10^{-1}$, (22)

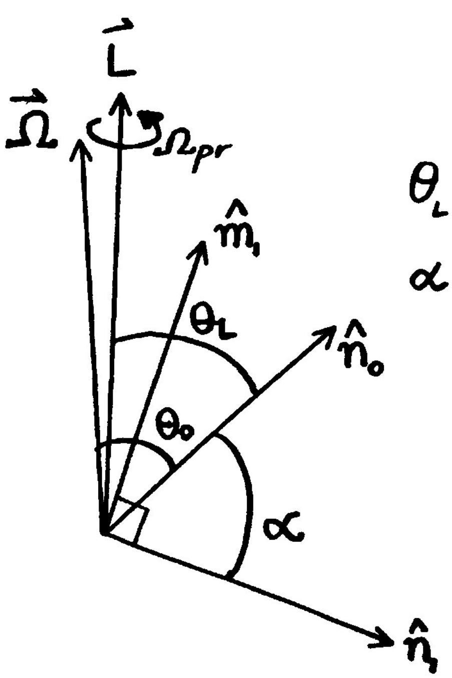
so that gravitational radiation poses no problem for the observed $\dot{P}$ values of millisecond pulsars.

ACKNOWLEDGMENTS

We thank Fred Lamb and Naoki Iwamoto for bringing this problem to our attention, Mal Ruderman and Jacob Shaham for useful discussions, and Jim Applegate and Roger Blandford for pointing out an error in our initial calculations. This research was supported by the research grants NSF PHY80-25605, NASA NSG-7653.

REFERENCES

Alpar, M. A., Cheng, A. F., Ruderman, M. A., and Shaham, J. 1982, Nature, **300**, 728.
Ashworth, M., Lyne, A. G., and Smith, F. G. 1983, Nature, **301**, 313.
Backer, D. C. 1984, these proceedings.
Backer, D. C., Kulkarni, R. S., Heiles, C., Davis, M. M., and Goss, W. M. 1982, Nature, **300**, 615.
Backer, D. C., Kulkarni, S. R., and Taylor, J. H. 1983, Nature, **301**, 314.
Baym, G., and Pines, D. 1971, Ann. Phys., **66**, 816.
Boriakoff, V. 1984, these proceedings.
Friedman, J. L. 1983, Phys. Rev. Lett., **51**, 11.
Landau, L. D., and Lifshitz, E. M. "Mechanics," Chapter VI.
Lyne, A. G. 1984, these proceedings.
Pandharipande, V. R., Pines, D., and Smith, R. A. 1976, Ap. J., **208**, 550.
Pines, D., and Shaham, J. 1972, Phys. Earth Planet. Interiors, **6**, 103.
Pines, D., and Shaham, J. 1972b, Nature Phys. Sci., **235**, 43.
Radhakrishnan, V., and Srinivasan, G. 1982, Current Science, **51**, 1096.
Ruderman, M. 1969, Nature, **223**, 597.
Smoluchowski, R. 1970, Phys. Rev. Lett., 24, 923.
Wagoner, R. V. 1984, Ap. J. **278**, 345.
Weinberg, S. "Gravitation and Cosmology," Chapter 10.



$$\theta_L = \theta_0 (1 - O(b\varepsilon_0))$$

$$\alpha = \frac{\pi}{2} - \theta_0 \left(1 - O\left(b\frac{\varepsilon_0}{\varepsilon_A}\right)\right)$$

The reference plane containing $\vec{L}$, $\vec{\Omega}$, $\hat{n}_0$ and the principal axes $\hat{m}_1$ and $\hat{n}_1$ of the triaxial solid crust neutron star. This plane precesses at the rate Ω_{pr} around the angular momentum axis $\vec{L}$.

DISCUSSION OF ALPAR'S PAPER

RUDERMAN: If you assume, contrary to the current fashion, that millisecond pulsars have weak surface magnetic fields but large buried magnetic fields, say of order 10^{12} gauss beneath the surface, and if that's a superconductor so you have flux tubes, you can get rather large strains induced by buried magnetic field. Most of that would be disguised if you had a homogeneous star--you wouldn't care what was buried--but this isn't homogeneous. So I'm really asking, can one say anything about the possible magnitude of buried magnetic fields in millisecond pulsars, because of the lack of gravitational radiation?

ALPAR: That depends on how the magnetic stresses compare to other strains.

RUDERMAN: But if you had 10^{12} gauss field distributed in 10^{16} gauss flux tubes, buried inside the millisecond pulsar...

ALPAR: So you are talking about local stresses, where the flux runs through. Then that might be a problem.

RUDERMAN: Just another way of getting triaxiality.

PINES: This precession is not the Chandler wobble.

SHAHAM: No, this _is_ the Chandler wobble.

PINES: No, this is the rotational frequency slightly modified by the triaxiality which is effective for gravitational radiation. Gravitational radiation does not come out at the wobble frequency.

APPLEGATE: I'm a little confused about why you were concentrating on precession. Just when this thing was discussed, when it had the large $\dot{P}$, Roger Blandford and I did just this sum. (We later found the problem done in Shapiro and Teukolsky and were pleased to find we'd got it right.) We calculated the precession would actually damp out rather quickly by gravitational radiation and you'd be left with a triaxial body rotating about one of its principal axes, and that was the long-lived source of gravitational radiation. If you then tried to estimate how nonaxisymmetric the crust could be by crustal strain, and you put it equal to the maximum that you could have assuming a strain angle of I think 10^{-2}, we got that we could explain a $\dot{P}$ of 10^{-15}. But it seems to me that in fact the precession is going to damp out fairly quickly.

PINES: You and Roger did the first part of your homework correctly, but the second part is a gross overestimate.

APPLEGATE: Oh, that's because we took the maximum amount of triaxiality the crust could support. The star is actually much more axisymmetric.

On the Secular Stability of Rotating Stars

James N. Imamura
Los Alamos National Laboratory, Los Alamos, NM 87545

John L. Friedman
University of Wisconsin, Milwaukee, WI 53201

Richard H. Durisen
Indiana University, Bloomington, IN 47405

Introduction

Our understanding of secular instabilities driven by gravitational radiation reaction (GRR) in rapidly rotating stars has greatly improved because of recent advances in Lagrangian variational techniques. (Here "secular instability" means an instability which grows on a dissipative time scale rather than on a dynamical one.) Using this technique, Friedman and Schutz (1978) have shown that <u>all</u> rotating, self-gravitating fluid equilibrium states are secularly unstable to nonaxisymmetric ($\xi \propto \exp(im\phi)$) GRR driven instabilities. Slowly rotating fluids are unstable to large m modes. In general, this "generic" instability has growth times τ_g which are very long. The τ_g are strong functions of the density of the fluid ρ and the wave number m of the mode. They increase as ρ decreases and as m increases. For solar density stars, the τ_g for all modes are much greater than all other relevant evolutionary time scales. Only for rapidly rotating white dwarfs (m = 2 mode) and neutron stars (m < 7 modes) are the τ_g small enough to make the instability physically important. Furthermore, even in these cases, GRR driven instabilities may not be effective. Work by Lindblom and Detweiler (1977) on the m = 2 mode of the Maclaurin spheroids, by Comins (1979a,b) on the general m modes of the Maclaurin spheroids, and by Lindblom and Hiscock (1983) on imperfect relativistic stars has shown that, when the dissipation due to viscosity is comparable to the energy loss due to gravitational radiation, viscosity damps the instability. In rapidly rotating neutron stars, viscosity damps modes with m > 5 (as shown later) allowing modes with m less than 5 to grow. It has been suggested that these low order GRR driven instabilities could determine the frequency of the millisecond pulsar (Fabian <u>et al.</u> 1983; Friedman 1983; Wagoner 1984). As such, the stability limits of the low order GRR driven modes are of interest.

In this work, we calculate the secular stability limits of rotating polytropes to nonaxisymmetric perturbations of low m. We consider polytropic indices ranging from 1 to 3 and several angular momentum distributions. Results are most conveniently presented in terms of the t-parameter, defined as the ratio of the rotational kinetic energy to the absolute value of the gravitational energy of the fluid. Previous work on polytropes considered only the m = 2 mode, which is unstable for values of the t-parameter greater than 0.14 ± 0.01 for the n values n = 1.5 and 3 and the angular momentum distributions tested (see Durisen and Imamura 1981). The GRR secular stability limit of the m = 2 mode for the Maclaurin spheroids (n = 0) was determined by Chandrasekhar (1970). GRR stability limits of higher m modes for the Maclaurin spheroids were located approximately by Comins (1979a,b) and more precisely by Friedman (1983).

Calculations

The equilibrium models are calculated using the polytrope version (Bodenheimer and Ostriker 1973) of the Ostriker and Mark (1968) self-consistent field code. Because $P \propto \rho^{\gamma}$, the equilibrium models rotate on cylinders and are specified by $\gamma = 1 + 1/n$, the total angular momentum, and the specific angular momentum distribution $j(m_s)$. Here m_s is the mass contained within a cylinder of radius s centered on the rotation axis. We consider the angular momentum distributions $j(m_s)$ of: (1) uniformly rotating spherical polytropes of indices n' (see Bodenheimer and Ostriker 1973); (2) polytropes which rotate such that $j(m_s) \propto m_s$; and (3) polytropes which rotate uniformly. Case (1) distributions concentrate more angular momentum near the surface of the star than do case (2) distributions. Further, in case (1) distributions, the higher n' distributions concentrate more angular momentum near the surface of the star than do the lower n' distributions.

The stability limits are calculated using the Lagrangian variational formalism developed by Bardeen et al. (1977) and Friedman and Schutz (1978) and the numerical techniques of Durisen and Imamura (1981). The variational principle provides limits on secular stability at points in a sequence of rotating models where the perturbed canonical energy changes sign. As noted earlier, the improved variational technique corrects the deficiencies of the tensor virial equation (TVE) method of Tassoul and Ostriker (1968) which had been extensively used to calculate the secular stability limits of rotating polytropes and white dwarfs. The TVE method is only valid for uniform rotation (UR). It fails for differentially rotating fluids because the eigenfunction implicit in the technique violates Kelvin's circulation theorem. This has the effect of producing perturbations for which the Eulerian variations of the physical variables are equal to zero but which, nonetheless, change the perturbed canonical energy. As a result, they affect the stability analysis while not changing the structure of the fluid. To overcome this difficulty, Bardeen et al. suggested a modified trial eigenfunction which is forced to obey Kelvin's circulation theorem and yet is qualitatively similar to the TVE one in the sense that the Eulerian perturbation of the surface densities due to each eigenfunction are equal. Because of the arbitrariness in the definition of the eigenfunction, limits derived using the Bardeen et al. prescription only yield sufficient conditions for instability. We test the Bardeen et al. formulation, in some cases, by dropping the constraint that the eigenfunctions be qualitatively similar to the TVE ones. To the accuracy of our calculations, we find that variations of the eigenfunction do not lead to stability limits which are more stringent than those found using the Bardeen et al. prescription.

Results

The secular stability limits for polytropes of indices n = 1, 1.5, and 3 and the angular momentum distributions $n' = 0$ and 1.5 and $j(m_s) \propto m_s$ are presented in Table 1, and the uniform rotation results are presented in Table 2. In Table 1, the mode numbers m are given in the first column and the critical values of the t-parameter for the various polytropic indices and $j(m_s)$ distributions are given in columns 2 through 5. The three listings in each n column are the stability limits in terms of the t-parameter for $j(m_s) \propto m_s$, $n' = 0$, and $n' = 1.5$, reading downwards. The format of Table 2 is similar to that of Table 1. The results for n = 0 are taken from Friedman (1983).

Table 1

Stability Limits for Differentially Rotating Polytropes

m	n=0[1]	n=1	n=1.5	n=3
		0.142	0.142	0.147
2	0.138	0.139	0.140	0.144
		0.137	0.137	0.135
		0.114	0.117	0.129
3	0.0991	0.101	0.104	0.114
		0.0830	0.0817	0.0845
		0.0962	0.101	0.119
4	0.0771	0.0808	0.0825	0.0960
		0.0568	0.0554	0.0565
		0.0840	0.0889	0.110
5	0.0629	0.0664	0.0705	0.0840
		0.0424	0.0407	0.0420

[1]the n = 0 results are taken from Friedman (1983)

Table 2

Stability Limits for Uniformly Rotating Polytropes

m	n=0[1]	n=1	n=1.5	n=3
2	0.138	....	....	....
3	0.0991	0.0848	....	....
4	0.0771	0.0610	0.0502	....
5	0.0629	0.0470	0.0376	....

[1]the n = 0 results are taken from Friedman (1983)

In contrast to the m = 2 mode, the stability limits for the m > 2 modes are functions of the polytropic index and the angular momentum distribution. The qualitative behavior of the stability limits (in terms of the t-parameter) is: (1) to decrease as $j(m_s)$ becomes more peaked near the surface of the star for a given n; and (2) to decrease as n increases if $n \lesssim n'$, and to increase as n increases if $n \gtrsim n'$. For UR, the stability limits occur at smaller values of t than for the Maclaurin sequence ($n=0, n'=0$). This behavior is important because it means that Maclaurin spheroid results for m > 2 cannot be indiscriminantly applied to compressible fluids. The secular stability limits must be determined separately for each equation of state and angular momentum distribution.

The stability limits (in terms of the t-parameter) decrease as m increases. That is, the onset of instability of successively higher m modes occurs at successively lower values of t. However, as noted earlier, because the growth times also increase as m increases, the high order modes are usually physically unimportant.

A point of interest concerns UR polytropes. It is well-known that, if $n > 0.808$, a UR polytrope cannot reach t = 0.14 before it attains break-up velocity at its equator and so never becomes secularly unstable to the m = 2 mode. However, because the onset of instability of the higher m modes occurs for lower values of t, all UR polytropes (as long as an equilibrium model is possible) are subject to GRR driven secular instabilities for some m. For $n \lesssim 1$, all modes with m greater than 2 can be reached by a UR polytrope. Because the effective polytropic index of a neutron star lies in the range 0.5 to 1, UR neutron stars can easily reach low order secular instability points.

Discussion

The relevant modes for neutron stars can be determined by considering the various time scales of the important physical processes. First, consider τ_g. A rough estimate for τ_g can be made from the work of Comins (1979b). Based on Maclaurin spheroids, Comins showed that

$$\tau_g = \frac{(m-1)((2m+1)!!)^2}{(m+1)(m+2)(1-\varepsilon^2)^{0.5}} \left(\frac{c}{R\omega}\right)^{2m+1} \frac{\omega+(m-1)\Omega}{2\pi G\rho} \text{ seconds.}$$

Here c is the speed of light, ω is the frequency of the mode in the lab frame, Ω is the angular velocity of the star, R is the radius, ε is the eccentricity, and G is the gravitational constant. Friedman (1983) calculates that, for a 1.4 $M_\odot$ and R = 10 km star, τ_g = 10 s, 2×10^4 s, 6×10^7 s, and 2×10^{11} s, for the m = 2 through 5 modes, respectively. Because viscosity can damp GRR driven instabilities, its importance needs to be estimated. From Friedman (see also Comins 1979b),

$$\tau_\nu \simeq \frac{R^2}{(m-1)(2m+1)\nu} \text{ seconds.}$$

Friedman estimates that the viscous coefficient ν is between 1 and 10^2 cm^2 g^{-1} in a neutron star. This gives $\tau_\nu < \tau_g$ for $m > 5$, and so viscosity stabilizes GRR driven instabilities for $m > 5$.

The stability limits for the m = 2, 3, and 4 modes found by us are not directly applicable to the millisecond pulsar because of their dependence on the compressibility of the fluid and $j(m_s)$. The correct values of t (and thus the limiting frequencies) must be determined by detailed calculations of rotating neutron stars. However, if neutron stars rotate uniformly and have effective polytropic indices in the range 0.5 to 1, we expect that their instability points are $t \simeq 0.08$ to 0.10 for the $m = 3$ mode and $t \simeq 0.06$ to 0.08 for the $m = 4$ mode. Our principal result, surprising in light of m = 2 mode calculations, is that stability limits for $m > 2$ modes are sensitive to the equation of state and angular momentum distribution.

Friedman et al. (1984) are currently examining the issue of the secular stability of neutron stars. They have constructed numerical models of relativistic rotating stars based on several proposed neutron star equations of state. They find that all UR neutron star sequences terminate between t = 0.09 and 0.12 showing that it is unlikely that neutron stars are secularly unstable to the m = 2 mode as has been claimed by Harding (1983), and Ray and Chitre (1983), but that higher order modes (m = 3 and 4) can be reached. They plan to perform a stability analysis similar to that described here. This will enable them to make direct comparisons between models, stability limits, and the millisecond pulsar.

This work was performed under the support of the National Science Foundation through grants PHY 84-41263 and AST 81-20367, and the United States Department of Energy.

References

Bardeen, J. et al. 1977, Ap. J. (Letters), 217, L49.
Bodenheimer, P., and Ostriker, J. P. 1973, Ap. J., 180, 159.
Chandrasekhar, S. 1970, Phys. Rev. Lett., 24, 611.
Comins, N. 1979a, M.N.R.A.S., 189, 233.
_____. 1979b, M.N.R.A.S., 189, 255.
Durisen, R. H., and Imamura, J. N. 1981, Ap. J., 243, 612.
Fabian, A. C. et al. 1983, Nature, 301, 222.
Friedman, J. L. 1983, Phys. Rev. Lett., 51, 11.
Friedman, J. L., and Schutz, B. F. 1978, Ap. J., 222, 281.
Friedman, J. L., Ipser, J., and Parker, L. 1984, Nature, submitted.
Harding, A. K. 1983, Nature, 303, 683.
Lindblom, L., and Detweiler, S. L. 1977, Ap. J., 211, 565.
Lindblom, L., and Hiscock, W. A. 1983, Ap. J., 267, 384.
Ostriker, J. P., and Mark, J. W.-K. 1968, Ap. J., 151, 1075.
Ray, A., and Chitre, S. M. 1983, Nature, 303, 409.
Tassoul, J. L., and Ostriker, J. P. 1968, Ap. J., 154, 613.
Wagoner, R. V. 1984, Ap. J. (Letters), in press.

DISCUSSION OF IMAMURA'S PAPER

VAN HORN: From your last graph, Jim, it looks as though you're excluding quite a large range of the soft equations of state.

IMAMURA: Right.

GOODMAN: How deep do the eigenfrequencies extend in your fluid star, say for $m = 3$?

IMAMURA: In principle, they go all the way to the center. But they're really concentrated near the surface, and they're more concentrated the higher m is.

GOODMAN: But won't the crust affect things radically?

IMAMURA: I think the $m = 3$ mode probably has a chance. It will limit the amplitude, for sure. That's a sort of a soft spot.

APPLEGATE: To what extent are these calculations general relativistic?

IMAMURA: They're general relativistic in the sense that the variational form included gravitational radiation. But our models are Newtonian fluids. John Friedman's calculations are general relativistic. They calculate uniformly rotating relativistic stars.

ALPAR: What kinds of temperatures do you use for the viscous dissipation times?

IMAMURA: Those times are a tenth of a microsecond--

PINES: You're assuming the stars are formed hot. That would not apply to the Alpar-Ruderman-Shaham stars, which formed rotating slowly and spin up when they're rather cold.

IMAMURA: The estimates for the viscous time scales correspond to rather hot temperatures.

ALPAR: So if the neutron star is cold you will stabilize at higher frequencies.

IMAMURA: I don't think so; if you look at the plot, it doesn't matter what $T/|W|$ seems to be. Once you get above about 0.02, these curves are becoming vertical.

ALPAR: Those viscous times will get shorter.

IMAMURA: Sure, but they're just going to damp out the higher-order modes. The different order modes aren't going to lead to different limiting frequencies. And for stiff equations of state they all seem to fall around 600 Hz.

THE BIRTH AND SLOW EVOLUTION OF FIZZLERS

J. E. Tohline

Department of Physics and Astronomy
Louisiana State University, Baton Rouge, LA 70803

ABSTRACT

If the initial ratio of rotational to gravitational energy β_o in the core of a highly evolved, massive star is $\beta_o >$ "β_{min}", the core will not collapse all the way to neutron star densities. Centrifugal forces will stabilize the object at sub-nuclear densities and a fizzler--not a pulsar--will be formed. A simple model governing global energy balance in these objects is used to predict what the critical value β_{min} for stellar cores is. It is very sensitive to the equation of state of matter at densities below nuclear density. A value $\beta_{min} \approx 10^{-2}$ may be realistic. Simulating a hot core collapse, we show that fizzlers having $\beta \approx 0.20$ are expected to form. These objects should contract slowly (nondynamically) as they cool or as they lose angular momentum by magnetic dipole radiation or gravitational wave radiation. They should often evolve to neutron star structures with rotation periods ~ 1 ms.

INTRODUCTION

The discovery of millisecond pulsars (Backer et al. 1982; Boriakoff, Buccheri, and Fauci 1983) has rekindled interest in the question of how rotation effects the late stages of evolution of massive stars. Can the collapse of a stellar core directly produce a neutron star whose rotation period is as short as 1 ms? If it can, then one mechanism for forming millisecond pulsars may be a direct one, as proposed by Brecher and Chanmugam (1983) and Arons (1983).

Only a very narrow range of initial rotation rates in a core can, on a dynamical time scale, directly produce a neutron star whose rotation period is ~ 1 ms. However, a wide range of initial conditions will produce objects called fizzlers (Shapiro and Lightman 1976) that are dynamically stable at subnuclear densities and that should, upon subsequent slow contraction, evolve to a rapidly rotating neutron star structure. If millisecond pulsars are to be formed with angular momenta derived directly from the fossil momenta of stellar cores, fizzlers must play an important role in this formation process. Tohline (1984; hereafter Paper I) has recently analyzed the collapse of rotating stellar cores using a simple model to describe fizzlers. This work will be discussed and extended here in an attempt to shed light on the problem of the direct formation of millisecond pulsars.

BASIC CONCERNS

When studying the nonrotating evolution of stellar cores, dynamical collapse toward neutron star densities can be initiated once the effective adiabatic exponent Γ of the core material drops below the value 4/3 (ignoring general relativistic effects; cf. Baym, Pethick, and Sutherland 1971). Dynamical collapse is not arrested until the core reaches nuclear densities, at which time the equation of state stiffens--that is, Γ rises to a value greater than 4/3. When rotation is included, however, the collapse can be stopped before nuclear densities are reached (LeBlanc and Wilson 1970; Müller, Różyczka, and Hillebrandt 1980; Müller and Hillebrandt 1981). This is because when rotation is included, $\Gamma > 4/3$ is no longer the criterion that governs the global stability of a self-gravitating, compressible gas. Instead, the critical value of Γ, Γ_c, below which dynamical collapse will occur takes on a value less than 4/3. The quantity Γ_c decreases monotonically as the value of β increases in an equilibrium spheroid, where

$$\beta \equiv \text{Rotational Kinetic Energy}/|\text{Gravitational Potential Energy}| .$$

The parameter β is sometimes called "$T/|W|$" and is equal to $\omega^2/(4\pi G\rho)$ in a sphere of uniform density ρ and uniform angular velocity ω. Ledoux (1945) has derived an expression for $\Gamma_c(\beta)$ for spherical structures and Chandrasekhar and Lebovitz (1962) have calculated $\Gamma_c(\beta)$ for uniform-density, compressible spheroids (see Figure 3 of Paper I). For $\beta \ll 1$, $\Gamma_c \approx 4/3 - 2\beta/3$.

If $\Gamma = 4/3 - \varepsilon$ in a stellar core, even a small amount of rotation, $\beta > 3\varepsilon/2$, will prevent the core from collapsing. Furthermore, since β must increase during a stage of compression (assuming conservation of angular momentum) once collapse is initiated, the stellar core can sometimes acquire a rotationally stabilized configuration before reaching nuclear densities. In these cases, the collapse "fizzles," not directly producing a neutron star/pulsar (Shapiro and Lightman 1976).

The frequency with which fizzlers form, and the value of β that they possess, depends critically on what the value of Γ is. Hence studies of the equation of state of hot core material during collapse are vital to our understanding of the formation of rapidly rotating neutron stars.

A SIMPLE MODEL

In the following model of rotating stellar cores, only Newtonian gravity has been incorporated. For most of the fizzler structures considered, the effect of general relativity (GR) on dynamical stability is small. Refinements to this model should include GR in order to more accurately specify the functions $\Gamma_c(\beta)$ and $\beta_{min}(\Gamma)$ defined below.

Let α be the absolute value of the ratio of thermal energy to gravitational potential energy in a stellar core. According to the virial theorem, an equilibrium configuration can exist only when

$$\alpha + \beta = 1/2 \quad . \tag{1}$$

(Here, surface pressure has been neglected.) Furthermore, as described above, the equilibrium will be dynamically stable only if

$$\Gamma > \Gamma_c(\beta) \quad . \tag{2}$$

Denoting initial values of core parameters by the subscript zero, core collapse will be initiated when either (a) Γ_o decreases to a value $\Gamma_o < \Gamma_c(\beta_o)$ or (b) one of the two quantities α_o, β_o decreases such that $\alpha_o + \beta_o < 1/2$.

During a phase of compression, the parameters α and β can be related to their initial values in a fairly straightforward manner. Using the model of Paper I, one finds that for a constant value of Γ,

$$\alpha\beta^{4-3\Gamma} \left[(\sin^{-1} e)/e\right]^{5-3\Gamma} (1-e^2)^{(\Gamma-1)/2} = \text{constant} \tag{3}$$

during a homologous collapse when angular momentum is conserved. In order to derive this expression, the assumption has been made that the eccentricity e of the oblate spheroidal core is at all times directly related to the value of β in the core through the analytic relation that governs flattening in a Maclaurin spheroid (see Paper I for a justification). The simultaneous solution of equation (1), equation (3), and the Maclaurin spheroid relation between e and β defines the equilibrium configuration to which a stellar core must evolve if Γ remains constant during collapse. In general, for $\Gamma < 4/3$, the equations permit two solutions, but only one is a dynamically stable configuration as specified by relation (2).

GENERAL RESULTS

Figure 1 shows what $\beta = \beta_{final}$ must be in stellar cores that are compressed at fixed values of Γ. Each solid line in the figure is <u>not</u> an evolutionary track but, instead, shows β_{final} for many different values of β_o. In order to obtain these results, collapse was initiated according to condition (a) above; $\alpha_o = 1/2 - \beta_o$. The upper envelope to all curves is the curve $\beta_{final} = \beta_o$. The point at which a curve of fixed Γ intersects this envelope defines the critical value of β_o, β_c, <u>above</u> which no collapse occurs at all. That is, the intersection point occurs where $\Gamma = \Gamma_c(\beta_o)$. Also, for any Γ, $\beta_{final} > \beta_c$. So, for example, if $\Gamma = 1.20$ during core collapse, since $\beta_c \approx 0.16$, all fizzlers must be formed with $\beta_{final} > 0.16$.

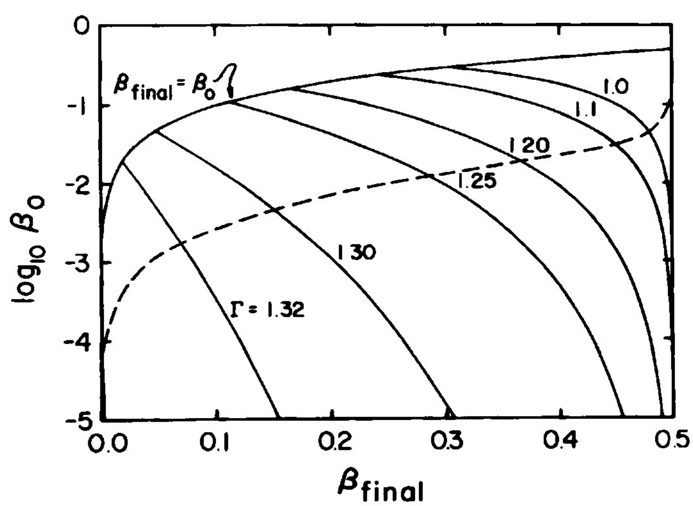


Fig. 1—The value of β_{final} at the end of collapse is shown for various β_o and Γ, where Γ is assumed to be held constant during collapse. Solid curves show results for fixed values of Γ, varying β_o. The dashed curve shows, for each β_o, when $\rho_{final}/\rho_o = 10^5$.

On the other hand, if $\Gamma = 1.32$ during collapse, fizzlers can form with β_{final} as small as 0.02.

Using the model of Paper I, there is a unique relationship between the ratio ρ_{final}/ρ_o of final to initial core density and the ratio β_{final}/β_o. The dashed curve in Figure 1 defines the locus of points for which $\rho_{final}/\rho_o = 10^5$. Since core collapse is usually initiated at a central density $\rho_o \sim 4 \times 10^9$ g cm^{-3} and nuclear density occurs near 4×10^{14} g cm^{-3}, the region between the dashed curve and the upper envelope in Figure 1 locates the parameter space in which fizzlers should exist. For a chosen value of Γ, the intersection of the solid curve with the dashed curve in Figure 1 identifies two important physical parameters: (1) The minimum value β_{min} of a stellar core that will produce a fizzler (any $\beta_o < \beta_{min}$ will allow direct collapse to a neutron star). (2) The maximum value of β_{final} that fizzlers (and directly formed neutron stars) should possess.

HOT CORE COLLAPSE

The above results were obtained assuming a fixed value for Γ during collapse. The model has also been generalized to investigate spheroidal compression along any variable adiabat. Figure 2 shows the results of core collapses which follow one specific $\Gamma(\rho)$ function taken from the work of Van Riper and Lattimer (1981; hereafter VRL). The chosen $\Gamma(\rho)$ approximates the Γ_H curve that VRL calculated during a spherical collapse in which radiation/neutrino transport was properly computed and in which a detailed equation of state for hot core material (optical depth multiplier b = 10) was included. The curve marked d = 1.00 was obtained, as in Fig. 1, using the initial condition $\alpha_o = 1/2 - \beta_o$. The other two curves (d = 0.95 and 0.90) show the effect of introducing a pressure deficit at the onset of collapse: $\alpha_o = d(1/2 - \beta_o)$.

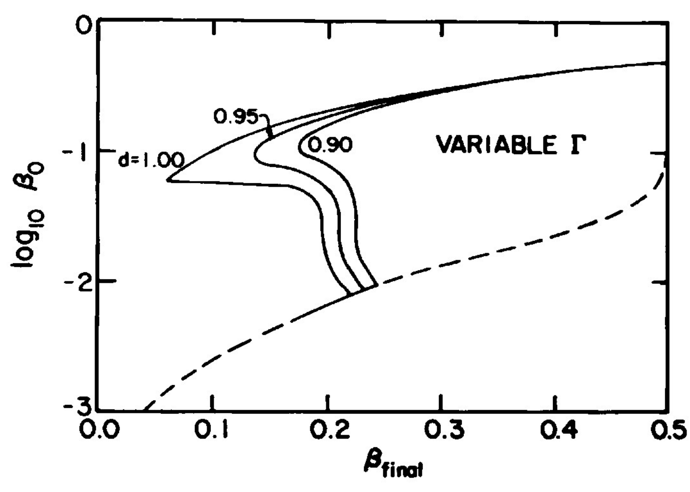


Fig. 2—As in Fig. 1, β_{final} is shown for various β_o, but here Γ is assumed to vary with density as prescribed by VRL (see text). The three curves are for different values of the initial pressure deficit d. The dashed curve shows $\rho_{final}/\rho_o = 10^5$, as in Fig. 1.

Using this "realistic" $\Gamma(\rho)$, $\beta_{min} \approx 10^{-2}$. Also, for a wide range of initial conditions, this $\Gamma(\rho)$ produces $\beta_{final} \approx 0.2$. (Using a $\Gamma(\rho)$ given by the VRL "adiabatic" evolution, Tohline and Chanmugam [1984] have found $\beta_{min} \approx 0.003$ and $\beta_{final} \approx 0.05$.) Therefore, if the VRL results are representative of the true behavior of hot core collapse, fizzlers should be formed as dynamically stable, axisymmetric objects ($\beta > 0.27$ is needed before nonaxisymmetric distortions will grow on a dynamical time scale).

SLOW EVOLUTION

Once formed, a fizzler should contract nondynamically toward a neutron star structure. The time scale on which it contracts will be governed by the rate at which it cools and/or the rate at which it loses angular momentum via, for example, magnetic dipole or gravitational wave radiation. Throughout slow contraction, $\alpha + \beta = 1/2$. If cooling dictates the shortest time scale, then α will drop and β must increase accordingly. Since β_0 is essentially a measure of the total angular momentum in the fizzler, it is clear that cooling alone will cause the fizzler's slow evolution to trace a (horizontal) path of constant β_0 toward the dashed line in Fig. 2. Very rapidly rotating neutron stars can be formed nondynamically in this fashion. If angular momentum loses drive the evolution, then the fizzler's evolution in Fig. 2 will be more vertical than horizontal. It's exact trajectory will depend sensitively on the equation of state of fizzler material during contraction, being exactly vertical only if $\Gamma = 4/3$ exactly. As long as $\Gamma < 4/3$, however, by eq. (3) the evolution cannot proceed to smaller β.

A quantitative estimate of the time scale for slow contraction is given by Shapiro and Lightman (1976) and by Tohline and Chanmugam (1984) to be $< 10^3$ years (in some instances $<< 10^3$ years). It will be difficult, then, to observe this phase of stellar evolution directly. But since fizzlers should evolve to neutron star configurations with $\beta \gtrsim 0.1$ (β in a millisecond pulsar is estimated to be ~ 0.1), their evolution is clearly relevant to the problem of the direct formation of millisecond pulsars.

ACKNOWLEDGEMENTS

It is a pleasure to thank A. Burrows for making some valuable comments regarding the cooling time scale of fizzlers and to thank G. Chanmugam for continued encouragement. This work was supported by the National Science Foundation through grant AST-8217744. The manuscript was prepared while enjoying a visiting scientist position at NRAO, Charlottesville. NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

REFERENCES

Arons, J. 1983, Nature, 302, 301.

Backer, D. C., Kulkarni, S. R., Heiles, C., Davis, M. M., and Goss, W. M. 1982, Nature, 300, 615.

Baym, G., Pethick, C., and Sutherland, P. 1971, Ap. J., 170, 299.

Boriakoff, V., Buccheri, R., and Fauci, F. 1983, Nature, 304, 417.

Brecher, K., and Chanmugam, G. 1983, Nature, 302, 124.

Chandrasekhar, S. and Lebovitz, N. R. 1962, Ap. J., 136, 1069.

LeBlanc, J. M., and Wilson, J. R. 1970, Ap. J., 161, 541.

Ledoux, P. J. 1945, Ap. J., 102, 143.

Müller, E., and Hillebrandt, W. 1981, Astr. Ap., 103, 358.

Müller, E., Różyczka, M., and Hillebrandt, W. 1980, Astr. Ap., 81, 288.

Shapiro, S. L. and Lightman, A. P. 1976, Ap. J., 207, 263.

Tohline, J. E. 1984, Ap. J., 285, 000 (Paper I).

Tohline, J. E., and Chanmugam, G. 1984, in preparation.

Van Riper, K. A., and Lattimer, J. M. 1981, Ap. J., 249, 270 (VRL).

DISCUSSION OF TOHLINE'S PAPER

REYNOLDS: What fraction of the final neutron-star binding energy do you release in the fizzler-neutron star collapse?

TOHLINE: It depends on what density your object is. There has been some hydrodynamic collapse stuff done; Leblanc and Wilson for example, the early stuff they did in the mid-seventies. They actually put rotation into the core. They formed fizzlers; they didn't form neutron stars. And they only released--oh, at least an order of magnitude down from the gravitational binding energy you would get all the way down to a neutron star.

REYNOLDS: In other words, 90% of the binding energy remains to be released on longer time scales.

TOHLINE: You can form fizzlers that do that.

PINES: It would seem offhand that a more likely prospect for forming observable fizzlers would be an accreting dwarf. If you form one in the core of a massive star in a supernova, then all the mantle material is going to come down and you'll never see your fizzler. Then the question is, what are the objects in the sky that look like fizzlers? I would suggest one, Cyg X-3, which is as yet not clearly explained. I think it's a very promising prospect for a millisecond pulsar, fairly newly formed, which you can't see very well because of all the junk around and the companion stars. If you scale, as Milgrom and I did years ago, the gamma-ray and X-ray output, it would scale with something rather faster than the Crab. Now one has these marvelously high-energy gamma-rays, totally inexplicable at the moment. So what observers ought to do is try to get a pulsed gamma-ray search going in the millisecond region. That's the only way you're going to see those pulses. I would think that would be what a fizzler might look like.

TOHLINE: I've wondered what it might look like, because it doesn't seem as if it would be obvious. It's probably right that cooling's going to dominate the future evolution of these things, in which case they may only last for a year. I will comment also: I tend to agree with you that if a fizzler forms during core collapse you're going to smother it by the envelope coming down. But there are other indications, for example Woosley and Bodenheimer's stuff where they put rotation in in order to enhance the explosion.

SHAHAM: As I understand it, your models do not include differential rotation.

TOHLINE: All I looked at was the global energy balance.

SHAHAM: In that case, could I ask about the β-values in which you thought there would not be any stable solution? And ask whether you think it's possible that actually the outer layers of the star might be shed as a disk and propagate outward with material going in. If you start from a system which did accrete matter onto a white dwarf, and eventually the white dwarf spun up, and accreted angular momentum and mass, and began to collapse and maybe was in one of your nonforeseeable states of evolution, it might begin to shed mass in a disk. And maybe one place to look for such a thing is SS433. Did you ever consider such a possibility?

TOHLINE: Well, the original stuff that Dick Durisen did of the differentially rotating white dwarf has it doing exactly what you're describing here--it sheds. It's close to a disk-like thing. And it's not a very thick disk. It just kind of peeled off the outer edge as the inner region collapsed.

STINEBRING: Does anyone want to speculate on whether fizzlers could produce coherent radio emission?

RUDERMAN: I think the answer is yes, somebody wants to speculate. I don't.

VAN DEN HEUVEL: Couldn't you make a thing like that in the way of Iben and Tutukov where you have all kinds of scenarios to produce two white dwarfs of about a solar mass or more which spiral in by any of several kinds of spiral-in processes--gravitational radiation, and so forth. You get something, say, of the order of two solar masses, and there will be an enormous amount of angular momentum in there.

TOHLINE: I have no objections.

SHAHAM: What is the temperature of the neutron star?

TOHLINE: The question is, what's the temperature Van Riper and Lattimer got. They form very hot neutron stars. So the fizzler itself is very hot. So, does the fizzler cool to a very low temperature before it becomes a rapidly rotating neutron star, or is it still hot? The cooling time scale is going to get you to a high $T/|W|$ neutron star, and the temperature only has to drop by about an order of magnitude. So I suspect you're still going to have a hot neutron star.

Thermal Origin of Neutron Star Magnetic Fields[1]

James H. Applegate, Roger D. Blandford, and Lars Hernquist
Theoretical Astrophysics, California Institute of Technology

ABSTRACT

Mechanisms by which magnetic fields can be generated on neutron stars are discussed. Applications to ordinary radio pulsars, millisecond pulsars, and rapidly spinning pulsars in plerionic supernova remnants are discussed.

Introduction

Timing observations of radio pulsars, analyses of the period changes in X-ray pulsars, the spectra of gamma-ray bursters, and the direct observation of X-ray cyclotron lines in various X-ray and radio pulsars all indicate that the neutron stars involved in these various activities possess surface magnetic fields of strength $\sim 10^{12}\,G$. The lack of pulsations from Galactic bulge X-ray sources and X-ray bursters, the finite lifetimes of radio pulsars, and the discrepancy between the timing and characteristic ages of old pulsars argue that the magnetization is not permanent. Direct evidence that neutron stars manufacture their own magnetic fields is provided by the discrepancy between the timing age of 1550 *yr* (Seward and Harnden 1982) of the pulsar embedded in the supernova remnant MSH 15-52 and the age of the remnant itself, between 5,000 *yr* and 12,000 *yr* depending on whether the remnant is in free expansion or the Sedov phase (Van Den Burgh 1984). The narrow range of field strengths inferred for most radio

[1] Research supported by NSF grants AST82-13001 and AST83-13725, and a Bantrell Fellowship at Caltech

pulsars (e.g. Manchester 1981), indicates that physics on the neutron star is responsible for determining the field strength. The unusual longevity of the field in Her X-1 suggests that its existence may be a by-product of accretion (Blandford, Applegate, and Hernquist 1983; hereafter BAH).

Field Generation Mechanisms

The top $\sim 1\,km$ of a neutron star consists of a liquid ocean of depth $150\, T_8 g_{14}^{-1}\, m$, where $10^8\, T_8 K$ is the temperature and $10^{14} g_{14}\, cm\, s^{-2}$ is the surface gravity, on top of a solid crust. A heat flux F_0 flowing through the solid crust in the presence of a small horizontal component of magnetic field generates a horizontal heat flux of magnitude XF_0, where $X = \omega_c \tau$ is the product of the electron cyclotron frequency and the relaxation time. This causes a horizontal temperature perturbation $\delta T \sim XF_0 / \kappa$, where κ is the thermal conductivity, which has an associated thermoelectric field $\delta \vec{E} = Q_0 \vec{\nabla} \delta T$, where Q_0 is the thermopower. The thermoelectric field has a non-zero curl by virtue of the misalignment of surfaces of constant density and temperature caused by the perturbation δT. The full perturbation of the electric field is $\delta \vec{E} = \vec{j} / \sigma_0 + Q_0 \vec{\nabla} \delta T - \vec{B} \times \vec{V}_{conv}$; the first term is ohmic decay, the second is the thermoelectric battery, and the third is a convection of field at the electron thermal drift velocity $\vec{V}_0 \simeq \vec{F}_0 / n_e \mu$. Field growth will occur if the thermoelectric battery builds up the field faster than ohmic decay can destroy it.

The strength of the thermal generation of field is measured by

$$\alpha = \frac{F_0}{n_e \mu} \frac{t_{ohm}}{z} = 0.5 T_8^{0.3} \left[\frac{26}{Z} \right] \qquad (1)$$

where n_e, μ, t_{ohm}, and z are the electron density, electron chemical potential, ohmic decay time and depth evaluated at the melt surface. The numerical value in (1) was obtained by BAH using the F-T_c relation of Gudmundsson *et al.* (1982), but with the Flowers and Itoh (1976; see also Itoh *et al.* 1984) transport coefficients. If the Yakovlev and Urpin (1980) values are used, the coefficient multiplying α must be lowered by a factor ~6. For boundary conditions demanding that all field is produced in the solid BAH found that $\alpha \geq 5$ is required if the field is to grow at all, and $\alpha \approx 20$ if the field is to grow fast enough to be interesting. Field generation by the solid alone cannot operate unless the electron relaxation time in both the solid and the liquid has been underestimated (relative to Flowers and Itoh [1976]) by a factor ≈ 3, or the effective Z in (1) is very low, $Z=2$.

A seed magnetic field in the liquid perturbs the heat flow by an amount $\delta\vec{F} = \vec{X}\times\vec{F_0}$ in the linear approximation. In general this perturbation will not be solenoidal, and the resulting local heating and cooling will lead to circulation in a manner akin to the Eddington-Sweet process. The fluid velocity adjusts itself to convect away the local entropy production; $T\rho(\vec{v}\cdot\vec{\nabla})S + \vec{\nabla}\cdot\delta\vec{F} = 0$,where S is the entropy per unit mass and $\vec{v}$ is the circulation velocity. The circulation velocity is approximately

$$v_{circ} \simeq X\frac{F_0}{\rho TS} \simeq 10^{-6}\, T_8^{1.3}\rho_7^{-5/3}B_8\, cm\, s^{-1} \tag{2}$$

In order for the magnetic field to be effective in generating circulation the circulation velocity must exceed the ohmic diffusion velocity, $V_{ohm} \simeq c^2/(4\pi\sigma_0 L) \simeq 3\times10^{-6}\rho_7^{-2/3}g_{14}\, cm\, s^{-1}$ and the thermal convection velocity $V_{conv} \simeq F_0/(n_e\mu) \simeq 5\times10^{-5}\, T_8^{2.3}\rho_7^{-4/3}g_{14}\, cm\, s^{-1}$. Circulation dominates if the field strength exceeds a few times 10^8 Gauss.

If the seed magnetic field is strong enough to drive circulation and the star is rotating, differential rotation will be set up and the circulating cells will be cyclonic. All of the ingredients of the dynamo process are present, and field amplification by the dynamo mechanism should occur. The turnover time of the circulation is $t_{circ} \simeq L/v_{circ} \simeq 30(L/100m)\, T_8^{-1.3}\rho_7^{-5/3}B_8^{-1} yr$. The growth time should not exceed t_{circ}; however, its exact value depends on the details of the mechanism. Because the ratio of differential rotation period to circulation time is very small, the field in the ocean is almost entirely toroidal. Poloidal field is produced in the ocean by the circulation, and toroidal field is convected into the solid at the thermal convection velocity V_{conv}. A subsurface horizontal field of the strength we envision may substantially decrease the surface X-ray flux from young neutron stars.

The field growth in the solid saturates when the magnetic stresses exceed the yield stress of the lattice, or when $XF_0/\kappa \sim T/z$. These limit the subsurface field to $10^{13}-10^{14}\,G$. The liquid dynamo probably saturates when $XF_0/\kappa \sim \delta T/z$, where δT is the temperature perturbation due to the local heating. This gives $B \sim 10^{12}\,G$. A similar limit is obtained from the requirement that the magnetic stresses be smaller than the thermally induced pressure fluctuations and therefore be unable to influence the circulation. The magnetic field is confined to the crust in our model; this allows ohmic decay to destroy the field in a few million years. This is in contrast to fossil field models where the field threads the core of the star.

Applications

Motivated by the failure to detect young pulsars in all but a few percent of SNR's., we argue that fast pulsars make large dipole moments rapidly and account for the Crab, MSH 15-52, and other plerions, whereas slow pulsars take longer than $\sim 10^4 yr$ to manufacture their fields, thereby delaying going on the air as radio pulsars until after their supernova remnants have dissipated. The most likely mechanism for this effect is that the liquid dynamo operates more efficiently in the fast pulsars because of the greater differential rotation. If we say that the Crab pulsar has a period of 30 ms and has made a field in less than 1,000 yr; the MSH 15-52 pulsar has a period of 150 ms and made a field in 5,000 yr; and that slow pulsars should delay going on the air for $\gtrsim 10^4 yr$, then a field generation time $\Delta t \propto P$ seems to be adequate to separate fast from slow pulsars. This is consistent with the notion from simple dynamo theory that the strength of dynamo action should be proportional to rotation frequency Ω, but requires that the field generation take many circulation times t_{circ}.

The millisecond pulsar PSR 1937+214 must be kept from developing a large field. One possibility is that PSR 1937+214 was born with its rapid rotation and is sufficiently more massive than ordinary pulsars for a pion condensate to form, resulting in rapid cooling and preventing the thermal generation of field. If PSR 1937+214 was spun-up in accretion, the problem becomes the avoidance of thermal generation of field by the heat liberated in the accretion (see BAH). A long epoch of accretion spin-up at a low accretion rate seems the best bet.

References

Blandford, R.D., Applegate, J.H., and Hernquist, L. 1983, *M.N.R.A.S.*, **204**, 1025.

Flowers, E., and Itoh, N. 1976, *Ap.J.*, **206**, 218.

Gudmundsson, E.H., Pethick, C., and Epstein, R.I. 1982, *Ap.J.* (*Letters*), **259**, L19.

Itoh, N., Yasuharu, K., Matsumoto, N., and Seki, M, 1984, preprint.

Manchester, R.N. 1981, In *Pulsars*, eds. W. Sieber, and R. Wielbinski (Dordrecht: Riedel)

Seward, F.D., and Harnden, F.R. 1982, *Ap.J.*, (*Letters*) **256**, L45.

Van Den Burgh, S. 1984, preprint.

Yakovlev, D.G., and Urpin, V.A. 1980, *Soviet Astr.*, **24**, 303.

DISCUSSION OF APPLEGATE'S PAPER

MANCHESTER: If it takes something like a million years for surface crustal fields to decay, doesn't it take that long for the sub-surface fields to get through and out?

APPLEGATE: No. Say for example you were to make a field by a dynamo in the liquid. The circulation is bringing field up to the surface. Also a point is that the neutron star is hotter when you're making the field than when the field is decaying, and all the time scales are shorter.

MANCHESTER: What are the time scales?

APPLEGATE: If the instability in the solid--the Nernst effect instability--is responsible for things, I don't think it can be much shorter than about several times 10^4 years. If the dynamo in the liquid is what's doing things, I would suspect of order a few hundred years. It's very hard to estimate the time scale for the liquid because the dynamo is nonlinear--the velocity depends on the magnetic field.

BACKER: Will you comment on the geometry of the field that's created? What the radio observations are testing is the dipole portion of this field. Is there going to be a coherent pattern that's developed?

APPLEGATE: I suspect when the field is made it's going to be made in loops that are roughly of size the melting depth. So you're going to end up with a tangled mess. As the field strengthens, there'll be some field reconnection; also ohmic decay will get rid of a lot of the small-scale structure. So I think you can build up a large-scale dipole. We have not been able to push this theory to the nonlinear regime. You can ask yourself what field configuration should be steady. Such configurations are usually axisymmetric things like the picture I showed.

VAN HORN: You mentioned the 10^8-year time scale of Her X-1, and said you were going to explain that by accretion, but I didn't hear that.

APPLEGATE: The hope was, we could use the heat produced in accretion to drive the magnetic field production. If you rely on this instability in the solid and put the numbers in, it doesn't make it. But the liquid dynamo might. The answer is, we really haven't done this stuff in detail. We'd like to be able to do it, but accreting sources are a little puzzling. You also have the X-ray sources in globular clusters, which don't have magnetic fields.

CHANMUGAM: What would happen if the star was formed with a strong field, greater than 10^9 gauss? Is there a bound? What would happen if there were a field of say 10^{11} or 10^{12} gauss?

APPLEGATE: Well, if there were a field of 10^{12} gauss throughout the star, presumably you could make a little bit more field with these processes before you ran into the saturation mechanisms. What I would imagine is that that field would go through the core and you'd never be able to get rid of it. So if you want to be able to turn pulsars off by ohmic decay and also have now-active radio pulsars evolve over a long period of time and be the same sort of neutron stars which are in old X-ray binaries in the galactic bulge which don't have magnetic fields, it might be a problem. One of the ways you could distinguish Her X-1 from the globular cluster X-ray sources is to have a seed field in Her X-1, but not in the others. The liquid dynamo will not work without the seed field. Also, you may require enough of a seed field to channel the accretion flow onto the poles as opposed to having the star uniformly heated.

KULKARNI: If you can explain the field in Her X-1, then all these neutron stars that get spun up should also have pulsar fields.

APPLEGATE: That's why I'm not sure I can explain Her X-1.

REYNOLDS: To the extent that you are able to put things together into low-order multipole fields, won't they tend to be aligned with the rotation axis?

APPLEGATE: No. The earth's field isn't aligned with the rotation axis.

REYNOLDS: Well, it's going to be very hard to make an orthogonal rotator that persisted that way, right?

APPLEGATE: Yes, but I can make a pulsar without making it orthogonal.

SHAHAM: Since I was the one who made the comment yesterday, I just wanted to say that for the millisecond pulsar, since the field now is a few times 10^8, you couldn't very well argue that when it was formed it didn't have at least that field as a seed.

APPLEGATE: The millisecond pulsar could be a bit of a problem for this theory. The difficulty is to arrange to go through all these contortions to make it, yet avoid making a strong field. Because obviously if it has a strong field it will spin down rapidly, and also if it has a strong field it cannot spin up to millisecond periods.

BRECHER: You want to explain the absence of observable radio pulsars in young supernova remnants. We've got two supernova remnants that are young with pulsars. There are three or four others that are young without, but are massive and presumably have disrupted or would not have produced pulsars anyway. What is it exactly you want to explain?

APPLEGATE: There are about 130 observed supernova remnants, and all supernova remnants are young compared to pulsars. Remnants last for at most 10^5 years, or somewhere between 10^4 and 10^5 years. Pulsars last between 10^6 and 10^7. So, if of order half of supernovae produce pulsars, half of the remnants should contain them.

THE STABILITY OF MAGNETIC FIELDS OF ISOLATED AND BINARY NEUTRON STARS

G. Chanmugam
Department of Physics and Astronomy
Louisiana State University, Baton Rouge, LA 70803

ABSTRACT

It is suggested that convective instabilities in cooling neutron stars may lead to magnetic field decay. Since rotation may have a stabilizing influence, the rotational history of the star is more important, than the age of the star, in determining whether its magnetic field decays or not.

INTRODUCTION

The absence of long period pulsars has led to the suggestion that pulsars turn off when their magnetic fields decay (Ostriker and Gunn 1969, Lyne, Ritchings and Smith 1975) on a time scale $\sim 8\mathrm{x}10^6$ yr (Lyne 1982). However, because of the high electrical conductivity in the <u>interior</u> of a neutron star (Baym, Pethick and Pines 1969) the time scale for <u>ohmic</u> decay is $\gtrsim 10^{12}$ yr (Chanmugam and Gabriel 1971). This has led to the suggestion that, instead, the field decay occurs as a result of instabilities. A popular model suggests that the magnetic field is stabilized by currents in the outer crust of a neutron star (Flowers and Ruderman 1977). When these decay on a time scale $\tau_{crust} \sim 5\mathrm{x}10^6$ yr, because of the lower conductivity in the crust, the external field is reduced significantly because of rearrangement of the currents in the interior of the neutron star. If there is no possibility of regeneration of magnetic fields (cf. Blandford, Applegate and Hernquist 1983) then this model implies that neutron stars with ages $> \tau_{crust}$ will have weak magnetic fields. However, the presence of strong magnetic fields ($\sim 10^{12}$ gauss) in the pulsing X-ray sources which are believed to have ages $\sim 3\mathrm{x}10^6 - 10^8$ yr (Lamb 1981) presents difficulties for this model.

An alternative mechanism for possible field decay occurring as a result of convective instabilities has been suggested (Tayler 1973 a,b, see also Vandakurov 1972, Chanmugam 1978), but its implications for pulsars and X-ray pulsars have not been fully explored. In this paper we show that this mechanism may be able to explain why the field decay times for isolated and binary pulsars are, in general, different.

CONVECTIVE INSTABILITIES

Vandakurov (1972) has considered the stability of toroidal magnetic fields in zero-temperature (T=0) degenerate stars and has shown that convective instabilities can occur in such stars even for weak magnetic fields. Tayler (1973b) has shown however that when the thermal correction $p_1(\rho,T)$ to the ideal degenerate pressure $p_o(\rho)$, where ρ is the density, is included, instabilities may occur over large regions of the star if the shape of the field is appropriate and the magnetic pressure $B^2/8\pi > p_1$. Here the total pressure $p = p_o(\rho) + p_1(\rho,T)$ with $p_1 \ll p_o$. Similar criteria for instabilities were obtained by Chanmugam (1978), who examined the stability of axisymmetric force-free fields (Easson 1976, cf. Arons and Spencer 1978) in an infinite cylinder, further supporting the view that convective instabilities can occur in degenerates stars. Since only the electrons and protons are coupled to the magnetic field, in the interior of a neutron star, $p_1 \propto n_p^{1/3} T^2$ where n_p is the proton number density (Tayler 1973b). Thus a necessary condition for instability with $n_p \sim 10^{37}$ cm^{-3} is

$$B \gtrsim 8\times10^{13}\ T_8 \quad \text{gauss}, \tag{1}$$

where $T_8 = T/10^8$K. If the surface field B_s is roughly a factor 100 less than the internal field this criterion is likely to be satisfy for most pulsars since $T \lesssim 10^8$K (Tsuruta 1979). However, rotation is likely to suppress the instability if the rotational energy is larger than the magnetic energy (Chanmugam 1979), i.e. if

$$B^2 \lesssim 16\pi^3\ \rho_p\ r^2\ P^{-2}. \tag{2}$$

For a proton density $\rho_p \sim \rho/10 \sim 5\times10^{13}$ g cm^{-3} and $r \sim 5$ km it follows that rotation is stabilizing if $P \lesssim 1$s, for $B_s \lesssim 10^{12}$ gauss.

If the fluid is convectively unstable, the field probably rises until it reaches the crust of the neutron star on a time scale comparable to the Alfvén travel time ~1s (see Parker 1979, p76). If the fluid is convectively stable the field rises because of magnetic buoyancy (Parker 1974), on a time scale ($\gtrsim 10^{10}$ yr) which depends on the rate of heat transfer.

APPLICATIONS

a) Isolated Neutron Stars

Consider an isolated pulsar which cools and spin down. Since rotation is likely to have a stabilizing influence, convective instabilities do not take place until P becomes $\gtrsim$ 1s. Such instabilities are likely to reduce the field in the interior. The field in the outer crust then undergoes ohmic decay on a timescale $\tau_{crust} \sim 5\times10^6$ yr consistent with observations (Lyne 1982).

Note that the millisecond pulsar PSR 1937+214 (Backer et al 1982) has a period <<1s and a surface magnetic field $B_s \sim 5\times10^8$ gauss. Thus criteria (1) and (2) for instabilities are not satisfied. Thus the suggestion, of Brecher and Chanmugam (1983) and Arons (1983), that this pulsar has retained its original magnetic field and spin, is consistent with this result.

b) Binary Neutron Stars

Consider next the case when the neutron star is formed in a massive close-binary with a rotation period < 1s. The rotation would then be braked down to a period ~ 1s in ~ 10^4 yr, after which it is further slowed down to a period ~100s on a time scale ~ 10^6 yr in a wind from the companion star (van den Heuvel 1977, Davies, Fabian and Pringle 1979, Lamb 1981). If the neutron star has cooled down sufficiently by the time the period has reached ~ 1s, convective instabilities are likely to cause field decay on a time scale ~ 5×10^6 yr. As the wind from the companion increases, accretion of angular momentum by the neutron star will cause it to spin up rapidly on a timescale of ~ 10^4 yr. Significant field decay may not yet have taken place, and the system appears as an X-ray source pulsing with a period ~ 10^{-2} to 1s. Note that extra heating of the neutron star due to accretion, compared to the case of isolated neutron stars, may prevent instabilities in some regions of the star, and hence slow down the field decay.

If the neutron star is formed in a low-mass binary, the time when field decay commences would depend on whether mass transfer begins before or after the period has reached ~ 1s. In the former case the neutron star would be kept rotating with a period near the equilibrium period for disk accretion (van den Heuvel 1977):

$$P_{eq} = 1\cdot6 \times B_{12}^{6/7}\, R_6^{18/7}\, (M/M_\odot)^{-5/7}\, \dot{M}_{17}^{-3/7}\ \mathrm{s}, \tag{3}$$

where $B_{12} = B/10^{12}$ gauss, $\dot{M}_{17} = \dot{M}/10^{17}$ g s^{-1} and R_6=R/10^6 cm. Note that $\dot{M}$~10^{17} g s^{-1} is about 0.1 times the accretion rate corresponding to the Eddington luminosity. Thus if accretion continues at such a rate for ~ 10^8 yr, as is believed to occur in cataclysmic variables, the magnetic field can last for a time >> τ_{crust}.

The possibility that the millisecond pulsar PSR 1937+214 was originally a slowly spinning neutron star in a close binary has been suggested by Radhakrishnan and Srinivasan (1982). In this model the neutron star is spun up after its magnetic field has decayed,the companion undergoing a supernova later with the binary becoming disrupted (cf. Ruderman and Shaham 1983). From the above discussion it follows that if accretion commences after the neutron star has cooled sufficiently and spun down to periods $\gtrsim$ 1s, and lasts for a time > τ_{crust}, field decay due to convective instabilities is possible although there are other difficulties if the binary was a massive one (e.g. Arons 1983).

The X-ray binary Her X-1 is believed to contain a neutron star with a magnetic field ~ 5×10^{12} gauss (Trümper et al. 1978). An evolutionary scenario for Her X-1 has been suggested by Sutantyo (1975) in which mass-transfer onto the neutron star commenced about 5×10^8 yr after the formation of the neutron star in a massive binary. The persistence of the magnetic field for such a long time is difficult to understand in our model, unless the shape of the field is such that the convective instabilities do not take place. An alternative evolutionary scenario in which the neutron star is formed from a white dwarf, which has been driven over the Chandrasekhar limit, has been suggested by Gursky (1976). If mass-transfer onto the neutron star, from a post-main-sequence star, commenced before the neutron star has either cooled too much or slowed down to periods $\gtrsim$ 1s, then field decay need not have taken place. However, the lifetime of the system is too short to explain its presumed large distance above the galactic plane, assuming it was formed in the galactic plane (van den Heuvel 1976).

ORIGIN OF FIELDS

In the above discussion we have tacitly assumed that the magnetic fields of neutron stars cannot be regenerated. Recently, Blandford, Applegate and Hernquist (1983) have suggested a novel, but complex, model in which the fields are produced in the crust as a result of rotation and thermal effects. This model is inapplicable to white dwarfs since they crystallize only after cooling off. This further implies that the reason why isolated magnetic white dwarfs have surface magnetic fluxes similar to that of the pulsars is a coincidence. We suggest instead that it is not necessary to abandon the view that both these classes of stars have fossil fields. In particular, note that the maximum surface magnetic fluxes $B_s R_s^2$ observed for magnetic white dwarfs is $\sim 5\times10^{25}$ gauss cm^2, with $B_s \sim 2\times10^8$ gauss and $R_s \sim 5\times10^8$ cm (Angel, Borra and Landstreet 1981), and for neutron stars $\sim 10^{25}$ gauss cm^2. These bounds are close to but below the maximum surface flux $\sim 10^{26}$ gauss cm^2 observed, with $B \sim 3\times10^4$ gauss and $R \sim 10^{11}$ cm, for any non-degenerate star (Parker 1979, p 766).

Convective instabilities may also be used to put a bound on the magnetic fields of white dwarfs. In the interior of white dwarfs, the thermal correction to the ideal degenerate equation of state is principally due to ion pressure and for stability one requires

$$B \lesssim 1\times10^{11}\ \rho_6\ T_7\ (A/2)^{-1/2}\ \text{gauss}\ , \tag{4}$$

where A is the average atomic mass and $\rho_6 = \rho/10^6$ g cm^{-3} (Tayler 1973 b). Since $\rho_6 \sim T_7 \sim 1$ the critical internal magnetic field is $\sim 10^{10}$ to 10^{11} gauss depending on the composition. The corresponding upper bound for the surface field B_s ($\sim 10^8$ to 10^9 gauss) is consistent with the observed fields for white dwarfs which are isolated (Angel, Borra and Landstreet 1981) and in binaries (Chanmugam and Ray 1984). Since magnetic white dwarfs are relatively slow rotators the effects of rotation are less important in determining this value.

CONCLUSIONS

In conclusion we emphasize that convective instabilities are likely to occur in the interiors of neutron stars and eventually lead to field decay. The time scale for field decay depends, however, on the strength of the magnetic field, and the rotational and thermal history of the neutron star. The existence of magnetic fields in some neutron stars in binaries for time scales $\gg 10^6$ yr seems possible.

This research was supported by NSF grant AST-8219598.

REFERENCES

Angel, J. R. P., Borra, E. F., and Landstreet, J. D. 1981, Ap. J. Supp., 45, 457.

Arons, J. 1983, Nature 302, 301.

Arons, J., and Spencer, R. G. 1978, Ap. J., 220, 640.

Backer, D. C., Kulkarni, S. R., Heiles, C., Davis, M. M., and Goss, W. M. 1982, Nature, 300, 615.

Baym, G., Pethick, C. J., and Pines, D.. 1969, Nature 224, 674.

Blandford, R. D., Applegate, J. H., and Hernquist, L. 1983, M.N.R.A.S., 204, 1025.

Brecher, K., and Chanmugam, G. 1983, Nature 302, 124.

Chanmugam, G. 1978, Ap. J., 221, 965.

__________ 1979, M.N.R.A.S., 187, 769.

Chanmugam G. and Gabriel, M. 1971, Astr. Ap., 11, 268.

Chanmugam, G. and Ray, A. 1984, Ap. J. in press.

Davies, R. E., Fabian, A. C., and Pringle, J. E. 1979, M.N.R.A.S., 186, 779.

Easson, I. 1976, Nature, 263, 486.

Flowers, E., and Ruderman, M. A. 1977, Ap. J., 215, 302.

Gursky, H. 1976, in Structure and Evolution of Close Binary Systems, p.19, eds. P. Eggleton, S. Mitton and J. Whelan (Dordrecht: Reidel).

Lamb, F. K. 1981, in Pulsars, p. 357, eds. W. Sieber and R. Wielebinski (Dordrecht: Reidel)

Lyne, A. G., Ritchings, R. T., and Smith, F. G. 1975, M.N.R.A.S. 171, 579.

Lyne, A. G. 1982, in Supernovae: A Survey of Current Research, p 405, eds. M. J. Rees and R. J. Stoneham (Dordrecht: Reidel).

Ostriker, J. P., and Gunn, J. E. 1969, Ap. J., 157, 1395.

Parker, E. N. 1974, Ap. Sp. Sci., 31, 261.

__________ 1979, Cosmical Magnetic Fields (Oxford: Clarendon Press).

Radhakrishnan, V., and Srinivasan, G. 1982, Curr. Sci., 51, 1096.

Ruderman, M., and Shaham, J. 1983, Comments Ap., 10, 15.

Sutantyo, W. 1975, Astr. Ap., 41, 47.

Tayler, R. J. 1973 a, M.N.R.A.S., 161, 365.

__________ 1973 b) M.N.R.A.S., 162, 17.

Trümper, J., et al. 1978, Ap. J. (Letters), 219, L105.

Tsuruta, S. 1979, Phys. Rept. 56, 237.

Vandakurov, Yu. V. 1972, Soviet Astr. - AJ 16, 265.

van den Heuvel, E. P. J. 1976, in Structure and Evolution of Close Binary Systems p. 35, eds. P.Eggleton, S. Mitton and J. Whelan (Dordrecht: Reidel).

__________ 1977, Ann. N. Y. Acad. Sci., 302, 14.

DISCUSSION OF CHANMUGAM'S PAPER

APPLEGATE: Neutron stars are not fluid everywhere. They have a solid crust, and the magnetic field is anchored in this solid crust. How can your convective instabilities operate in a solid?

CHANMUGAM: The instabilities operate in the interior. It will break off the field there, and it will move to the crust.

CHENG: Do you take into account superconductivity and superfluidity?

CHANMUGAM: I don't know what effects superconductivity and superfluidity will have, but I should point out that I haven't really used anything about the nature of the conductivity in the core, except that it's highly conducting. I've assumed that simple MHD is valid.

RUDERMAN: The effect of superconductivity is to increase the magnetic tensions by roughly the ratio of the critical field inside a flux tube to the average field. If the average field is 10^{12} gauss, it would make the local value of $B^2/8\pi$ about 10^4 times larger. The effect is quantitatively very important, and it goes in the direction of making all magnetic effects larger by a good factor.

CHANMUGAM: But what happens to the field outside the superconducting line?

RUDERMAN: You just think of the flux as a flux tube. The flux tube breaks up into little wires. The tension in each wire, times the number of wires per square centimeter, has gone up by the ratio of the critical field to the average field which is a big number, several orders of magnitude. So I think the numerical results would be changed in a rather dramatic way. It may help, because you already assume the magnetic field inside to get good results is about 10^5 larger. It would be even more without that assumption.

GOODMAN: I don't really understand the physics of this in great detail, but if you have a horizontal component of magnetic field along the polar direction of a rotating star, is rotation then ineffective in suppressing the instability?

CHANMUGAM: I don't know. It's very hard to make calculations of field stability. The problems that you can study are very simple things like toroidal field and so on. In the absence of rotation I've used the standard Bernstein *et al.* stability criteria.

GOODMAN: One reason I asked is I wonder if the instability might tend to selectively eliminate non-aligned field?

CHANMUGAM: That I don't know.

SHAHAM: If the magnetic fields of white dwarfs are 10^6 - 10^8, a range of two orders of magnitude, why don't young neutron stars exhibit the same range?

CHANMUGAM: Magnetic fields of white dwarfs are bimodal. They are between 10^6 and 10^8, but 90% of them have much weaker fields. We have never detected them--they are only upper bounds. Some of the upper bounds are 10^5, 10^4, 10^3--It could be that the magnetized white dwarfs are those that didn't become neutron stars.

VAN DEN HEUVEL: Couldn't dynamo action during the collapse completely change the picture? Because it could come from any little seed field you have. Since you have such an enormous change in rotation during the collapse, I would imagine you could build up any field.

CHANMUGAM: I'm trying to make the point that it is not a simple function. You have to put more complicated things in.

VAN HORN: I have two questions. One is, you said that the Applegate, Blandford and Hernquist mechanism did not work in white dwarfs. Why?

CHANMUGAM: You have to have a crust, and you have to have a heat flux. In the case of white dwarfs, you don't have a crust, and the star has cooled off.

VAN HORN: Second question is, as you know better than I, Ganesh, isn't it true of the AM Her stars which are white dwarfs in close binaries, that the magnetic field inferred is of order a few times 10^8 gauss?

CHANMUGAM: A few times 10^7 gauss. It was originally thought that they were a few times 10^8 gauss, but they all end up at a few times 10^7.

IV. SEARCHES--PAST, PRESENT, AND FUTURE

SEARCHES FOR SHORT PERIOD PULSARS AT JODRELL BANK

A.G.Lyne

Nuffield Radio Astronomy laboratories, Jodrell Bank, Macclesfield, England.

ABSTRACT

Two separate approaches are presently being taken at Jodrell Bank in the quest for short period pulsars. One experiment consists of a high frequency survey of the galactic plane for highly dispersed and/or short period pulsars which would not have been visible in the major surveys carried out at around 400 MHz. The second experiment is designed to detect millisecond pulsars using MERLIN as a filter for small diameter, linearly polarised sources, followed by a periodicity search on likely candidates using the 76m MKIA telescope alone.

Recent studies of the galactic distribution and evolution of pulsars (Lyne, Manchester and Taylor 1984) indicate that there may be a substantial number of undetected young luminous pulsars in the Galaxy with flux densities above the survey limits. These pulsars are likely to

a) have short periods

b) be distant and therefore have large dispersion measures and scattering

and c) be near to their birthplace, i.e. at small z-distance.

Because of b) and c) they will lie at very low latitudes. Most such pulsars would not have been detected in previous surveys because of dispersion or scatter broadening of the pulses in the interstellar medium, and also because of the poor sensitivities of the survey instruments at low galactic latitudes where the galactic background radiation is frequently several hundred degrees. Furthermore, none of the published major surveys have been sensitive to periods of less than 30ms and even the Crab pulsar with a period of 33ms has not been detected in them.

A new survey is nearing completion at Jodrell Bank using the 76m telescope at 1400 MHz. The survey covers galactic longitudes from 358 to 120 degrees and latitudes from -1.0 to +1.0 degrees. Eight contiguous bands of 5MHz are recorded on magnetic tape at intervals of 2ms and subsequently processed on a Cyber 205 for pulse trains having periods between 4 and 8000 milliseconds and dispersion measures up to 60,000 pc/cm**3.

The system noise at high latitudes is typically equivalent to 45 Jy on two circular polarisations so that the dwell time of 520 seconds on each beam area of the sky provides an rms noise of 0.22 mJy. The survey is thus capable of detecting pulsars with a flux density of 0.3 mJy (6 sigma) for a 4% duty cycle and of 1.3mJy (6 sigma) for a 50% duty cycle. The sensitivity is not degraded greatly by galactic background noise even when right on the galactic plane.

Figure 1 shows the areas of dispersion measure/period space covered by the major surveys and the present one which has a DM/P of 32,000 pc/cm**3. The interstellar scattering limits were derived from the work of Sutton (1971) which showed that the scatter broadening varies with frequency f(MHz) and dispersion measure DM(pc/cm**3) as

$$T=(DM/1000)^3(318/f)^4 \text{ seconds.}$$

Clearly interstellar pulse broadening provides the major restrictions in the low frequency surveys. We can see that the new survey increases by a factor of about 6 both the dispersion measure space and the period space of the previous surveys. Eighty percent of the observations have now been made and processing of the data is now in progress.

The MERLIN-based search for millisecond pulsars uses the MKIA telescope and the telescopes at Defford and Knockin at 408 MHz, providing resolutions of about 1 and 2 arcseconds resolution respectively. Fringe frequency/delay maps are made for 5 minute observations on each beam area (see for example Lyne et al 1982). The rms noise on these maps amounts to about 7 mJy for each of the two baselines. Sources stronger than about 25 mJy are identified in the MKIA-Defford maps and the maps from both baselines studied for evidence of resolution and linear polarisation. For a source of this strength, 25% linear polarisation can be detected at the 2 sigma level. For stronger sources, the percentage of linear polarisation detectable will be correspondingly greater.

This instrument is being used to study a number of candidate fields:

Scintars	110
Steep spectrum sources	200
Supernova remnants	150
Gamma-ray sources	16
Odds and ends	20
TOTAL----------------------	496

An intermediate latitude survey is also in progress with longitudes from 0 to 120 degrees and latitudes +/-4 to +/-10 degrees. The observations of the discrete objects and one third of the survey have been completed. The analysis of this data will be finished shortly. The follow-up program with the MKIA will be carried out in the first instance at 408 MHz or 610 MHz, with searches for periodicity form 0.5 milliseconds upwards. These observations, if required, will be made in August of this year.

REFERENCES

Lyne,A.G., Anderson,B. and Salter,M.J., 1982. Mon.Not.R.astr.Soc. 201,503.
Lyne,A.G., Manchester,R.N. and Taylor,J.H., 1984. In preparation.
Sutton,J.M., 1971. Mon.Not.R.astr.Soc., 155,51.

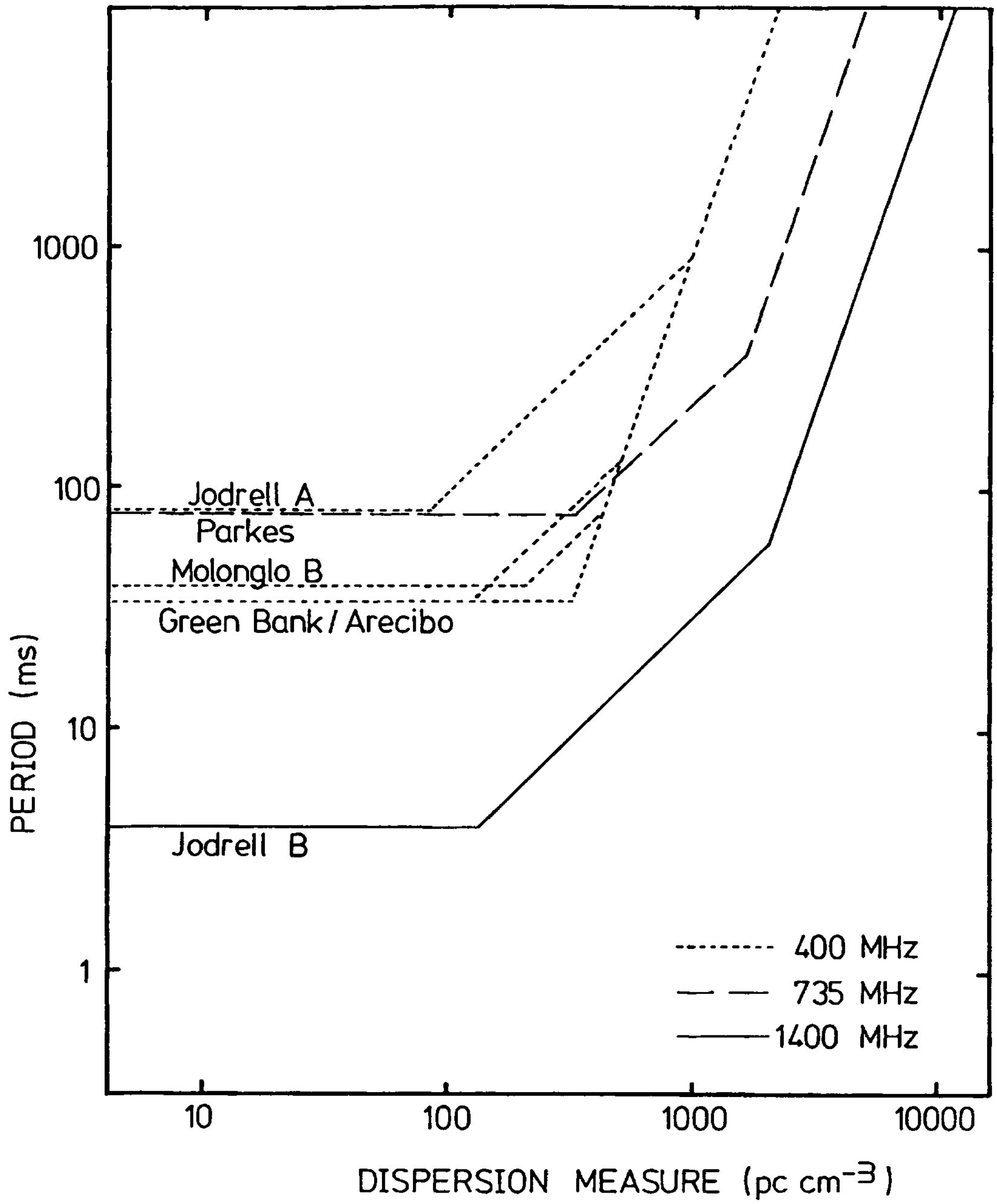


FIGURE 1 The Dispersion Measure/Period limits of the published major surveys and that of the new 1400 MHz survey at Jodrell Bank. The horizontal lines are determined by the sampling rate, the 45^{o} lines by dispersion in the receiver filters and the lines with gradient 3.0 by interstellar scattering (after Manchester and Taylor 1977 based mainly upon the data of Sutton 1971).

DISCUSSION OF LYNE'S PAPER

TAYLOR: I'm not sure I understand how the maps are made with Merlin. They're 50 x 50 and cover almost a degree, and yet I thought the resolution was half an arc-second.

LYNE: We don't do a true mapping process. The independent delay channels, which are determined by the bandwidth of the interferometer, are at roughly 1' intervals, so that if you look at a single delay channel, that will give you information about the sky in a strip about 1' in width. And then, depending upon where the source is across that strip, you will have a certain fringe frequency. Taking the Fourier transform of the data you receive from one delay channel gives you the fringe frequency, which places the source on the strip. You get 64 independent positions along the strip. You will only get small sources getting through the fringe lobes on the sky, and then you can position them using this property of the fringe frequency.

WEISBERG: Is your 3° - 10° latitude search a polarization search or a periodicity search?

LYNE: That's basically a polarization search.

KULKARNI: One of the things to not throw away is the circular polarization information. As you know, PSR 1953 is not linearly polarized, so it might be helpful to look at your V maps for those sources that are not strongly linearly polarized.

LYNE: True. Unfortunately we add our two circulars together at an early stage in order to reduce the amount of data.

KULKARNI: In a lot of the surveys we find a surprising number of steep-spectrum, unpolarized sources. A lot of these have other identifications, and so they are not pulsars, but circular polarization is truly Galactic as far as we know, so that's why I'm urging that attention be paid to the circular polarization.

LYNE: That's a good point.

Southern Hemisphere Searches for Short Period Pulsars

R. N. Manchester

C.S.I.R.O., Division of Radiophysics
Sydney, N.S.W., Australia

ABSTRACT

Two searches of the southern sky for short period pulsars are briefly described. The first, made using the 64-m telescope at Parkes, is sensitive to pulsars with periods greater than about 10 ms and the second, made using the Molonglo radio telescope, has sensitivity down to periods of about 1.5 ms. Four pulsars were found in the Parkes survey and none in the Molonglo survey, although analysis of the latter is as yet incomplete.

Previous large-scale pulsar surveys, e.g. Davies *et al.* (1972,1973), Hulse and Taylor (1974, 1975), Manchester *et al.* (1978), Damashek *et al.* (1978, 1982), have been at relatively low radio frequencies, around 400 MHz, and have seriously discriminated against pulsars with periods of less than about 200 ms, especially for high dispersion measures. Since nearly 70% of the 279 pulsars found in the surveys which form a flux-limited sample, that is, excluding the Arecibo surveys, are south of the equator, it is clearly important to search the southern sky for both millisecond pulsars and pulsars of intermediate period which were missed in the earlier surveys. This is especially true for the more distant, high dispersion, pulsars since these are concentrated in the sector toward the Galactic centre.

Table 1 gives a summary description of two such surveys. The Parkes survey, undertaken in several sessions since 1981, is at a frequency of 1.4 GHz and, with a sampling interval of 2 ms, is specifically designed to find high dispersion pulsars of intermediate period. The Molonglo survey, with its shorter sampling interval of 0.25 ms, is directed toward the detection of pulsars with periods in the millisecond range. Both searches have been toward specific objects, for example, supernova remnants, steep spectrum radio sources, etc., although the Parkes search of several large COS-B γ-ray error circles was effectively an unbiased search of several square degrees near the galactic plane. For both surveys, the analysis procedures are similar to those of the second Molonglo pulsar survey (Manchester *et al.*, 1978).

Table 1. Searches for Short Period Pulsars.		
	Parkes	Molonglo
Group	N. D'Amico (U. Palermo) R.N. Manchester (CSIRO) I.R. Tuohy (A.N.U.)	N. D'Amico (U. Palermo) J.M. Durdin (U. Sydney) R.N. Manchester (CSIRO) W.C. Erickson (U. Maryland)
Frequency	1405 MHz	843 MHz
Polarizations	2	1 Circular
HPBW	15'	43" × 2°
Bandwidth	4 × 5 MHz	8 × 200 kHz
Sample Interval	2 ms	0.25 ms
Analysis	VAX 11/780 (AAO) IBM 3033 (Palermo)	VAX 11/750 (CSIRO) VAX 11/780 (AAO) IBM 3033 (Palermo)
Period range	10 ms - 2 s	1.5 ms - 1 s
DM range	0-1600 cm^{-3} pc	0-500 cm^{-3} pc
Obs. time/position	17.5 m	8.75 m
Limiting Sensitivity	~1 mJy	~5 mJy
Sessions	Nov. 1981 (4 d) Mar. 1982 (4 d) May 1984 (2 d)	Sept. 1983 (2 d) Oct. 1983 (3 d) Oct. 1983 (3 d) Apr. 1984 (2 d)
Objects searched	SNR COS-B error circles Binary stars Compact X-ray objects	SNR COS-B candidates Steep spectrum radio sources Compact x-ray objects
Beam areas searched	244	~100
Solid angle	15 sq deg	~2.5 sq deg
Analysis completeness	~90%	~50%
Pulsars detected	4	0

The Parkes survey has been relatively successful in that it has found four pulsars of relatively short period and high dispersion measure. One of these, PSR 1509-58, was first detected by Seward and Harnden (1982) as an X-ray pulsar; the radio detection has been described by Manchester *et al.* (1982). Table 2 gives the basic parameters for the four pulsars and Figure 1 shows the integrated profiles (PSR 1509-58 excepted). Three of the four pulsars have periods of less than 200 ms and two have dispersion measures greater than any previously known. A more complete description of the Parkes observations and pulsars detected will shortly be submitted for publication.

Table 2. Basic Parameters for Pulsars Detected at Parkes					
PSR	R.A. (1950) h m s	Dec. (1950) ° ′ ″	Period s	DM cm^{-3} pc	Mean S mJy
1338-62	13 38 30	-62 07 00	0.1932	880	2.5
1509-58	15 09 58[1]	-58 56 57[1]	0.1502	235	1.5
1758-23	17 58 15	-23 05 00	0.4158	1140	5
1758-24[2]	17 58 15	-24 53 00	0.1248	250	1

1. X-ray position from Seward and Harnden (1982)
2. Confirmed at Jodrell Bank by A.G. Lyne (private communication)

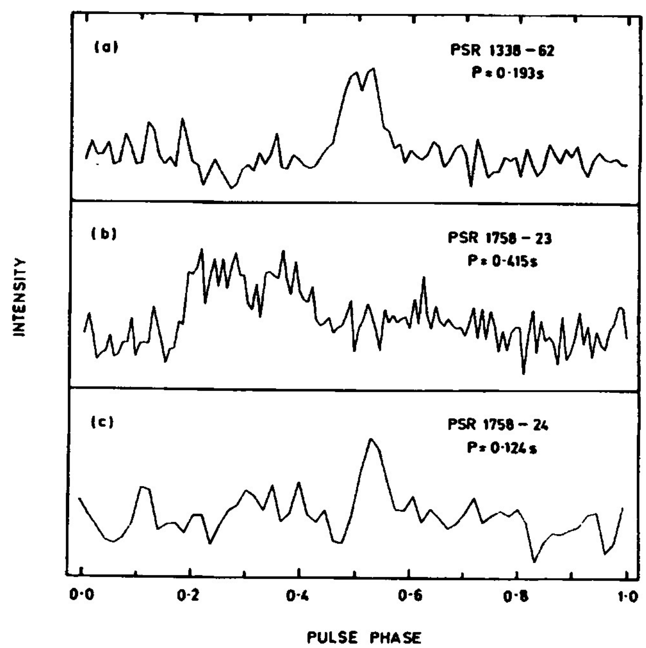


Figure 1. Integrated profiles for three of the pulsars detected in the Parkes pulsar search.

So far the Molonglo survey has covered a very small solid angle on the sky and analysis of even these data is as yet incomplete. No new pulsars have been detected. At least as far as the steep spectrum radio sources, mainly selected from a list compiled by Erickson (1983), are concerned, we can say that none of those observed contains a strong ($\gtrsim$ 15 mJy) pulsar with period of a few milliseconds or more.

Clearly there remains considerable scope for searches of the southern sky for short period pulsars.

References

Damashek, M., Taylor, J.H., & Hulse, R.A., 1978. *Astrophys J.*, **225,** L31.

Damashek, M., Backus, P.R., Taylor, J.H., & Burkhardt, R.K., 1982. *Astrophys. J.*, **253,** L57.

Davies, J.G., Lyne, A.G., & Seiradakis, J.H., 1972. *Nature* **240,** 229.

Davies, J.G., Lyne, A.G., & Seiradakis, J.H., 1973. *Nature Phys. Sci.*, **244,** 84.

Erickson, W.C., 1983. *C.S.I.R.O., Division of Radiophysics Internal Report*, RPP 2698.

Hulse, R.A., & Taylor, J.H., 1974. *Astrophys. J.*, **191,** L59.

Hulse, R.A., & Taylor, J.H., 1975. *Astrophys. J.*, **201,** L55.

Manchester, R.N., Lyne, A.G., Taylor, J.H., Durdin, J.M., Large, M.I., & Little, A.G., 1978. *Mon. Not. R. astr. Soc.*, **185,** 409.

Manchester, R.N., Tuohy, I.R. & D'Amico, N., 1982. *Astrophys. J.*, **262,** L31.

Seward, F.D. & Harnden, F.R., 1982. *Astrophys. J.*, **256,** L45.

DISCUSSION OF MANCHESTER'S PAPER

REYNOLDS: Did the limit you quoted yesterday on 0540-693 come out of the Parkes work?

MANCHESTER: They were observations made at Parkes and Molongolo. They have about the same flux density limit of [?????].

REYNOLDS: The X-ray duty cycle is about 50%. Is that the appropriate flux limit for such a duty cycle?

MANCHESTER: I think I assumed a duty cycle of around 12.5%.

STINEBRING: So is your plan to continue along the same lines at Molongolo and Parkes?

MANCHESTER: To some degree, but I'm going off to Jodrell Bank for six months, so there won't be any more observing in the southern hemisphere for six months. It's fair to say that the southern hemisphere is pretty rich, richer than the northern hemisphere, surely, and the northern telescopes still can't get down to the good part which is -50 to -60 degrees, so there are good arguments for continuing. There is another group down there, doing some work: Peter McCulloch, Pip Hamilton, and John Ables. I think it will be done eventually. By whom and how, I'm not sure.

BUCCHERI: For the pulsars inside the three gamma-ray error boxes, did you start a timing analysis and an attempt to measure $\dot{P}$?

MANCHESTER: No. One has to have a lot of stamina to time pulsars as weak as these. Unless one has a lot of objects that you want to time, it's a pretty big effort for just a few results. I am trying to get a fairly large scale timing program going at Molongolo. Molongolo is very well suited for timing right now. It has circular polarization and good instantaneous sensitivity. You could time 100 pulsars in a day.

KULKARNI: Regarding this [?] of binary stars and X-ray sources, we've looked at a lot of them with the VLA--this is really long-shot stuff. Looking at them in continuum is a somewhat better approach, because only if you see some continuum flux is there some chance that there will be a pulsar there. It really is very sensitive. You can go down to less than a millijansky in a routine snapshot. First of all I wouldn't expect pulsed emission from radio stars. Despite this, if there is some emission, I wouldn't expect it to be detectable because the dispersion measure is going to be so high that looking at a typical low frequency would not show a lot of pulsars in such systems.

MANCHESTER: I agree, but nobody has ever found a pulsar in a Her X-1 type binary system. As far as the continuum emission goes, we don't have a VLA in the south so we can't do that. It is quite easy to pick up the pulsed emission from PSR 1509, however, so I think it is worth looking at the binary systems.

BACKER: That's the second comment I've heard about the dispersion measure in the vicinity of a main sequence star being a problem in detecting pulsars, and I'm not sure I understand that. We don't see the dispersion measure from our solar wind normally--the only detection of it was on the Crab pulsar within about a degree of the sun.

MANCHESTER: No, I was talking about accretion systems.

BACKER: All right, accretion systems are a different story.

MANCHESTER: You'd have to get a binary system in which the companion star is in its main sequence phase--it hasn't expanded up yet. An O star probably has too strong a stellar wind for pulses to get through, but a B star or later should be OK, at least according to my estimates.

BORIAKOFF: PSR 1953 was looked at very quickly with the VLA after our discovery to make sure that it was there. It took 45 minutes of VLA integration to get a 6σ result at the lowest frequency, so that mode of search doesn't seem too promising.

KULKARNI: Perhaps Miller [Goss] could tell us the sensitivity of the VLA.

GOSS: In a 5-minute integration you get an rms noise in Stokes parameter I of about 0.8 mJy.

MANCHESTER: It's really confusion that gets you in a lot of these systems. PSR 1509, for example, is sitting on the edge of the supernova remnant...

GOSS: You have to use high resolution to kill the confusion. A second of arc in the Galactic plane kills almost all the confusion.

BORIAKOFF: I have an unpublished observation of PSR 0950+08 when it was close to the sun, and at 18 solar radii you can see the change in dispersion measure very clearly.

TAYLOR: By working hard, but surely not at the level that it would mask a pulsed signal. But my point is that in unbiased surveys of the sky we find almost 400 pulsars, but in none of those cases do we find pulsars that are orbiting around B stars.

MANCHESTER: Sure, but that's all been done around 400 MHz, Joe.

TAYLOR: If a lot of them are in orbit around B stars then some of the orbits will be wide...

VAN DEN HEUVEL: Still, I think the neutron star itself does something to the wind and the surroundings of the B star because the neutron star has a non-negligible gravitational attraction and pulls the wind in its direction.

BACKER: Also, the low-frequency electromagnetic wave blowing material out of its way.

VAN DEN HEUVEL: We know a lot of cases of B stars that have neutron stars orbiting around them in very wide orbits. There are orbits that have periods of more than a year. The case of X Persei where the orbit is almost 600 days. And the only way you can see them is as X-ray sources and not as radio sources. I suspect that we underestimate the gas which the B star is blowing out.

MANCHESTER: You may be right, but that's not a good reason for not looking.

The Period Distribution of Pulsars

R. J. Dewey, G. H. Stokes, D. J. Segelstein, J. H. Taylor, and J. M. Weisberg

Joseph Henry Laboratories, Physics Department
Princeton University, Princeton, NJ 08544

ABSTRACT

The searching methods used to discover most of the known pulsars have had sharply reduced sensitivities to periods less than a few tenths of a second, and virtually *no* sensitivity to periods < 30 ms. This selection effect produces a bias in the observed period distribution, and has probably prevented the detection of a number of interesting objects. We discuss the period bias quantitatively and estimate its effect on present knowledge of the pulsar period distribution.

In the period range 1 - 100 ms, the facts remain highly uncertain. In an effort to improve the situation observationally, we have begun surveys at both Green Bank and Arecibo designed specifically to detect fast pulsars. These surveys should be sufficient to establish whether the distribution of pulsar periods is bimodal, with a second peak in the millisecond to tens-of-milliseconds range.

Sensitivities of Pulsar Surveys

Of the 368 pulsars now known, 349 were detected in one or more of the extensive surveys carried out by Hulse and Taylor (1974, 75), Manchester *et al.* (1978), Damashek *et al.* (1978, 1982), and Dewey *et al.* (1984). These four surveys used similar observational techniques and similar computer algorithms for recognizing pulsar signals. Their sensitivities depended in the usual way on such constants as antenna gain G, number of polarizations N_p, total bandwidth B, and integration time t. In addition, the sensitivities depended on sky background temperature T_{sky} and on a number of parameters of the pulsars themselves, including period P, intrinsic pulse width w, and dispersion measure DM. In each survey some compromises were made in order to maximize the number of detectable pulsars while keeping data storage and data analysis tasks manageable. In practice, the compromises meant allowing the minimum detectable pulsar flux densities to increase for periods below a few tenths of a second and dispersion measures above some minimum.

A simple analysis shows how the sensitivity of a pulsar survey must depend on period and dispersion measure. If DM_o is the dispersion measure for which dispersive smearing is equal to the data sampling interval τ, then for a pulse of intrinsic width w the observed width will be approximately

$$w_e = \left[w^2 + (\beta\tau)^2 + \left(\frac{\tau\, DM}{DM_o} \right)^2 \right]^{\frac{1}{2}} . \tag{1}$$

Here $\beta\tau$ represents the time resolution of the data, as determined by the sampling interval and the time constants of the anti-aliasing filters used (usually $\beta \approx 2$). For long period, low dispersion pulsars the first term of this equation dominates, and the pulsed waveforms are not much distorted by instrumental effects. The minimum detectable mean flux density for such pulsars is given by

$$S_o \approx \left[\frac{10\,(T_r + T_{sky})}{G \sqrt{N_p\, B\, t}} \right] \left[\frac{w}{P} \right]^{\frac{1}{2}} , \tag{2}$$

where T_r is the receiver noise temperature, G is the antenna gain in K Jy^{-1}, and the numerical factor 10 allows for a 7 σ detection threshold and an extra $\sim\sqrt{2}$ for system losses of various kinds. For faster and more highly dispersed pulsars, the minimum detectable flux density is larger, because the pulsed signal is smeared according to Equation (1). The resulting detection threshold can be shown to be

$$S_{\min} = S_o \left[\frac{P\, w_e}{w\,(P - w_e)} \right]^{\frac{1}{2}} . \tag{3}$$

Table 1 lists the relevant parameters of the four surveys mentioned above, and Figure 1a illustrates the resulting dependences of sensitivity on period. In computing the curves of Figure 1a, we have used the fixed dispersion measure 60 cm^{-3} pc and sky background temperatures typical of the regions actually searched (see Table 1). In addition, we have assumed a fixed duty cycle that is typical of most pulsars, $w / P = 0.04$. We have assumed $\beta = 2$ for all the surveys except the two Princeton fast pulsar searches, where $\beta = 1.4$ is assumed.

Table 1. Parameters of Six Pulsar Surveys.									
Survey	G (K/Jy)	N_p	B (MHz)	t (s)	T_{sky} (K)	T_r (K)	τ (ms)	DM_o (cm^{-3} pc)	PSRs
UMass-Arecibo	14	2	8	137	120	110	16.7	638	50
Second Molonglo	5	1	3.6	41	90	210	20	182	224
UMass-NRAO	1.3	2	16	137	50	170	16.7	61	51
Princeton-NRAO (I)	1.3	2	16	137	55	30	16.7	61	83
Princeton-NRAO (II)	1.3	2	8	132	70	30	2	57	
Princeton-Arecibo	14	2	0.96	39	120	80	0.33	53	

The Period Distribution

Figure 1b is a histogram of the periods of all known pulsars, on the same horizontal scale as the sensitivity curves in Figure 1a. The number of presently known pulsars falls rapidly below $P \approx 0.5$ s, even though the survey sensitivities are only beginning to roll off gently at that period. Thus, the peak in the histogram at $P \approx 0.7$ s must be a real effect, and not the result of observational selection alone. Of course, observational bias has made the short period fall-off somewhat steeper than that of the true pulsar population.

It is possible to estimate the number of pulsars that have escaped detection because of the reduced sensitivities of surveys at short period and high dispersion. If we assume that DM is proportional to distance and that the pulsar luminosity function (the space density of pulsars with luminosity greater than L) is proportional to L^{-1} (see Lyne *et al.* 1984, Dewey 1984), then for a given P and DM the number of detectable pulsars will be reduced in proportion to $S_o \,/\, S_{\min}(P\,,DM\,)$. By using the pulsars found in the UMass-Arecibo, Second Molonglo, and UMass-NRAO surveys, scaling the number in each bin of P and DM by the ratio $S_{\min}(P\,,DM\,)/\,S_o$, and then integrating over DM, we obtained the corrected period distribution shown in Figure 1c. It should be noted that the correction factors increase to as

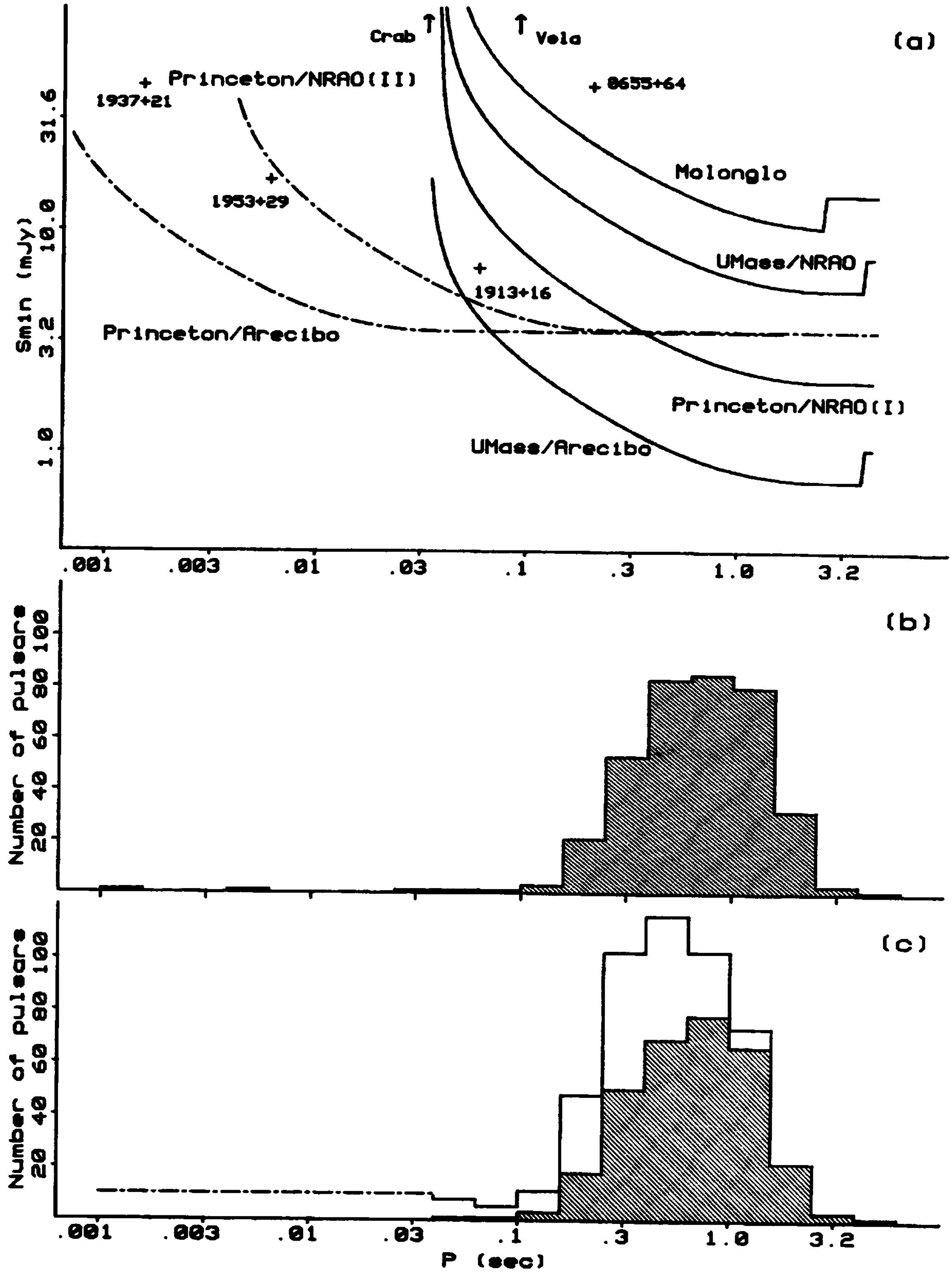


Fig. 1. (a) The minimum detectable flux densities of six pulsar surveys as a function of period, for $DM = 60 \text{ cm}^{-3}$ pc. (b) The observed distribution of known pulsar periods. (c) The observed distribution of periods for pulsars found in the Arecibo, Molonglo, and UMass-NRAO surveys (shaded histogram) and an estimate of the true distribution, corrected for reduced sensitivity at short period and high dispersion measure.

much as ~ 8 at $P \approx 0.05$, so the uncertainties are correspondingly large in this region. Finally, to obtain a *very* rough idea of the number of pulsars with even shorter periods, we note that in the mini-survey that detected PSR 1953+29, Boriakoff *et al.* (1983 and private communication) found a total of nine pulsars — one of which had a period in the millisecond range. The broken-line extension in Figure 1c is based on this fact, and is placed so as to make the area under it equal to one-ninth of the total area of the corrected histogram.

New Surveys for Fast Pulsars

The discovery of millisecond pulsars PSR 1937+21 and 1953+29, and the importance of binary pulsars PSR 0655+64 and 1913+16 and the Crab and Vela pulsars, make a very strong case for undertaking surveys optimized for the detection of short period pulsars. We have begun two such efforts — one using the NRAO 92 m antenna to survey a large fraction of the region $|b| \lesssim 15°$, $15° < l < 230°$, and the other using the Arecibo telescope and covering approximately 360 square degrees in the region $|b| \lesssim 9°$, $40° < l < 70°$. As shown in Figure 2 and documented in Table 1 and Equation (2), each survey will reach a typical minimum flux density of about 3 mJy. The total bandwidths, number of receiver channels, sample rates, and integration times have been chosen so that the Green Bank survey can have good sensitivity to periods in the tens-of-milliseconds range, for moderately large dispersion measures, and still cover a substantial area of sky. The Arecibo survey is complementary: though much more limited in sky coverage, it extends to six times shorter periods and maintains its sensitivity better at large dispersion measures.

In these surveys the data-handling problem is a formidable one. With three-bit quantization of the data samples, each survey will fill several hundred computer tapes. We are assembling a small but powerful computer system that will be dedicated to the task of processing these tapes. It contains an array processor capable of 10 million floating-point operations per second, and will require several hours to process each tape.

Approximately 2500 square degrees have already been covered in the Green Bank survey, and 105 square degrees at Arecibo. Tests on known pulsars have been made each observing day in order to verify equipment performance, and sensitivity checks with known pulsars and pulsed calibration signals confirm that the surveys are reaching the flux densities indicated by the curves in Figure 2. Full scale processing of the survey data will commence soon.

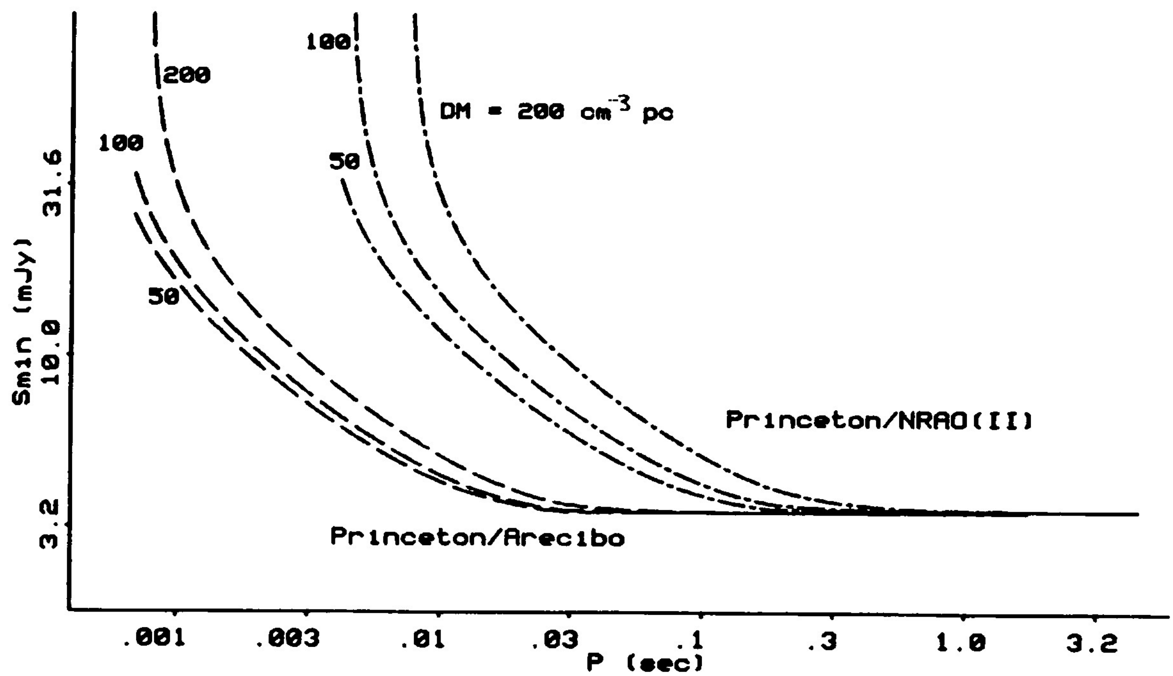


Fig. 2. Minimum detectable flux densities for the two Princeton fast pulsar surveys.

Present knowledge of the space density and luminosity function of pulsars (e.g. Lyne *et al.* 1984, Dewey 1984) and our estimates of the pulsar period distribution above 30 ms, suggest that the Green Bank survey should detect a total of ~150 "normal" pulsars, and the Arecibo survey ~50. Thus, if the number of pulsars with periods < 100 ms is as much as a few percent of the total, some new fast pulsars should be found. If most pulsars are born with short periods and large period derivatives, as was generally believed before the discovery of PSR 1937+21, then on theoretical grounds not many millisecond pulsars would be expected (Lyne *et al.* 1984). However, the short periods and small period derivatives of PSRs 0655+64, 1913+16, 1937+21, and 1953+29 suggest the existence of a second category of pulsars, with much weaker magnetic fields, which keep their short periods for much longer times. Because three of these four pulsars are presently in gravitationally bound binary systems, it seems likely that the evolution of fast pulsars may be rather different than that of the run-of-the-mill variety. In particular, the fraction of fast pulsars that are in binary systems may be relatively large.

References

Boriakoff, V., Buccheri, R., and Fauci, F., 1983. *Nature.* **304,** 417.

Damashek, M., Taylor, J.H., & Hulse, R.A., 1978. *Astrophys J.*, **225,** L31.

Damashek, M., Backus, P.R., Taylor, J.H., & Burkhardt, R.K., 1982. *Astrophys. J.*, **253,** L57.

Dewey, R.J., 1984. Unpublished Ph.D. thesis, Princeton University.

Dewey, R.J., Taylor, J.H., and Weisberg, J.M., 1984. In preparation.

Hulse, R.A., & Taylor, J.H., 1974. *Astrophys. J.*, **191,** L59.

Hulse, R.A., & Taylor, J.H., 1975. *Astrophys. J.*, **201,** L55.

Lyne, A.G., Manchester, R.N., and Taylor, J.H., 1984. *Mon. Not. R. Astr. Soc.*, submitted.

Manchester, R.N., Lyne, A.G., Taylor, J.H., Durdin, J.M., Large, M.I., & Little, A.G., 1978. *Mon. Not. R. Astr. Soc.*, **185,** 409.

DISCUSSION OF DEWEY'S PAPER

MANCHESTER: Of the 50 and 150 pulsars that you expect to detect in these two surveys, how many do we already know about.

DEWEY: About half. Maybe a little more than half.

STINEBRING: I'd like to make a comment that I can't really back up in any way. But, I think that the attempt to correct the period distribution for the sensitivity roll-off you have at short periods is being done overly pessimistically. I find it hard to believe that with the 1.6 millisecond pulsar and particularly I'm struck by the 6 millisecond pulsar, which I don't think is connected with the gamma ray source, meaning that it is then just a field pulsar at 6 milliseconds, and with all the talk of pulsars rising up out of the graveyard and being recycled for another life at shorter periods, it seems like there's the possibility of a much richer population at shorter periods than you were showing.

DEWEY: We're certainly hoping that's true. As I said, the uncertainties become very large. In fact we decided not to put error bars on the graph, because that would suggest that we know something about the uncertainties. The problem in that extrapolation is that it's very difficult to extrapolate from having seen no pulsars. When you scale 0 by 0 you still get 0, where what you probably should be doing is scaling 0.5 by 10 and getting 5.

LYNE: Did you say at what frequencies the searches were at?

DEWEY: Green Bank is at 390 MHz and Arecibo is at 430 MHz.

TOHLINE: These new surveys are still cutting off at 1 millisecond, and that's still a slowly rotating neutron star. I just wondered if people are waiting to see what this produces, or if there is an attempt to look shorter than that, or if that's just an impossible task.

STINEBRING: Send her some of your computer tapes.

DEWEY: As was mentioned earlier, the data-processing problem goes up as basically the inverse square of the period. Our view is that we'd like to see what comes out of these two searches before going further. Also, you either have to sacrifice sensitivity or time resolution at some point, or go out and get a Cray. And we can't quite afford a Cray.

REYNOLDS: Maybe in view of Dan's comment we should start calling these resurrected pulsars. In which case yesterday's session could be "day of the living dead."

TWO LOW-FREQUENCY SEARCHES FOR FAST PULSARS

Mary A. Stevens, Carl E. Heiles, and D. C. Backer
Radio Astronomy Laboratory, University of California, Berkeley

W. M. Goss and U. J. Schwarz
Kapteyn Astronomical Institute, University of Groningen, The Netherlands

J. S. Albinson
Netherlands Foundation for Radio Astronomy, Dwingeloo, The Netherlands

and

A. Purvis
Mullard Radio Astronomy Observatory, Cavendish Laboratory, Cambridge, U.K.

ABSTRACT

Two low-frequency surveys of the galactic plane have recently been completed. One survey used the NRAO 300-ft telescope at Green Bank looking for the frequency structure induced by interstellar scintillation. It covered the plane from l=15 to 235 degrees and |b| < 5 degrees as well as selected fields where previous observations indicate the possible existence of pulsars. The other survey was conducted using the Westerbork Synthesis Radio Telescope looking for highly polarized compact sources. This covered the plane from l=0 to 90 degrees and |b| < 1.3 degrees.

INTRODUCTION

Two recent surveys make use of known non pulse-related properties of pulsars to search for new pulsar candidates. Both surveys were conducted at meter wavelengths, exploiting the fact that pulsars are steep-spectrum objects so that low-frequency surveys are more sensitive to their detection. In addition, low-frequency surveys are preferable because the beam is large, allowing relatively fast coverage of the sky. One survey is a search for sources exhibiting interstellar scintillation (ISS). The other survey is an aperature synthesis search for polarized sources. This survey takes advantage of the fact that many pulsars are strongly linearly polarized with with the percentage polarization increasing with lower frequency.

I. NRAO ISS SURVEY

We (Stevens, Heiles and Backer) used the Green Bank 300-ft transit telescope to survey the galactic plane for frequency structure due to ISS at 360 MHz. ISS is caused by scattering of radio waves due to interstellar electron density irregularities. At meter wavelengths a source must have an angular diameter no greater than 10^{-6} arcsec and have a large brightness temperature to exhibit ISS. The only known sources meeting these criteria are pulsars. ISS is manifested as random intensity fluctuations with fine structure in frequency and time. Characteristic scales of these fluctuations range from kHz to MHz in frequency and from minutes to hours in time.

The frequency structure, characterized by the decorrelation bandwidth, varies roughly as the inverse fourth power of the dispersion measure.

In order to be sensitive to the large range of dispersion measures known for pulsars, we had to cover a large range of spectral resolution. We achieved this by splitting the 384 channel correlator into three separate receivers. One receiver used the minimum available bandwidth of 39 kHz with 192 channels for a resolution of 200 Hz. The second receiver had a total bandwidth of 312 kHz with 96 channels giving a resolution of 3 kHz. The other receiver had a bandwidth of 5 MHz using 96 channels for a resolution of 50 kHz. Thus we are easily sensitive to all decorrelation bandwidths between 1 kHz and 1 MHz. While we may not be able to detect scintillation from sources with very large dispersion measures, our range of resolution is quite large and covers a very interesting region of parameter space.

We observed at constant galactic latitudes by varying the declination of the telescope as the sky drifted by. The beam was 45 arcminutes FWHM so a source would pass through the beam in approximately 3 minutes. Spectra were recorded sequentially with integration times of 20 seconds. Averages of series of these scans are used as a reference for each individual spectrum. At the present stage of analysis, we are able to detect spectral features arising from scintillation at the 100 mJy level by computing the RMS deviation of each spectrum. More sophisticated analysis should improve this detection level.

This survey covers 2400 square degrees for $|b| < 5$ and $l=15$ to 235 degrees. In addition to this coverage of the galactic plane, we observed specific regions of the sky where the possible existence of pulsars is indicated.

II. WESTERBORK 327 MHz POLARIZATION SURVEY

Using the new 327 MHz receivers at WSRT we (Stevens, Heiles, Backer, Goss, Schwarz, Albinson, and Purvis) have just completed the observations for mapping the first quadrant of the galactic plane in both linearly polarized and total intensity. At this frequency the primary beam is 2.5 degrees FWHM with a resolution of 1 arcminute. Pulsars should stand out as highly polarized point sources.

Six fields covering the Sagittarius Arm region were observed for a full 12 hours each. The RMS sensitivity in the polarized-intensity maps of these fields is 1 mJy. Therefore, a 10 mJy pulsar whose integrated flux is at least 30 percent polarized should be detectable. Short-cut observations of $1^1/2$ hours total integration time were done for the rest of the galactic plane from $l=0$ to 90 degrees, stepping 2 degrees between fields.

The bandwidth of these observations is 2.5 MHz. Differential rotation of the polarization vector across the band at 327 MHz due to ISM Faraday rotation is $1.3 \times 10^{-2} \times$ RM radians. A rotation measure (RM) of 350 radians m^{-2} would cause a rotation of 4.5 radians resulting in serious depolarization. We therefore retained 8 channels of "line" data for all observations. Thus in cases of such large RMs, the effect reduces to 0.6 radians across each 300 kHz band.

One of the full synthesis fields was centered on the millisecond pulsar 1937+214. In the polarization map, the pulsar stands out clearly as a point source with the strongest polarized flux in the field. In the total intensity map, the pulsar is indistinguishable from 4C 21.53W.

DISCUSSION OF STEVENS'S PAPER

KULKARNI: The same comment I made to Andrew [Lyne] is, Mary, that I hope you're not throwing away your V data.

STEVENS: We're observing with parallel dipoles, in which case you have to assume that V is zero.

STINEBRING: I think you're making too much of the possibility of using the circular polarization. Because if you were to take the whole pulsar population with standard periods and do integrated circular polarization, my guess is that the average would be 5% to 10%, at the most. Which is, of course, very big compared to everything else...

KULKARNI: Very big. It may be that there are objects even more interesting than pulsars that may have high circular polarization.

STINEBRING: More interesting than pulsars?

STEVENS: I should mention that the 1 mJy rms is for a 12-hour synthesis. But it's also for one that's right in the Sagittarius arm region so you have the highest galactic background. Well, we do go down to 0° so it will be higher there, but on many of the shorter scans that may even compensate for the shorter integration.

DAVIS: Can you not actually combine your individual narrow-bandwidth maps on an assumed rotation measure in the sense of searching for rotation measure as an indicator of polarization and get the full sensitivity of the wide bandwidth? In the same way, say, that one searches for different values of dispersion measure in the processing of normal pulsars.

STEVENS: Well you ought to be able to fit it. The linear polarization should be constant across the band, but the other problem is that you have ionospheric Faraday rotation, and it's not clear yet how well that can be calibrated out.

Proposed U. C. Berkeley Fast Pulsar Search Machine

Shrinivas R. Kulkarni, D. C. Backer, Dan Werthimer and C. Heiles
Radio Astronomy Laboratory, U. C. Berkeley, Berkeley, Calif.

ABSTRACT

With the discovery of 1937+21 by Backer _et al._ (1982) there is much renewed interest in an all sky survey for fast pulsars. At U. C. Berkeley we have designed and are in the process of building an innovative and powerful, stand-alone, real-time, digital signal-processor to conduct an all sky survey for pulsars with rotation rates as high as 2000 Hz and dispersion measures less than 120 cm^{-3} pc at 800 MHz. The machine is anticipated to be completed in the Fall of 1985.

Our search technique consists of obtaining a 2-dimensional Fourier transform of the microwave signal. The transform is effected in two stages: a 64-channel, 3-level digital autocorrelator provides the radio frequency to delay transform and a fast 128K-point array processor effects the time to intensity fluctuation frequency transform. The use of a digital correlator allows flexibility in the choice of the observing radio frequency. Besides, the bandwidth is not fixed as in a multi-channel filter bank. In our machine, bandwidths can range from less than a MHz to 40 MHz. In the transform plane, the signature of a pulsar consists of harmonically related peaks which lie on a straight line which passes through the origin. The increased computational demand of a fast pulsar survey will be met by a combination of multi-CPU processing and pipeline design which involves a fast array processor and five commercial 68000-based micro-processors.

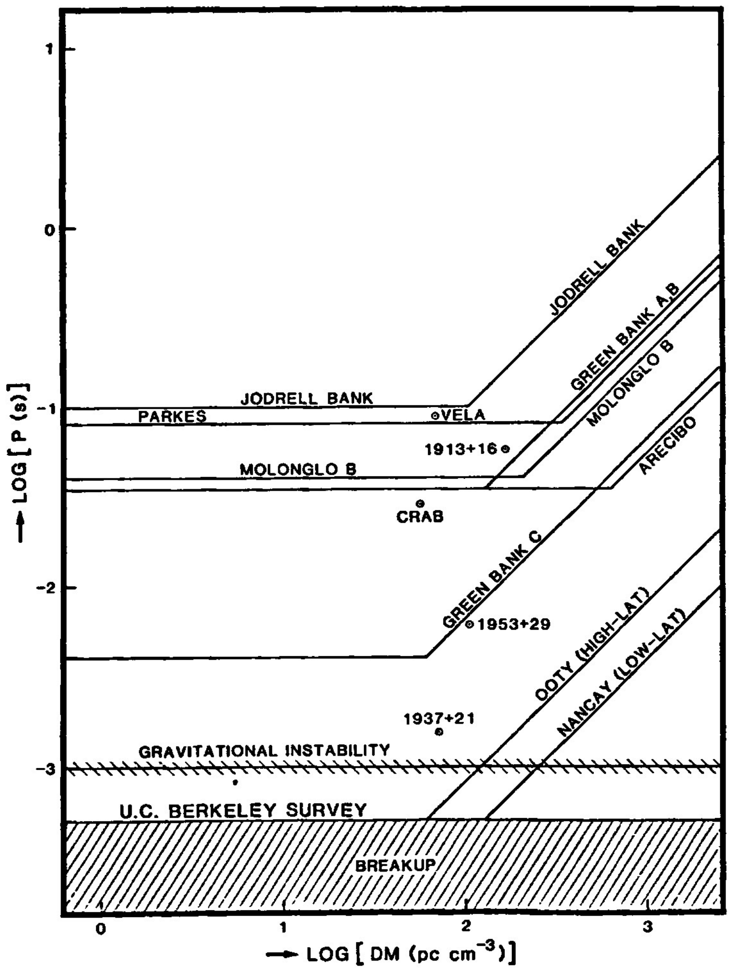
INTRODUCTION

Numerous directed searches have been conducted since the discovery of 1937+21. However the sky coverage of the directed searches has been insignificant. The undirected searches such as the search for highly polarized, compact low-latitude sources and scintars have been continuum searches and hence have not been as as sensitive as the searches for pulsed signals. None of these searches have, as of today, reported the discovery of a fast pulsar. This probably indicates that the sky is not teeming with _numerous_ and _bright_ fast pulsars. The only statistic that we have is the detection of a faint, fast pulsar in a systematic survey of about 5 sqaure degrees by Boriakoff _et al._ (1983). For this reason we believe that additonal pulsars will be mainly found by unbiased, sensitive pulsed-signal searches.

For a given sensitivity limit in flux density, one can easily show that the memory and the computational load increases as $P_{min}^{-2}\ DM_{max}$ where P_{min} and DM_{max} are respectively the minimum pulse period and maximum dispersion measure sought. This quadratic increase with P_{min}^{-1} makes real-time searches very attractive. Another advantage of a stand-alone real-time fast pulsar search machine (FPSM) is that surveys can be conveniently conducted at different observatories and marginal detections can be immediately verified and followed up.

Our search has been motivated by two questions:
(1) What is the maximum rotation rate for neutron stars?
(2) What is the galactic population of fast pulsars?

The answers to these questions require an all-sky survey with high sensitivity and with a minimum period beyond the present minimum of 1.6 ms. In Fig. 1 we show the region of P and DM parameter space that the FPSM can cover at a typical low frequency (327 MHz and labelled as the Ooty survey) and at a typical high frequency (1400 MHz and labelled as the Nancay survey). The sensitivity of these two (hypothetical) surveys is 35 and 0.8 mJy respectively.



THEORETICAL BASIS OF THE FPSM

The microwave signal from a pulsar is pulsed in time and dispersed in radio-frequency as a result of propagation through interstellar plasma. Thus the peak intensity of the signal traces a diagonal ridge in a time-radio frequency plot, the slope of which is related to the dispersion measure. The ridges are separated by a pulse period P along the time axis and a radio-frequency interval B_0 along the radio-frequency axis. Since adjacent ridges are separated by a time-interval P, B_0 simply corresponds to the radio-frequency bandwidth across which the dispersive delay is equal to P. B_0 clearly decreases with increasing DM and in particular, the ridges will be perpendicular to the time axis in the zero DM case. Since this pattern is periodic along both the axis, the 2-dimensional Fourier transform simply consists of peaks which lie on a straight line passing through the origin. The projections of peaks onto the transform axes are harmonically spaced with separations of 1/P in frequency (inverse time) and $1/B_0$ in delay (inverse radio-frequency). This 2-dimensional Fourier transform relation is the basis of the FPSM.

This 2-dimensional Fourier relationship was first recognized by Hamilton et al. (1973) and subsequently used by Komesaroff et al. (1973) for a survey of low latitude, high DM pulsars. The correlator-based approach employed by Heiles et al. (1983) in obtaining an HI absorption spectrum towards the 1.6 ms pulsar has many features in common with the FPSM.

The FPSM can be used for arrival-time measurements if the UTC epoch of the start of an integration is recorded. The complex Fourier amplitudes of the harmonics can be combined to yield the identical pulse arrival-time that is determined by traditional arrival-time measurements with signal averagers and template correlation. The FPSM can then be used to determine accurate pulse period, spin decay rate and if applicable, binary orbital parameters, for any objects discovered in the survey. The correlator-based approach to pulse timing is a promising method to obtain large bandwidths for sensitive measurements. We are looking into implementation of this technique for use at NASA's DSN telescopes.

HARDWARE DESCRIPTION OF FPSM

The FPSM is a pipelined digital-processor with successive operations being done in processors (68000-based micro-processors) tied to an industry standard (the Multibus). A block diagram of the planned device is shown in Fig. 2. The parallel architecture is pipelined with several buffer memories so that all processors can work simultaneously. A detailed description of the sub-systems follows.

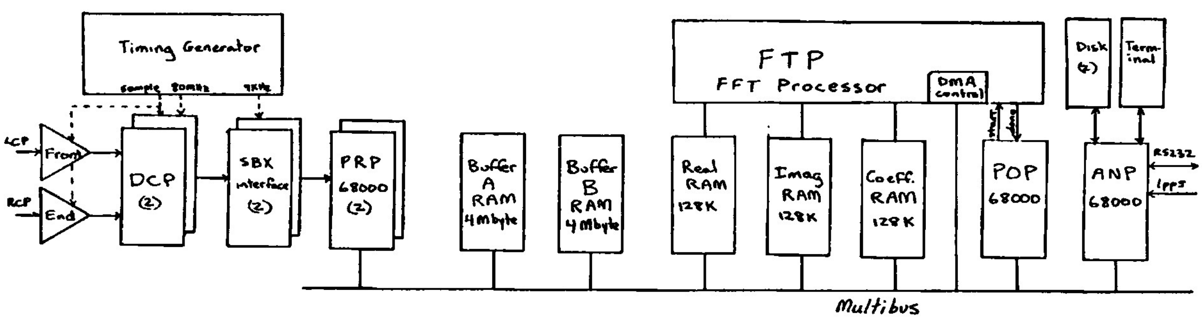


Figure 2
System Architecture

The IF signals from the telescope, separately in each polarization, are converted to baseband by the front-end electronics, filtered to a bandwidth B and then digitized at the Nyquist rate and passed to a 64-channel 3-level digital correlator (DCP). The DCP is a copy of the U. C. Berkeley's Radio Astronomy Laboratory correlator and can operate at clock rates upto 80 MHz. The correlator outputs are integrated for 250 μs and passed to the pre-processor (PRP). The PRP consists of two commercial 68000-based microcomputer boards each with a small local memory. Every 250 μs, the PRP adds the two polarizations together, subtracts a baseline value, scales the result down to 4 bits and saves this into one of the two 4-Mbyte buffer memories. At the end of 32.8 s, one of these giant buffers is full and the post-processor (POP) initiates a direct memory tranfer of 128K data points, corresponding to 32.8 s of time-series of the output of a correlator channel, to the FFT processor (FTP). This 32.8 s is the basic cycle of the FPSM in the sense that the sequence of operations is repeated every 32.8 s. POP then normalizes the power spectra from the FFT processor and selects channels with power above a pre-determined threshold and passes this information to the analysis processor (ANP).

In the transform plane, the signature of a pulsar consists of harmonically related peaks which lie on a straight line which passes through the origin. Assuming that the fluctuation frequency is represented by the x-axis and the delay by the y-axis, one can easily show that the slope of this line is proportional to the DM of the pulsar. The 2-dimensional Fourier transform is divided into 128 sectors. A sector is defined to be the area bounded by two lines passing through the origin. By convention, the mean angle (measured from the x-axis) subtended by sectors increases with sector index number.

The first 64 sectors are divided such that they span one delay step at the highest, unaliased fluctutation frequency. In the absence of quantization of the 2-dimensional transform, each of these 64 sectors correspond uniquely to pulsars with a different range of DM. Due to the finite size of the pixels of the transform, a certain amount of overlap is allowed. After overlap, all the sectors contain the same area and also the total amount of DM covered by each sector is the same. We intend to save a total 100,000 amplitudes which corresponds to about 1,500 points per spectrum.

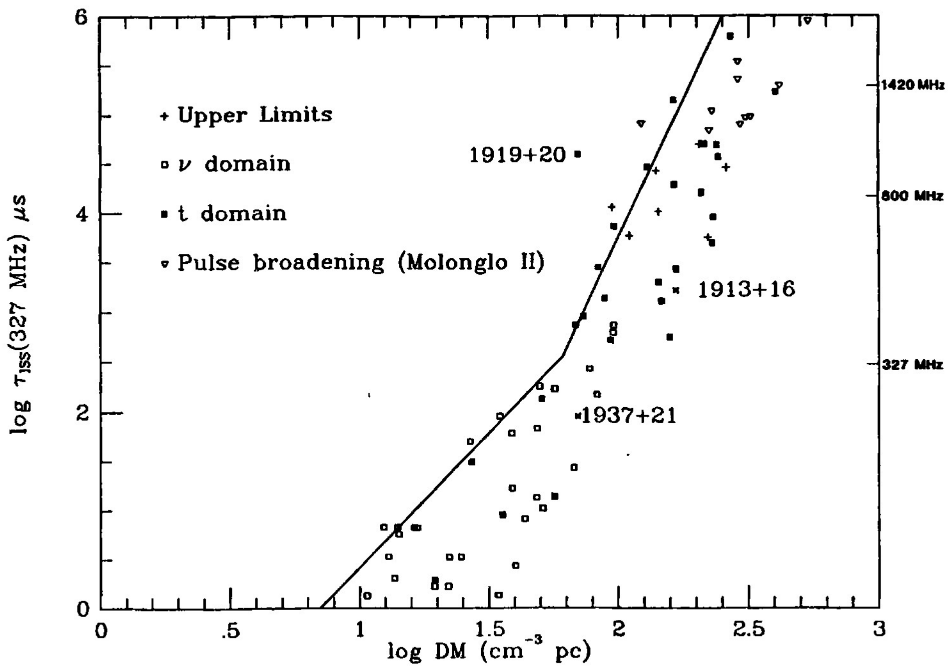
The next 64 sectors are divided in such a way that each of them has the same area as any of the first 64 sectors. These sectors, unlike the first 64 sectors, cover unequal amounts of DM. Aliasing of the fluctuation frequency introduces complications. However these can be taken care in a simple manner which we do not discuss here.

ANP searches for a harmonically related pattern, sector by sector. A histogram is formed in frequency by adding every amplitude into the frequency bin corresponding to the first through the tenth harmonic. In this manner all the clipped amplitude information for a pulsar is accumulated in a single bin corresponding to the fundamental with a weight corresponding to the amplitude. This includes data which is split between the pixels. The other additions are strewn randomly throughout the histogram. Candidate pulsar events will then be subject to a second iteration utilizing the complex data and also the periodicity along the delay axis is checked.

Since only the first 5 or so harmonics of a fast pulsar are present in our transform we are considering using a variable clipping scheme. This results in an optimal signal detection threshold at all fluctuation frequencies. Recognizing that harmonic summing is essentially incoherent averaging across fluctuation frequency we have a provision in the FPSM to incoherently average the transform in time. It is quite easy to show that for the fast pulsars this does not result in any significant degradation in the signal to noise ratio.

INTENDED SURVEY(S)

Our first priority is a survey of the galactic plane using the 300' Green Bank telescope. For a specified DM_{max}, we find, after taking into account of the galactic background and typical pulsar spectral index, that the signal to noise ratio of detection of a pulsar is roughly independent of



the observing frequency from 300 MHz to 1400 MHz. Beam area considerations make low frequencies attractive. The opposing factor is that the smearing time arising from interstellar scattering increases as $\nu_{RF}^{4.4}$ where ν_{RF} is the observing radio-frequency (Cordes, Weisberg and Boriakoff 1984). This time also goes as DM^n where n is ~1 for low DM and ~4 at large DM (Fig. 3). At any given ν_{RF}, there is maximum DM above which even the first harmonic of a 1 ms pulsar is suppressed by interstellar scattering. These limits on DM are shown by tick marks on the left, vertical axis for three choices of ν_{RF}. The conclusion is that an observing frequency of 800 MHz is the optimum frequency for the FPSM Green Bank survey. The subsequent surveys will depend very much on the Green Bank survey and hence will not be discussed at this point.

REFERENCES

Backer, D. C., Kulkarni, S. R., Heiles, C. E., Davis, M. M. and Goss, W. M.: 1982, Nature 300:615

Boriakoff, V., Buccheri, R. and Fauci, F.: 1983, Nature 304:417

Cordes, J. M., Weisberg, J. M. and Boriakoff, V.: 1984, in press

Hamilton, P. A., McCulloch, P. M., Ables, J. G., Komesaroff, M. M. and Cooke, D. J.: Astrophys. Lett. 15:163

Heiles, C. E., Kulkarni, S. R., Stevens, M. A., Backer, D. C., Davis, M. M. and Goss, W. M.: 1983, Astrophys. J. 273:L75

Komesaroff, M. M., Ables, J. G., Cooke, D. J., Hamilton, P. A and McCulloch, P. M.: 1973, Astrophys. Lett. 15:169

DISCUSSION OF KULKARNI'S PAPER

STINEBRING: Are you worried at all about interference? I know it's not going to be that big a deal at higher frequencies, but what I see in your design that worries me a little bit is your 32 second averaging window. If you pick up any interference and that gets into the correlated products, then that entire 32 second interval is going to get wiped out. Have you worried much about that?

KULKARNI: It's not a problem of averages. The problem is that our array processor has a 128 K limitation.

STINEBRING: Well, take for contrast the machine that's being constructed at Green Bank. There the spectral estimates are being performed very rapidly and you at least have the possibility of dropping out obviously interfered sections of data. You won't really have that opportunity, I don't think.

KULKARNI: It depends what kind of interference it is. We can excise off stuff, but again it costs us time, and everything is about running at its limit. In the post-processor we can knock off whatever we want, depending on what kind of interference it is...too high or correlation coefficient or something in one frequency channel that clearly isn't right. But since we're taking a filter bank approach we don't have to be extremely smart about what data we throw away since it is all organized by frequency channel.

FISHER: I was wondering about this scheme of throwing away all data that isn't above a certain threshold. Does that have the property that (1) it tends to be more sensitive to low duty-cycle pulsars and (2) do you not tend to throw away all harmonics? Wouldn't you be better off adding up the harmonics before checking them and throwing them away?

KULKARNI: I mixed up two different issues there. In each 32 second interval the averaging is done before the clipping. The averaging is done without clipping, and in the end we might not clip depending on exactly what analysis scheme we are using.

MANCHESTER: I think you've missed Rick's point. If you throw out a lot of values before you see if they are harmonically related, you're going to lose out.

KULKARNI: To some extent that is correct. People make a lot of the issue of harmonic summing, but look at it in the following way. All harmonic summing schemes are basically incoherent averages, and work only if--I've done a calculation on this--if each harmonic is above about 1.6σ. There's no information below 1.6σ at all. If all the harmonics are 1σ and you're going to get 16 harmonics, then that's a 4σ event and you won't detect it. You're only sensitive if each harmonic is above 1.6σ, and if they are below your signal is going to go as the fourth root of N, where N is the number of harmonics in the sum.

TAYLOR: Shri, did I understand correctly that your machine does a 128 K transform in 3 seconds?

KULKARNI: 0.3 seconds.

DAVIS: Is it not true that either this machine or the next machine could do a 2^{20} - 2^{24} point transform by just extending the memory, because you have longer to compute it. So that as memory prices come down you will be able to increase the size of the machine considerably.

BACKER: N log N. Don't forget the log N factor.

DAVIS: OK, within a factor of 1.5 or 2.

A CAMBRIDGE-VLA CONTINUUM SEARCH FOR FAST PULSAR CANDIDATES.

A. Purvis*, J. E. Baldwin, P. J. Warner
Mullard Radio Astronomy Observatory
Cavendish Laboratory,
Madingley Road, Cambridge CB3 OHE.
W. M. Goss**, J. H. van Gorkom,
National Radio Astronomy Observatory
Socorro, NM 87801
S. R. Kulkarni, C. Heiles,
University of California,
Department of Astronomy, Berkeley, CA 94720

Summary

The millisecond pulsar was found because of its compactness and steep radio spectrum. If more rapid pulsars are in our Galaxy then they might be discovered by looking first for similar anomalous properties. This paper describes such a search. A new interplanetary scintillation survey has just been completed northward of -10° declination. This survey is most sensitive to sources of size less than an arcsecond which are bright at low frequencies. It is ideal for selecting compact steep-spectrum objects. We describe how a sample of candidate fast pulsars has been assembled by (a) selecting the smallest IPS sources at low galactic latitudes, (b) determining a list of candidate source positions from existing catalogues and new data from the Cambridge Low Frequency Synthesis Telescope and (c) eliminating those with double radio morphology using the VLA.

1. INTRODUCTION

The task of finding additional fast pulsars is enormous unless one can find a way to discriminate promising candidates. The millisecond pulsar was first suspected as peculiar by its brightness at 26.3MHz (Viner and Erickson, 1975) and anomalously strong interplanetary scintillation, hereafter IPS, as pointed out by Duffett-Smith and Readhead (1976, DSR76). In searching for similar objects one strategy is to concentrate on steep-spectrum objects exhibiting IPS.

The extent to which a source scintillates depends upon its solar elongation and the increase of IPS as a source approaches the Sun can be calibrated with respect to angular size. It is therefore possible to select the smallest scintillating sources. Angular size is a particularly useful parameter in tracking down local objects. Extragalactic sources, no matter how small, when viewed at low latitudes have their images broadened due to bad seeing through the interstellar medium. Radiation from a compact galactic source

*Present Address, Dept. of Physics, University of Durham, Durham. DH13LE
** On leave from Kapteyn Astronomical Institute, University of Gronigen, The Netherlands

traverses less of the irregular plasma and its image is less smeared than adjacent, extragalactic sources.

Rickard and Cronyn (1979) re-analysed the earlier IPS data of Readhead and Hewish (1974, RH74), and suggested that if interstellar scattering was stronger than that determined by DSR76, then 4C21.53 could be of galactic origin and represent a new class of objects which they called 'scintars'. Purvis (1983) found 4C21.53 to have an angular size about three times smaller than the upper limit quoted by RH74 and concluded that even with the low value of scattering measured by DSR76 its distance could only be a few kpc.

Recent work on the new IPS survey of Purvis et. al. (1984a) has revealed that interstellar scattering at $|b| \leq 10°$ could be three times that determined by DSR76. Consequently any low-latitude source having an angular size less than half an arcsec might well be within our Galaxy.

In this paper we discuss first the selection of the smallest sources exhibiting IPS in the plane and then the problem of obtaining an accurate position for the object responsible. Compiling source spectra from a number of flux density catalogues was the next task. This resulted in a list of 134 objects whose morphology and polarization properties were required from VLA observations. Objects with double structure were excluded from the sample resulting in about 62 compact sources which could be bright at low frequencies and therefore candidate millisecond pulsars.

2. IPS DATA

Method

Interplanetary scintillation is only observed for sources which contain components ≤2.0 arcsec. Double sources scintillate because of hot spots in their outer lobes and SNRs (supernova remnants) only if they contain a compact core. The scintillations are produced by electron density fluctuations in the solar wind. These plasma irregularities modulate the phase of the plane wavefronts from a distant compact source and, beyond the Fresnel distance, give rise to a random spatial diffraction pattern. This pattern drifts across the radio telescope with the projected speed of the solar wind producing intensity fluctuations at the detector output on the timescale of one second. Angular size information is contained in the scintillation signal and can be extracted by monitoring the increase in scintillation with decreasing elongation. Such trends have been calibrated with respect to the angular size of the compact component by Readhead, Kemp and Hewish (1978, RKH78). In this investigation we have applied their calibration to derive θ, the mean angular size of the scintillating component(s) in a source and S, the flux density of the scintillating component(s).

Observations

The data considered here are a subset of a new survey of over 3000 sources which exhibit IPS, (Purvis et. al., 1984a). These data were recorded with the 3.6-hectare array at 81.5MHz in two sessions, each of 14 months duration. The array is phased to form 16 beams spaced at 6° intervals along the telescope's meridean having a half power beamwidth of $0.°45\sec(d)$ in right ascension and $5.°5\sec(52°-d)$

in declination, d. The second session repeated the first 14 month survey with the beams shifted about 3° to the north. Sixteen independent receivers monitor the 16 beams continuously and observe sources at transit. Scintillating sources were selected by averaging sections of the daily declination strip scans which were at an optimum elongation for IPS and finding beam shaped profiles on the resulting composite record. Every source was monitored daily, its scintillating flux density plotted against elongation and calibrated using the solar wind model of RKH78.

Interstellar Scattering

The overall distribution of the raw angular sizes is shown in Figure 1. The data have been binned on a grid 5°X5° square. For each cell containing more than one source, a simple mean angular size was evaluated and plotted on a grey scale spanning 20 divisions over the interval 0.1-2.0 arcsec. Strong interstellar scattering in the galactic plane is show up directly from the angular size distribution. The scattering appears more pronounced in a region $|b|\leq10°$ by a factor of three times that implied by the calibration of DSR76. Earlier determinations were based on statistical methods and the implications of this new measurement are discussed by Purvis et. al. (1984b). This result has an important bearing on the search for millisecond pulsars. Any source with an angular size less than 0.5 arcsec seen at $|b|\leq10°$ may be galactic.

Selecting Scintars

A list of fields was compiled in both the galactic anti-centre (3-8 hours RA) and centre (17-23 hours RA) directions which contained IPS sources and which had a diameter less than the anticipated interstellar scattering angle. Declination limits between 2° and 38° were selected to match the sky accessible to the Arecibo 300m telescope. Sources with $\theta\leq0.5$ arcsec with $|b|\leq10°$ were considered as prime candidates and other sources with $\theta<0.6$ arcsec up to $|b|\leq15°$, possible candidates. The prime sources constitute 25% of the sample. Table 1 lists the IPS properties of 46 scintar fields, 22 in the anti-centre and 24 in galactic center directions. The mean value of $|b|$ for the anti-centre sources is ~ 6° and for the centre sources ~ 10°.

Of the 41 scintars listed by Rickard and Cronyn (1979) from RH74 (excluding 4C21.53), seven lie within our defined sky area, though they all are in the anti-centre direction. Rickard, Cronyn, Perley and Erickson (1983) have made VLA observations of the brightest objects in these fields and found two to be unresolved with a beam of ≤2 arcsec and five to have a double structure. Of the unresolved objects, 4C23.14 was included in this programme but 4C08.21 was not because of its large (IPS) angular size. Of the double objects, 3C150 exceeded our angular size criteria and the IPS data for 3C154 were not available due to a daily calibration period. 3C115 and 3C158 were possible candidates but dominated their field and 4C29.18, another possible source, was not included because its surrounding field appeared empty on a 6C map. A further 11 interesting fields were included in the program for reasons other than IPS observations at 81.5MHz (Table 2).

Sensitivity

The 3.6-hectare array is confusion limited to total flux density at 2.4Jy per beam area. The scintillation confusion level at high galactic latitudes has been determined by Duffett-Smith, Purvis and Hewish (1980) to be 0.45Jy per beam area at a solar elongation of 40°. At low galactic latitudes, because of interstellar scattering, it is anticipated that the scintillation confusion level will drop to 0.2Jy for extragalactic objects,but the effect of compact galactic sources is unknown. The telescope sensitivity is degraded in these regions due to the large background temperature and system noise determines the sensitivity of the array. The 2 sigma detection level for scintillating flux density in the galactic centre region is 0.6 Jy and in the anti-centre region 0.4Jy. (The scintillating flux density of PSR 1937+21 is about 7 Jy at a solar elongation of 40°.) Thus, for a source with a measured angular size of 0.6 arcsec (having a scintillation index of 0.3 at 40° degrees elongation) the detection level is 2Jy in the galactic centre fields. This increases markedly at declinations less than 10° because the zenith angle exceeds 45° and the background noise due to the galaxy increases.

Positional accuracy

Having selected promising fields containing a compact source in the galactic plane, it is then necessary to tie down a position to the accuracy required for a pulse search using a large telescope. Although the half power beamwidth of the 3.6-hectare array is about 0.°5X6°(RAxDec), it is possible to estimate a scintar position to much better than this in the absence of serious confusion. Since the averaged records contain about 100 days observation of a source profile, it is possible to determine the RA of a source to ±4 arcmin. Also, by comparing signals on adjacent beams recorded simultaneously, a declination may be determined to ±90 arcmin accuracy. The compact source in 4C21.53 was found by Backer et. al. (1982) to be 16.3 seconds of time earlier and 8 arcmin north of the IPS position determined by Purvis (1983) using the 3.6-hectarce array.

3. DETECTING PULSARS

The 3.6-hectare array was formed by extending the original 4-acre aerial used in the discovery of pulsars. The new instrument has twice the collecting area and might be expected to detect many of the known slow pulsars, in addition to any possible new fast pulsars. If the signal of a pulsar is not dispersed then it appears like an IPS source which does not change its scintillating flux density with solar elongation. This results in a large angular size being fitted and such a source would not meet the criteria adopted to discriminate fast pulsars. Pulsars appear to be continuum sources for $D/P \geq 3$kpc/sec (D is the distance and P the period) for typical interstellar electron densities. These sources, like 4C21.53, would appear as compact sources having a flux density equal to the time averaged pulse profile. Figure 2 presents two short sections of averaged scintillation record in the galactic centre region. The fastest known pulsar (PSR 1937+21) follows the first known pulsar (PSR 1919+21) on the same declination strips (beams centred at 23°24' and 20°10').

Though both pulsars give comparable deflections, PSR 1937+21 has an IPS angular size of 0.27 arcsec and PSR 1919+21 ≥2.0 arcsec.

No scintillating flux (>0.6 Jy,) was detected from the 6.5 millisecond pulsar discovered by Boriakoff et. al. (1983).

4. SOURCES IN THE FIELDS OF SCINTARS

Since the IPS positions are poorly determined there will be several sources with flux densities greater that 0.1Jy at 151MHZ within the area of interest. (The candidate scintars will have S_{151}>0.5Jy for any spectral index up to 3). The positions of such sources were obtained from existing surveys and from observations with the new Low Frequency Synthesis Telescope at Cambridge which was being commissioned at 151MHz during November December 1983.

The existing surveys at our disposal were, in order of increasing frequency: The Cambridge 6C survey at 151MHz, the University of Texas UT survey at 365MHz and the Bologna B2 survey at 408MHz. These catalogues were used mainly to gain positional information rather than flux density data.

In the few months preceding the VLA observations, we had access to the new Low Frequency Synthesis Telescope at Cambridge which can provide maps with a resolution of up to 70X70 cosec (d) arcsec with an rms sensitivity of 20mJy in a 12h observing run over a field of 5-10°. A typical map is presented in Figure 3. At that time the flux density scale at low galactic latitudes, the positional coordinate system and the corrections for the effects of the ionosphere were poorly established, but the data were adequate to provide a complete list of candidate objects to be mapped by the VLA.

As a result 134 source positions were noted as being possible identifications of the scintillating objects.

5. VLA OBSERVATIONS

These 134 candidates were observed with the Very Large Array (VLA) of the National Radio Astronomy Observatory* in Socorro, New Mexico. The observations are described in Table 3. The purposes of the observations were: (1) determination of the morphologies of the sources in order to eliminate extragalactic double sources from the sample, (2) a measurement of the spectral index between 1415 and 1635 MHz, and (3) a determination of the linear polarization characteristics of the sources. Based on these three criteria a list of point sources was derived which formed the basis of the pulse search at Arecibo (see the contribution of Heiles et. al., this volume). For some of the sources it was possible to use lower frequency information (e.g. the UT survey or 151 MHz data from the Cambridge telescope) in a determination of the spectral index. From the VLA measurements themselves at 1415 and 1635 MHz, it is possible to derive an estimate of the spectral index. However because of the small difference in frequency of 225 MHz ($\Delta f/f$=0.14) between the two observing frequencies (Table 3), the errors in spectral index are substantial. For example for an rms noise of 0.8 mJy (A array observations) and a mean source flux density of 50 mJy the error in α is ± 0.15 (1σ).

*Operated by Associated Universities, Inc. under contract with the National Science Foundation.

Steep spectral indices ($\alpha>1; S\alpha\nu^{-\alpha}$) are characteristic of pulsars; by contrast most extragalactic sources (e.g. Owen et. al., 1983) have $\alpha<1.3$. As an example, Sieber (1973) has shown that the median value of α for 33 pulsars is ~1.5. The 1.5 millisecond pulsar has a spectral index of 2.2 over a frequency range from 30MHz to 1.5GHZ. Eleven of the 62 un-ambiguous point sources (see Table 3) have spectral indices ≥1.5; none of these showed pulses.

It is possible that some of these compact (≤1" arcsec for the A array observations) steep spectrum sources are related to the presumably extragalactic sources with steep spectra ($\alpha>1$) studied by W. D. Cotton and his colleagues (e.g. Cotton, 1983; Cotton et. al., 1984). As an example the source 2147+145 has an $\alpha = 1.4$ and is not optically identified. Roughly 50% of the flux density arises from a component $3X10^{-3}$ arcsec in size.

An additional characteristic of pulsars is the presence of large amounts of linear polarization. In fact the recognition of appreciable linear polarization in 4C21.53 as observed by the WSRT in the course of 1982 provided the final impetus for the discovery of PSR 1937+21 in late 1982 (Backer et. al., 1982). The percentage polarization was found to be 28% at 49cm and 15% at 21 cm. A large swing in polarization across the pulse will obviously contribute to the de-polarization of the integrated continuum source. Typical compact extragalactic sources as observed with single dish radio telescopes with beam sizes of 8-12 arcmin show 3 to 5% polarization at 18 and 20 cm (e.g. Simard-Normandin et. al., 1980; Gardner et. al., 1975). Only three of the 63 compact sources observed with the VLA show >9% polarization at either 1415 or 1635 MHz. None of these three showed pulses.

In a future publication we will describe these observations in detail and present a list of source parameters. The patchy nature of the interstellar scattering medium will be discussed. In addition, the Arecibo pulse search will be described.

REFERENCES

Backer, D. C. Kulkarni, S. R., Heiles, C., Davis, M. M. and Goss, W. M. 1982, Nature 300, 615.

Boriakoff, V., Buccheri, R. and Fauci, F. 1983, Nature 304, 417.

Cotton, W. D., Owen, F. N., Geldzahler, B. J. Johnston, K., Baath, L. and Romney, J. 1984, Astrophy. J. 277, L41.

Cotton, W. D. 1983, Astrophys. J. 271,51.

Duffett-Smith, P.J. and Readhead, A.C.S. 1976 Mon. Not. R. astr. Soc. 174,7.

Duffett-Smith, P.J., Purvis, A. and Hewish, A. 1980. Mon. Not. R. Astr. Soc. 190,891.

Garndner, F. E., Whiteoak, J. B., and Morris, D. 1975, Australian J. Phys. Astrophys. Suppl. 35, 1.

Owen, F. N., Condon, J. J. and Ledden, J. E. 1983, Astron. J. 88,1.

Purvis, A. 1983. Mon. Not. R. astr. Soc. 202,605.

Purvis,A., Hewish, A. Tappin, S.J., Rees, W.R. and Duffett-Smith, P.J. 1984a, in preparation.

Purvis, A. et.al. 1984b, in preparation.

Readhead, A,C,S, and Hewish, A, 1974 Mem. R. Astr. Sòc. 78,1.

Readhead, A.C.S., Kemp, M.C. and Hewish, A. 1978 Mon. Not. R. Astr. Soc. 185,287.

Rickard, J.J. and Cronyn, W.M. 1979. Ap. J. 228, 755.

Rickard, J.J., Erickson, W.C., Perley, R.A. and Cronyn, W.M. 1983 Mon. Not. R. astr. Soc. 204,647.

Sieber, W. 1973, Astron. Astrophys. 28, 237

Simard-Normandin, M., Kronberg, P.P., and Neidhofer, J. 1980, Astron. Astrophys, Suppl. Ser. 40, 319

Viner, M.R. and Erickson, W.C. 1975 Astron. J. 80,931.

Table 1. 46 scintar fields are listed together with the IPS parameters taken from Purvis et. al. (1984a). Fields have been selected according to the criteria θ_{IPS} <0.6 arcsec, $|b| \leq 15°$ and $2°<d<38°$. The seven scintars listed by Rickard and Cronyn (1979) from RH74 in the area of area of sky considered here are denoted by asterisks; all conform to the angular size limit. $S_{81.5}$ is the flux density originating within a qaussian component of scale θ_{IPS}.

1.

SCINTAR FIELD	θ_{IPS} (arcsec)	$S_{81.5}$ (Jy)	NOTES
0345+33	0.11	10.6	
0420+34*	0.41	9.3	
0423+30	0.59	4.4	
0428+34	0.32	6.0	
0506+29	1.2	9.8	Ooty IPS source with steep spectrum
0514+23*	0.49	6.4	
0518+29*	0.61	7.6	
0525+28	0.59	4.7	
0538+19	0.48	8.6	
0544+18	0.38	6.7	
0547+32	0.52	3.8	
0553+30*	0.91	6.3	
0554+13	0.59	16.8	
0611+26*	-	-	Calibration Period
0617+09	0.6	6.0	
0619+15*	0.52	14.1	
0620+36	0.42	8.3	
0625+31	0.48	5.0	
0630+08*	1.54	13.6	
0632+19	0.2	5.7	
0634+30	0.54	3.5	
0659+05	0.45	4.4	
1749+02	0.4	7.8	
1820+19	0.59	7.6	
1825+06	0.44	7.8	
1838+24	0.35	13.3	
1904+27	0.27	7.9	
1905+07	-	-	IPS source in SNR field
1906+20	0.35	7.9	
1908+09	-	-	IPS source in SNR field
1908+17	0.33	6.3	
1919+30	0.43	4.9	
1940+10	0.6	12.4	
1948+13	0.58	9.4	
1952+16	0.46	7.7	
2019+17	0.55	5.4	
2019+23	0.65	10	
2025+16	0.53	7.9	
2029+20	0.48	5.2	
2033+19	0.47	6.1	
2039+19	0.39	5.6	
2046+22	0.6	7.8	

2111+30	0.52	12
2121+29	0.44	8.8
2130+34	0.33	3.4
2207+37	0.21	7.0

Table 2.
11 additional fields. Only 1835+01 shows IPS at 81.5MHZ .

0601+01	-	-	Ooty IPS source
0635+24	-	-	Ooty IPS source
0646+16	-	-	Ooty IPS source
0657+17	-	-	Ooty IPS source
1846-00	-	-	3C391 (SNR)
1853+01	-	-	pulsar present (Mohanty et al)
1909+04	-	-	W50 SNR
1926+19	-	-	CG54, extended at 5GHz
1929+22			7% polarized at 610 MHz (WSRT)
1951+32	-	-	CTB 80
2014+37	-	-	CTB 87

Table 3.
VLA Scintar Observations

Dates:	25 November 1983	27 February 1984
Array:	A	B
Bandwidth:	50 MHz	100 MHz
Resolution:	1.3 arcsec	4.1 arcsec
Frequencies:	1415, 1635 MHz	1415, 1635MHz
Time/source:	3-5 min	6-7 min
Rms noise, I:	0.8mJy	0.5 mJy
Rms noise, Q and U:	0.3 mJy	0.2 mJy
Sizemaps:	2.6 or 5.2 arcsec	8.5 arcmin
No. of Doubles:	32	6
No. Point Sources*:	52	10
Mean α, point sources**:	1.0±0.1	
Mean polarization, point sources:	5±1%	

*Un-ambiguous classification.
** Both dates, rms error of mean.
*** Both dates (31 upper limits not included), rms error of mean.

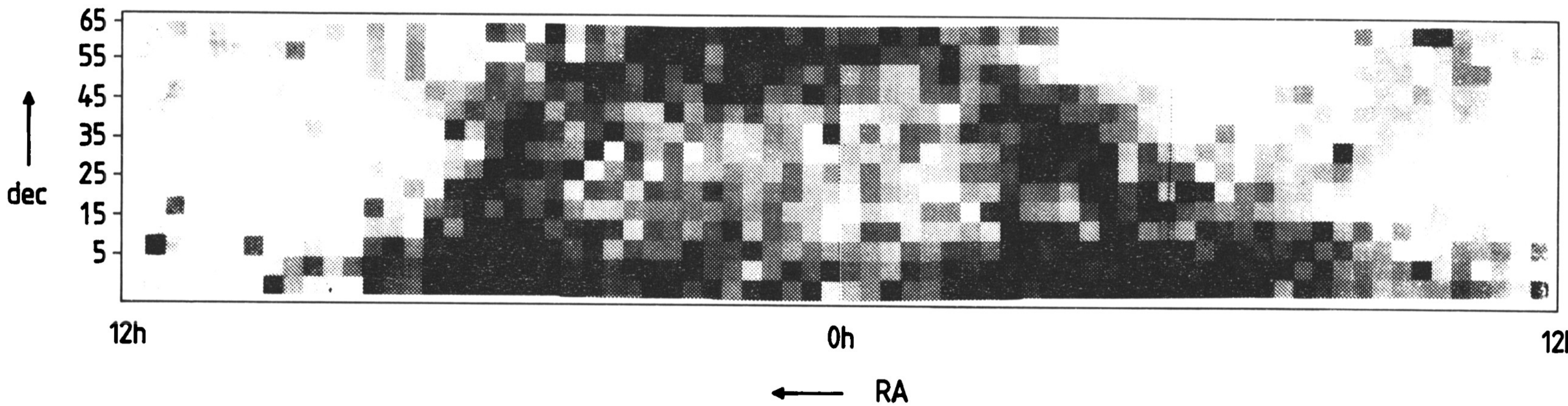


Figure 1

Figure 1. The distribution of angular size as determined by IPS across the northern sky, taken from Purvis et. al. (1984b). The galactic plane arching up at the end of the sidereal day is obvious. seen. The darkest grey shade corresponds to a mean angular size of 1.9-2.0 arcsec and lightest 0.0-0.1 arcsec.

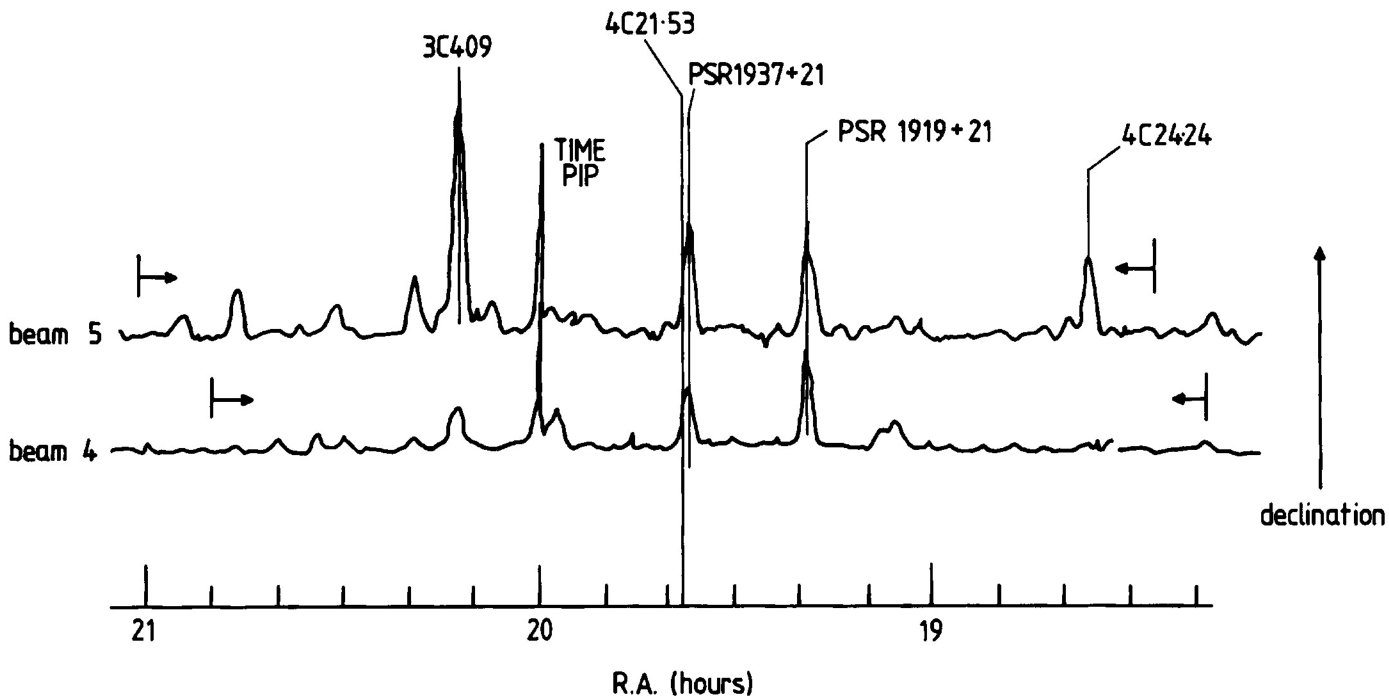


Figure 2. Two short sections of averaged scintillation record are shown. PSR 1937+21 follows PSR 1919+21 on the same declination strip scan (beam 5 has declination 23°24', beam 4 declination 20°10'). The vertical bars with inward pointing arrows refer to |b|<15°

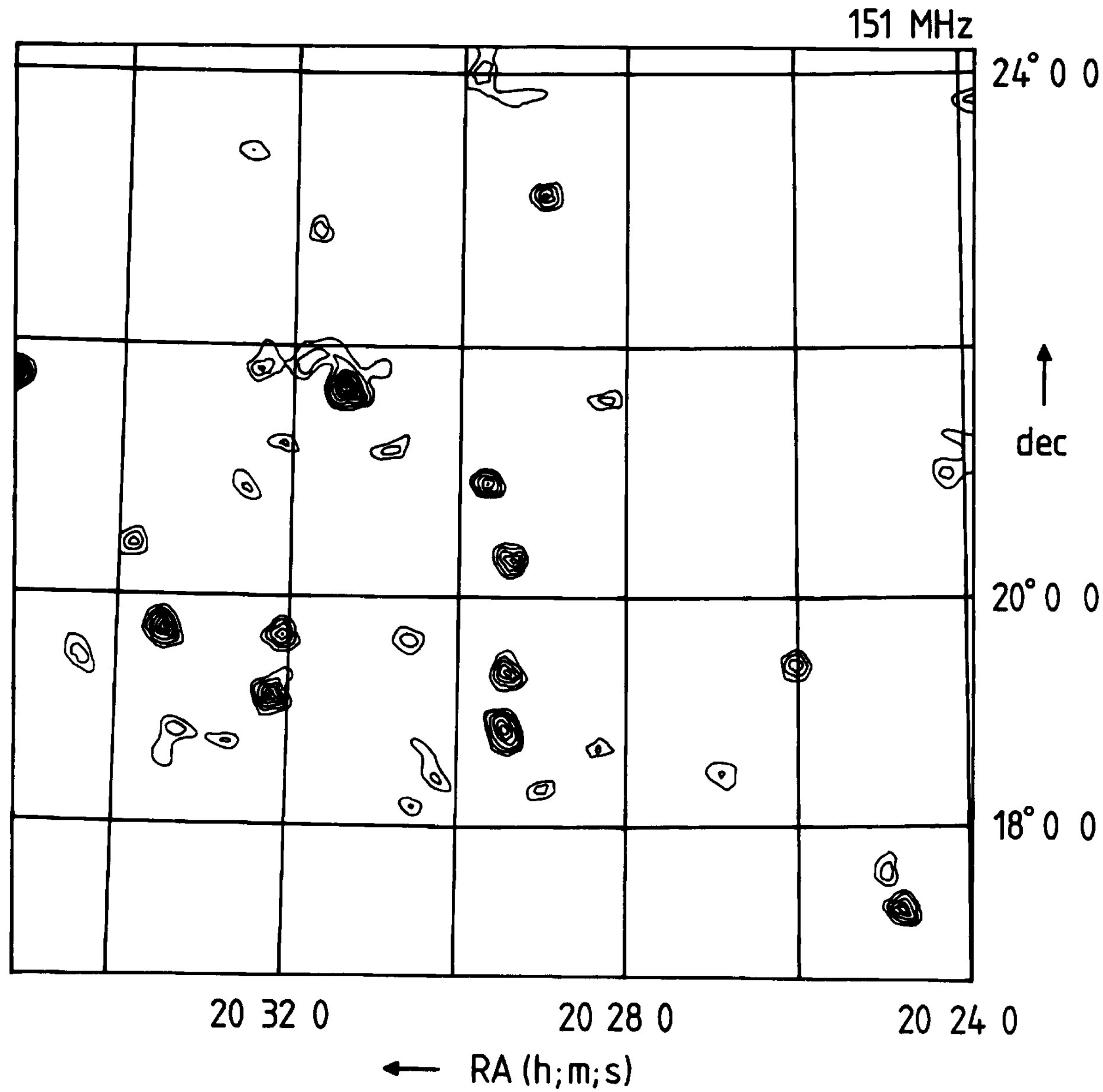


Figure 3. A 151MHz map taken of the scintar field 2029+20 illustrates the confusion problem of the 6° declination beam of the 3.6-hectare array. The angular resolution is 70"X200".

DISCUSSION OF GOSS'S PAPER

DAVIS: PSR 1937 itself is shining through [a cloud in the interstellar medium]. If it's truly at 5 kiloparsecs at the tangent point, then it's already halfway through the galaxy and we were just lucky that it did not get broadened.

GOSS: Yes, I agree with that.

TAYLOR: Did you detect any known pulsars?

GOSS: A lot of the classical pulsars were detected, but of course they were thrown away immediately.

TAYLOR: I think that it's significant that you were able to detect other pulsars besides PSR 1937.

GOSS: Slow pulsars, in fact, have the interesting property that when they are blindly looked for in this scintillation data they come out as large sources because once a second is just about the same frequency that the IPS data is going at, so it has very little variation with solar elongation. So PSR 1919+21 ends up in the survey as a large source. It has to have a large enough dispersion measure and or smearing so that it is no longer pulsing at 80 MHz, with this bandwidth.

BACKER: Just a comment about the Galactic center. One can look for scintars at a slightly higher frequency. In fact, the Ooty array has seen a heavy zone of avoidance toward the Galactic center. I don't know if they have a list of scintars.

GOSS: I think they do. Some of them have ended up in our list also.

ARECIBO SEARCH OF PULSAR CANDIDATES FOR PULSES AND INTERSTELLAR SCINTILLATION

Carl Heiles and Shrinivas R. Kulkarni, U. C. Berkeley

and

Alan Purvis, Univ. of Durham

and

W. M. Goss and J. H. Van Gorkom, NRAO

1. CANDIDATE SOURCES

The candidate sources were mainly obtained from the Cambridge Interplanetary Scintillation/VLA survey, described in the previous paper read by Goss (Purvis et al, 1984). A small collection of sources from the Ooty interplanetary scintillation (IPS) survey (Anantakrishnan and Rao, 1983), filled supernova remnants ('plerions', see Weiler, 1983), X-ray binaries, and other exotic sources were also searched. The bulk of our candidate sources exhibit IPS at low radio frequencies, which is indicative of small angular size. Such sources do not suffer angular broadening by interstellar scintillation (ISS), and thereby should be fairly nearby if they are located at low galactic latitudes. Such sources are commonly known as 'scintars' (Rickard and Cronyn, 1979).

In choosing which sources to observe first, we selected 'preferred' sources from these surveys using two secondary selection criteria, which are based on the characteristics of the 1.6 msec pulsar: high spectral index and high linear polarization. As our search progressed with negative results and discouragement, we occasionally modified our secondary selection criteria to include sources having abnormally low spectral index, ANY unusual property, and high variability index in the Texas Survey (Douglas et al. 1980).

All sources searched have flux density at 1400 MHz > 10 mJy and, of course, declination between 0° and 39° because we used the Arecibo telescope for this search.

2. TECHNIQUES

2.1. INTERSTELLAR SCINTILLATION

We used Arecibo's 1008-channel autocorrelator to search for spectral and temporal fluctuations in received source flux in a similar way as Backer et al (1982). That is, we recorded each polarization with 504 spectral channels over a 20-MHz bandpass. A total of 32 spectra were recorded at intervals of 20 seconds. In processing the data, we averaged the two polarizations and performed a two-dimensional autocorrelation of the data. We visually examined three displays: contour maps of the autocorrelation function, and one-dimensional cuts along the frequency and time-delay axes passing through the

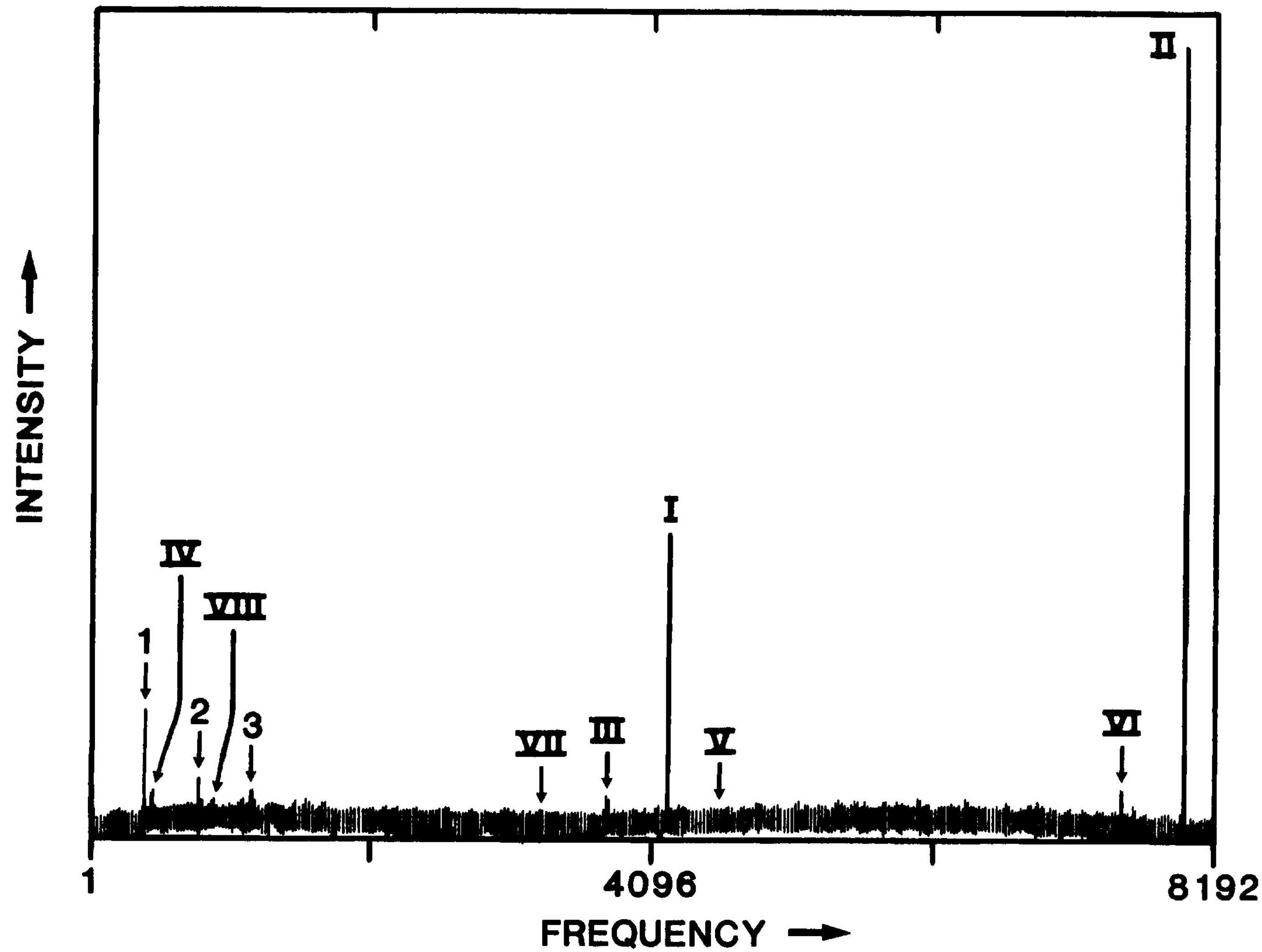


Figure 1. Draftperson's sketch of the Fourier spectrum of the 1.6 msec pulsar. Sampling frequency is 2500 Hz, so the frequency scale ranges from 0 at the left to 1250 Hz at the right. Roman numerals indicate harmonics of the pulsar, all of which but number I are aliased at least once. Arabic numerals indicate harmonics of the 60 Hz line frequency.

origin. We observed the 1.6-ms pulsar and found clear evidence for ISS. Unfortunately, none of the candidates that we observed exhibited the remotest evidence of scintillation.

2.2. PULSES

The pulse search program was done in three runs in April 1983, February 1984 and March 1984. Here we discuss the details of the last two runs. In the February run, we sampled orthogonal linear polarizations. Linear, rather than circular, polarization was used to account for the remote possibility that we might view a pulsar 'pole on', in which case its total intensity would be time-independent but its position angle might rotate. We observed both polarizations at four different center frequencies, separated by 5 MHz, to minimize the possibility of missing a pulsar because we happened to be observing at a minimum of the interstellar scintillation pattern. At each frequency we sampled the signal from a wide (1 MHz) and a narrow (0.25 MHz) bandwidth. We used two different bandwidths to enhance our sensitivity to both weak pulsars and pulsars having high dispersion measure. For these bandwidths, dispersion measures of 600 and 150 cm^{-3} pc, respectively, broaden incoming pulses by 1 msec. The March run used exactly the same setup as the February run except that circular polarization signals were sampled.

We filtered each signal through an RC time constant of 0.5 msec (2000 Hz) after detection, and sampled each signal every 0.4 msec (2500 Hz). The RC time constant does not cut off sharply above half the Nyquist frequency, 1250 Hz, so that pulsars having harmonic content above 1250 Hz are detectable as aliased signals. We observed each source for five or ten minutes. In reducing the data, we analyzed each of the eight channels separately. We performed 16K FFT's on each signal and incoherently averaged the FFT's over the full integration time.

The nominal 1-σ noise for this arrangement is about 0.7 mJy for a single pulse harmonic. However, owing to interstellar scintillation and our limited number of observing frequencies, the actual sensitivity for any given source can vary by a fairly large factor. This can be easily appreciated by looking at dynamic pulsar spectra, e.g. that of the 1.6 msec pulsar in Backer et al (1982). Nevertheless, we are confident that none of the sources observed show pulsations down to the level of a few mJy. This confidence comes from our routine test observations of the 1.6 msec pulsar, performed every day. We observed this pulsar with the VLA in Winter, 1984, and found it to have a 1400-MHz flux density of about 10 mJy; it was detected each day at Arecibo with a signal-to-noise ratio of at least ten at two of the four observing frequencies.

It is instructive to examine the 8192-point power spectrum of the 1.6 msec pulsar in detail, shown in Figure 1. This spectrum contains a total of nine spectral peaks. Harmonics of the pulsar are numbered with Roman numerals. The most prominent are the first and second harmonics (I and II). The second harmonic, at 1284 Hz, lies above half the Nyquist frequency and is thus aliased.

The second harmonic is more than twice as strong as the first. This occurs because the interpulse is strong, almost as strong as the main pulse. This situation seems to be common for fast pulsars because of the growing ellipticity of the emission cone with decreasing pulsar period, as shown by Narayan in a paper to be presented tomorrow at this meeting (Narayan, 1984).

The fact that fast pulsars tend to have strong interpulses, and thus stronger second harmonics than fundamentals in the Fourier spectra, has a very important ramification for searches for fast pulsars. Specifically, FOR SIGNAL-TO-NOISE REASONS, the signal-processing scheme should not preclude the detection of second harmonics of the fastest possible pulsars. An increase of sensitivity of more than a factor of two is obtained from the second harmonic, as opposed to the fundamental. This enhancement is more than can be easily obtained by sampling larger bandwidths with lower time resolution.

The other pulsar harmonics are much smaller and include the third, fourth, sixth, and eighth harmonics of the pulsar, all aliased at least once. Note that the even harmonics are stronger than the odd ones. Three peaks in the spectrum, labelled with Arabic numbers, are unrelated to the pulsar; they are the first three harmonics of the AC line frequency, which is 60 Hz in the United States.

3. RESULTS

This section is mercifully short. There were no positive detections of either interstellar scintillation or pulses. We examined about 45 sources for scintillation and about 90 for pulses. The full details of all our efforts and the candidates are in preparation and will be published elsewhere.

4. CONCLUSIONS

Our candidates include all reasonable scintars and a few sources chosen for other reasons. All have 1400-MHz flux densities larger than about 10 mJy. All reasonable candidates above this flux limit, and many unreasonable ones, within the Arecibo declination range were observed.

We conclude that PSR1937+21 is the only strong, fast pulsar within the Arecibo declination range. This does not necessarily mean that strong, fast pulsars might not exist in other declination ranges. However, we consider that possibility unlikely because other observers, using other telescopes, have not experienced that certain rush of elation that comes with success, either.

The implication is that fast pulsars are likely to be distant. Being distant, they are likely to have high dispersion measures. Having high dispersion measures implies that they will exhibit too much ISS to suffer IPS. Thus, we conclude that fast pulsars are NOT likely to be scintars.

Another possible candidate selection criteron is strong low-frequency linear polarization. This is being pursued by Stevens and her collaborators at WSRT, as explained previously by her at this meeting (Stevens, 1984). We hope that this effort will be successful, but the absence of strong linear polarization in the 6-msec pulsar is a bad omen, at least for generating a

COMPLETE list of candidates.

We conclude that the best search technique is a sensitive, undirected search for dispersed pulses. 'Undirected' here is used to mean either a complete, unbiased search of a very large number of known sources or, what might be simpler, a blind survey of large areas of sky at frequencies optimally chosen for different regions of the Galaxy. As described in an earlier paper at this meeting (Kulkarni, 1984), we at Berkeley are pursuing this approach.

REFERENCES

Ananthakrishnan, S. and Rao, P. 1983, personal communication.

Backer, D.C., et al, 1982, Nature, 300, 615.

Douglas, J. N., Bash, F. N., Torrence, G. W. and Wolfe, C., 1980, Univ. of Texas, Publications in Astronomy # 17

Kulkarni, S. 1984, paper presented at Millisecond Pulsar Workshop.

Narayan, R. 1984, paper presented at Millisecond Pulsar Workshop.

Purvis et al. 1984, paper presented at Millisecond Pulsar Workshop.

Rickard, J.L., and Cronyn, W.M. 1979, Ap J 228, 755.

Stevens, M. 1984, paper presented at Millisecond Pulsar Workshop.

Weiler, K.W., 1983, in Supernova Remnants and Their X-Ray Emission, ed J. Danziger and P. Gorenstein, D. Reidel Publishing Co.

DISCUSSION OF HEILES'S PAPER

STINEBRING: It seems premature to say that PSR 1937 is the only strong, fast pulsar. You've shown that it's the only strong, fast pulsar that you can find traveling down the path you traveled, starting with the scintar list and going through this filtering process.

HEILES: Yes. We're also restricted to declinations within the Arecibo range [0 - 40°]. But I think we're discouraged enough that we're happy to have anyone else out there doing it.

KULKARNI: I'd like to comment on Dan's [Stinebring] comment. The point is that the scintar survey is an all-sky survey. And if there is a pulsar that is 10 mJy at 20 cm and a kiloparsec away it should be seen in that list, which was the point that Carl [Heiles] was trying to make. Don't forget that it's an unbiased survey.

BACKER: The scintars are only along the Galactic plane.

VAN DEN HEUVEL: We have five strange objects, four binaries and one isolated millisecond pulsar, and three of them have 19^h right ascension. Doesn't that mean we're biased already?

TAYLOR: That's because of the Australians. It's just that they've been found in the northern hemisphere in the accessible part of the Galactic plane. If they had been found in the southern hemisphere they'd be just as likely to be 15^h - 16^h.

VAN DEN HEUVEL: Why is 19^h so special?

TAYLOR: Because of Arecibo. Even the survey we finished up in May is primarily responsive to pulsars in the first quadrant of the Galactic plane.

ARECIBO PULSAR SEARCHES IN CONNECTION WITH GAMMA-RAY SOURCES. STATUS OF THE EXPERIMENT.

V. Boriakoff[1], R. Buccheri[2], F. Fauci[3]

1 NAIC, Cornell University, Ithaca, N.Y.
2 IFCAI-CNR, Palermo, Italy
3 Istituto di Fisica dell'Università, Palermo, Italy

ABSTRACT

We report on the status of an experiment set up at the Arecibo Observatory for the search of fast pulsars in spatial coincidence with some of the gamma-ray sources of the 2CG catalogue. As a first result two new pulsars have been discovered : PSR1953+29 (a binary pulsar with 6.1 ms pulsation period and 117.3 days orbital period) and PSR1848+04, a low-magnetic-pulsar with 0.284 s pulsation period.

INTRODUCTION

An experiment to search for fast pulsars in spatial coincidence with some of the gamma-ray sources of the 2CG catalogue has been set up by a Palermo-NAIC collaboration. The programme of observation was announced at the I.A.U. Symp. n. 95 "PULSARS" (see Buccheri, 1981). The scientific justification was based i) on the knowledge that the only firmly identified gamma-ray sources of the 2CG catalogue (Swanenburg et al.,1981) were two pulsars, the Crab and the Vela pulsars, known to emit gamma rays (photon energy above 50 MeV) at the radio pulsation period, and ii) on the finding by Buccheri,Morini and Sacco (1981) that several other fast and high braking power pulsars can be visible in gamma rays in the hypothesis of a gamma-ray luminosity decreasing with the pulsar age (as indicated by the Crab and Vela cases).
The discovery by Seward and Hardnen (1982) of PSR1509-58 (see also Manchester, Tuohy and D'Amico, 1982), a pulsar with 150 ms pulsation period and 1.54×10^{-12} s/s period derivative, is in line with these predictions being this pulsar in spatial coincidence with a gamma-ray source of a list published by Wills et al., 1980.

THE EXPERIMENT

The experiment of search has been set up in order to look inside the error boxes of 5 out of the 22 low-latitude gamma-ray sources, those visible by the Arecibo radiotelescope (2CG036+01, 2CG054+01, 2CG065+00, 2CG075+00 and 2CG195+04). The table I lists the characteristics of the experiment

Table I

Receiver center frequency, f (MHz)	318	430
No. of polarizations, n	1	2
Type of polarization	linear	circular
System temperature, T (°K)	240	120
Antenna Efficiency, ε (°K/Jy)	7	11
Bandwidth per filter, B (KHz)	250	250
Total number of filters, M	30	30
Time constant, τ (ms)	4.12	4.12
Integration time, Δt (s)	550	550
Sampling interval, S (ms)	4.167	4.167
Minimum observable flux, Φ (mJy)	4.5	1.1

and fig. 1 shows the error boxes investigated so far : the left size of the figure refers to 318 MHz measurements while the right side refers to 430 MHz observations; the large circles are the gamma-ray source error boxes and the small circles represent the radio beams.

The minimum observable pulsar flux (continuum equivalent) has been calculated using the formula

$$\Phi = (T/\varepsilon)\,\frac{9.2}{n\ M\ B\ \Delta t} \qquad (1)$$

which allows for a 6 σ's signal in the output power spectrum for a pulsation effect with small intensity and small duty cycle (see Burns and Clark, 1969 and Buccheri and Sacco, 1984).

The validity of eq. 1 is obviously limited to the case when the smearing δt of the duty cycle due to the interstellar dispersion is small compared with the pulsar period, this is

$$\delta t = 8300\ (B/f^3)\ DM = \alpha P \quad \text{with} \quad \alpha \quad 1 \qquad (2)$$

where P is the pulsar period in s and DM is the dispersion measure in pc/cm^3. Fig.2 shows eq.2 in the DM-P plane at 430 MHz (fig.2a) and 318 MHz (fig.2b) and for two values of α. Above the line with α=1 the region is unvisible by our experiment and so is in principle the region of values of P less than 8.334 ms (twice the sampling interval S).

It can be seen from the figures that at the minimum value of the period observable by this experiment (8.334 ms) only distances up to DM=30 pc/cm^3 (430 MHz) or DM=10 pc/cm^3 (318 MHz) can be investigated. Higher values of DM are however accessible for larger periods and/or for pulsars with fluxes larger than the minimum observable one.

Of the two new pulsars discovered with this experiment, PSR1953+29 is located in a region of the DM-P plane not visible by the experiment. It was actually seen because of two concurring factors : a) its flux is well above the minimum observable (15 mJy at 430 MHz, see Boriakoff et al., these proceedings) and b) the possibility of aliasing was left open in the FFT analysis phase thus allowing the possibility of observing periods lower than 8.334 ms.

PSR1848+04

Table II lists the observed and derived parameters for PSR1848+04 (one of the pulsars discovered with this experiment) and fig. 3 shows its light curve at 318 MHz. It is interesting to notice the double, or perhaps triple, -peak structure of the first pulse and the presence of an interpulse at 210° distance from the first pulse.
The pulsar shows a quite wide duty cycle (more than 100° longitude) and a very low period derivative which indicate an old timing age and a fairly low magnetic field.

The analysis of the data relative to the observations shown in fig.1 is 80% complete and, apart the discoveries of PSR1953+29 and PSR1848+04, the result is negative.

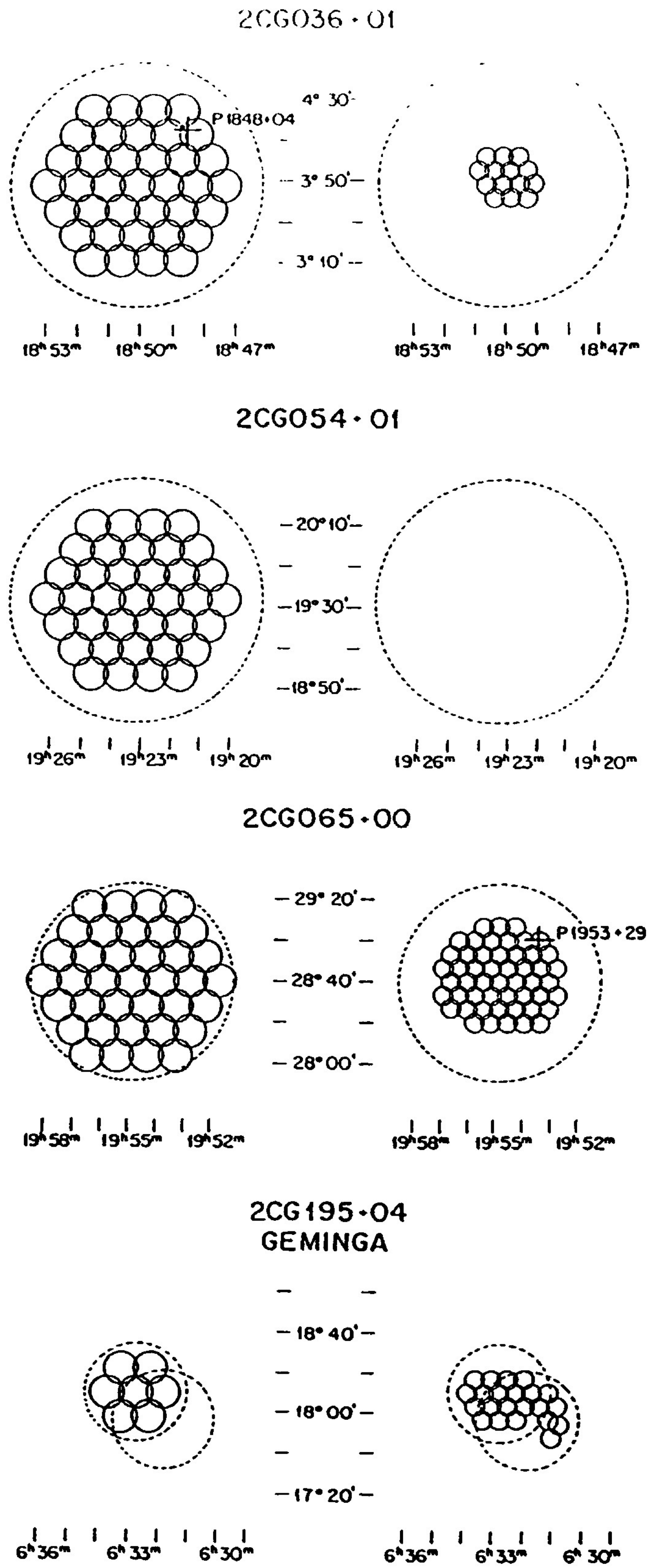


Fig.1

Fig. 2

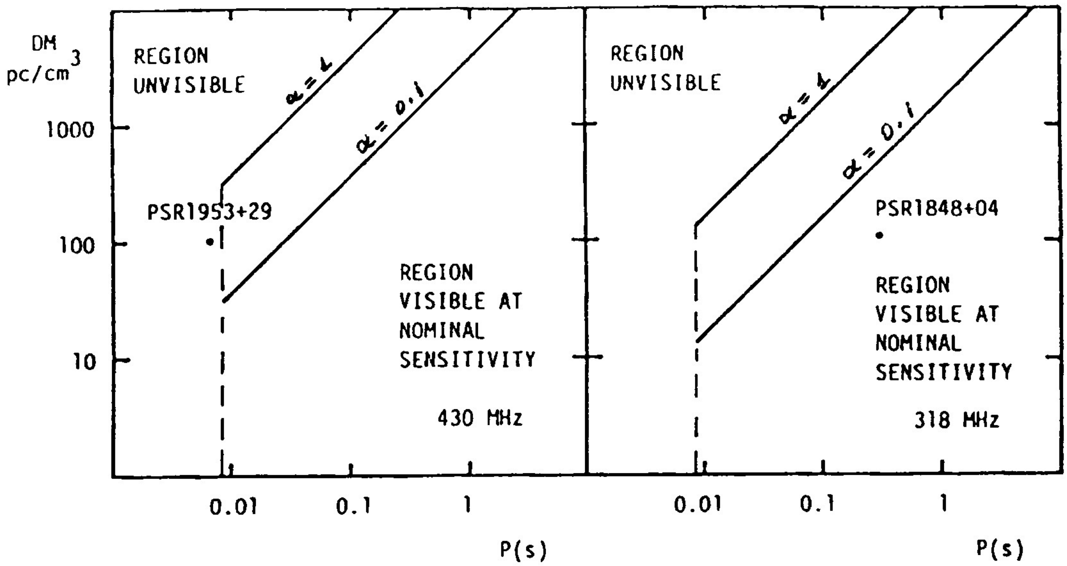


Table II

Right Ascension (1950.0) from VLA	$18^h\ 48^m\ 34^s.39$
Declination (") "	4° 14' 35".6
Position error	0".1
Dispersion measure (pc/cm^3)	112.0 +/- 0.2
Period (s)	0.2846970 +/- 5×10^{-9}
Period derivative (s/s)	(0.16 +/- 0.01)$\times 10^{-17}$
Epoch (JD)	2445062.761
Timing age (years)	2.8×10^{9}
Magnetic field (Gauss)	2.1×10^{10}
Distance (pc)	3700

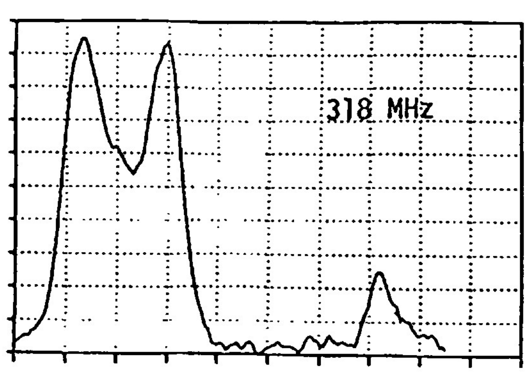


Fig. 3 Light curve of PSR1848+04

REFERENCES

V. Boriakoff, R. Buccheri, F. Fauci, K. Turner, M. Davis
These proceedings

R. Buccheri
IAU Symp. n.95 "Pulsars", Reidel, Dordrecht, p.241, 1981

R. Buccheri, B. Sacco
Proc. of the Intern.Workshop on Data Analysis in Astronomy, Erice, 1984

R. Buccheri, M. Morini, B. Sacco
Phil. Trans. Roy. Soc. London, A301, 495, 1981

V.R. Burns, B.G. Clark
Astron. Astrophys., 2, 284, 1969

R.N. Manchester, I.R. Tuohy, N.D'Amico
Astrophys. J.,262, L31, 1982

F.D.Seward, F.R.Hardnen
Astrophys. J.,256, L45, 1982

B.N.Swanenburg, K. Bennett, G.F. Bignami, R. Buccheri, P. Caraveo, W. Hermsen, G. Kanbach, G.G. Lichti, J.L. Masnou, H.A. Mayer-Hasselwander, J.A. Paul, B. Sacco, L. Scarsi, R.D. Wills
Astrophys. J., 243, L69, 1981

R.D. Wills, K. Bennett, G.F. Bignami, R. Buccheri, P. Caraveo, N. D'Amico, W. Hermsen, G. Kanbach, G.G. Lichti, J.L. Masnou, H.A. Mayer-Hasselwander, J.A. Paul, B. Sacco, B.N. Swanenburg
Proc. of a COSPAR Symp. "Non Solar Gamma Rays", Pergamon Press, 43, 1980

DISCUSSION OF BUCCHERI'S PAPER

KULKARNI: Am I not right in saying that neither PSR 1848+04 or PSR 1953 are associated with gamma ray sources.

BUCCHERI: Yes, I think they are not associated with gamma ray sources. Naturally, we cannot go back and re-fold the gamma ray data directly because the gamma ray observations were made several years ago, and then it's not possible to extrapolate so far. But, looking at the energy released by these objects with very small period derivatives, it doesn't seem that they could be gamma ray sources.

KULKARNI: What is the flux of the gamma ray sources?

BUCCHERI: The flux is about 10^{-6} photons/cm^2/sec.

UNIDENTIFIED: What energy photon?

BUCCHERI: Photons of energy about 0.9 [?] Mev.

V. GENERAL THEORETICAL ISSUES; SUMMARY

ELONGATED BEAMS AND MILLISECOND PULSARS

Ramesh Narayan[*]
Theoretical Astrophysics, California Institute of Technology
Pasadena, CA 91125, U.S.A.

ABSTRACT

It is argued on the basis of a variety of observations that pulsars have long fan-beams. The elongation is extreme in short period pulsars and decreases at longer periods. As a consequence fast pulsars have interpulses and relatively small variation of polarization position angle. In PSR 1937+21 the magnetic dipole axis and the line of sight appear to be tilted from the rotation axis by ~80° and ~40° respectively.

INTRODUCTION

It is widely accepted that pulsar radiation originates near the magnetic poles of a neutron star, from where it is beamed in twin cones. Gunn and Ostriker (1969) deduced from the observed pulse widths that the east-west angular size of the cones is ~15° (directions are relative to the rotation axis). It is usually assumed that the beam is circularly symmetric about the magnetic axis. Only recently has an effort been made to independently determine the north-south dimension of the beam and the results have been startling. It now appears that pulsar beams are highly elongated in the north-south direction, and that the elongation is a strong function of the pulsar period.

[*] On leave from : Raman Research Institute, Bangalore 560080, India

ARGUMENTS FOR ELONGATED BEAMS

(a) Figure 1 shows a pulsar beam viewed down the magnetic axis and the track of the line of sight to earth, offset from the magnetic pole by an angular distance β. If the field geometry is simple and the position angle of the linear polarization of the (radio) radiation is parallel (or perpendicular) to the projected direction of the magnetic field lines at the point of emission (Radhakrishnan and Cooke 1969), the total swing in the polarization angle θ is given by

$$\theta = 2\tan^{-1}(w/2\beta)$$

The distribution of ω/β and thus θ in a random collection of pulsars clearly depends on the shape of the beam, in particular on its elongation. Narayan and Vivekanand (1983a) used this to make a statistical analysis of the measured θ in 30 bright pulsars. They concluded that short period pulsars ($P \lesssim 0.4$ s) have highly elongated beams, the size in the north-south direction being 5 times or more larger than that in east-west. The ratio is 2.5 for 0.4s $< P <$ 1.2s and $\sim$1 (that is circular beams) for $P >$ 1.25s. The observations of Ashworth *et al.* (1983) and Stinebring (1983) show that PSR 1937+21 has a small θ (Fig. 2). This is in good agreement with the above results which predict for this pulsar an extremely elongated beam and hence on the average a small θ.

(b) It is known (e.g. Manchester and Taylor 1977) that interpulses are much more common in fast pulsars. For instance, two of the three fastest pulsars known today, 1937+21 and 0531+21, have interpulses, while none of the more than 100 pulsars with $P >$ 0.8s has an interpulse. The most natural explanation is that fast pulsars have elongated beams, while slow pulsars do not (Narayan and Radhakrishnan 1983).

(c) Hankins and Cordes (1981) showed on the basis of detailed observations on the interpulse of PSR 0950+08 (P = 0.25s) that conventional pictures are

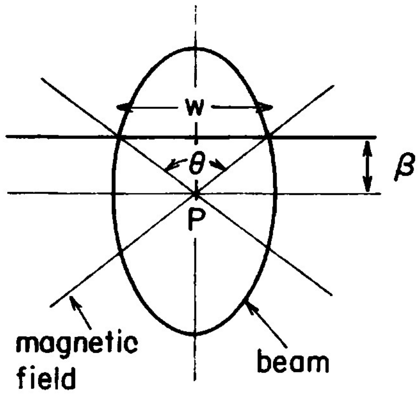


Fig. 1. Pulsar beam seen down the magnetic axis at P. The pulse width is w. The linear polarization position angle is expected to swing by θ within the pulse.

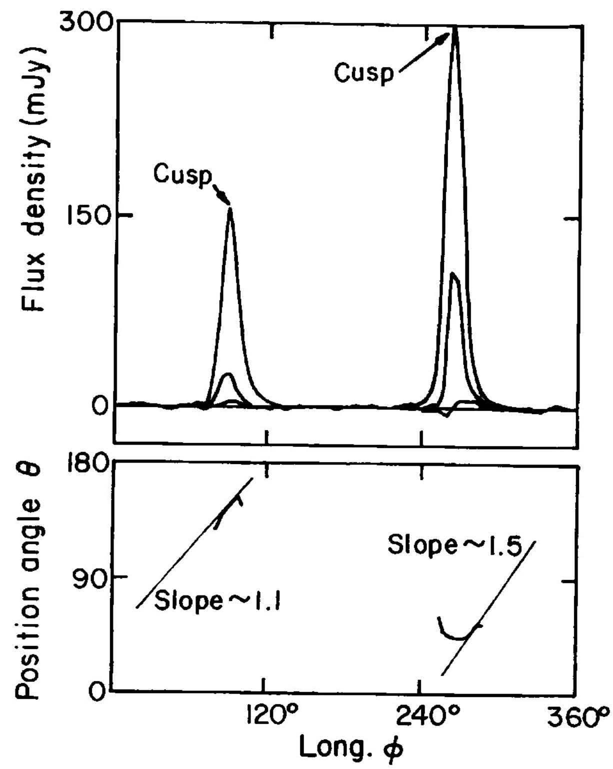


Fig. 2. Adapted from the observations of PSR 1937+21 by Stinebring (1983). Note the cusps in the flux density profiles of both the main and inter-pulse. The polarization position angle gradients $|d\theta/d\varphi|$ in the two pulses are estimated as shown.

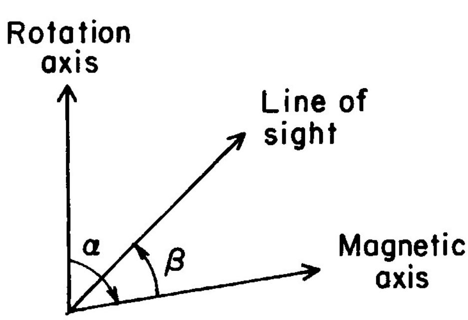


fig. 3. Relative orientations of the rotation axis, line of sight to earth, and magnetic axis in PSR 1937+21 corresponding to the centre of the main pulse. It is estimated that $\alpha \sim 80°$ and $\beta \sim 40°$.

incompatible with their data. Narayan and Vivekanand (1983b) proposed a new model which appears to satisfactorily explain all the discrepancies. A feature of this model is a highly elongated beam with axial ratio greater than 5.

(d) PSR 1937+21 (Fig. 2) and the Crab pulsar 0531+21 (optical) both have sharp cusps in their main and inter-pulse profiles. A circularly symmetric beam can have a discontinuity only at the center and it is most unlikely that the orientation would be exactly right in two pulsars to see the cusp, that too from both poles. It is much more natural to assume a wedge discontinuity in the beam, oriented along the north-south direction (Backer 1984, private communication). This clearly requires an asymmetry in the beam and since the cusps are seen in two of the fastest spinning pulsars, the asymmetry must decrease as the pulsar slows down.

The above arguments, based on a variety of approaches, all seem to suggest that fast pulsars have very long beams and that the beam shrinks as the pulsar slows down.

BEAM GEOMETRY IN PSR 1937+21

Fig. 2 reproduces the polarization observations of Stinebring (1983) on PSR 1937+21. The position angle of the linear polarization does not show a monotonic behavior in either the main or inter-pulse; there is also a shift of 90° between the two pulses. Stinebring argues that both phenomena can be accounted for by orthogonally polarized radiation being present on the leading edge of the main pulse and the trailing edge of the interpulse. Let us accept this and concentrate only on the trailing edge of the main pulse and the leading edge of the interpulse. Since the slope of θ vs. pulse longitude φ is the same in both pulses, the line of sight to earth must pass between the magnetic and rotation axes at the main pulse. (Fig. 3 shows the geometry at the peak of the main pulse). Following Narayan and Vivekanand (1982), the magnitude of the slope in the main pulse is given by

$$|d\theta/d\varphi| = |\sin\alpha/\sin\beta|$$

where α and β are defined in Fig.3. For the interpulse, β should be replaced by $\beta + \pi - 2\alpha$. From Fig. 2, the slope is ~1.1 at the main pulse and ~1.5 at the interpulse, and so $\alpha \sim 80°$ and $\beta \sim 40°$. The line of sight is thus ~60° from the magnetic pole at the interpulse. Since the interpulse is nearly half as strong as the main pulse, the beam might possibly extend much more than 60° on either side of its center. This is consistent with the arguments for highly elongated beams in fast pulsars. (More recent observations at 430 MHz by Stinebring *et al.*, this volume, suggest that $\alpha \sim 90°$ and $\beta \sim 25°$.)

REFERENCES

Ashworth, M., Lyne, A. G. and Smith, F. G. 1983, *Nature*, **301**, 313.

Gunn, J. E. and Ostriker, J. P. 1969, *Ap. J.*, **160**, 979.

Hankins, T. H. and Cordes, J. M. 1981, *Ap.J.*, **249**, 241.

Manchester, R. N. and Taylor, J. H. 1977, *Pulsars* (San Francisco : Freeman).

Narayan, R. and Radhakrishnan, V. 1983, *Curr. Sci.*, **52**, 46.

Narayan, R. and Vivekanand, M. 1982, *Astr. Ap.*, **113**, L3.

Narayan, R. and Vivekanand, M. 1983a, *Astr. Ap.*, **122**, 45.

Narayan, R. and Vivekanand, M. 1983b, *Ap. J.*, **274**, 771.

Radhakrishnan, V. and Cooke, D. J. 1969, *Ap. Letters*, **3**, 225.

Stinebring, D. R. 1983, *Nature*, **302**, 690.

DISCUSSION OF NARAYAN'S PAPER

CHEVALIER: One thing that does not seem to fit with this are these plerion type objects which are thought to be powered by young fast pulsars but only a couple of them show evidence for a radio pulsar; but most do not, and it had been thought that those were due to the beaming factor.

NARAYAN: My hope is that they really are pulsars and that you have to look deeper to find them. But certainly that is a bit of a problem.

HARDING: I want to suggest one way that you can get that geometry coming naturally from a hollow-cone model. You may have thought of this, but if you just have emission coming from one half of the polar cap and the polar cap opens up as the period gets shorter, then you automatically have a long narrow beam of emission. It's kind of a crescent and you might not be able to distinguish it from an elliptical beam.

NARAYAN: We are talking about more than just a crescent. We are saying that if you took the diameter of this crescent and took the vertical dimension, then this dimension is five times more than this. It's not just half a circle.

HARDING: No, I'm not talking about half a circle, I'm talking about half of a hollow cone, where emission occurs around the rim of the polar cap preferentially so that as you open up the polar cap and you're only looking at half of a hollow cone you assume a long, narrow type of geometry.

NARAYAN: I'm not sure. I think it will also affect the pulse width.

MANCHESTER: I was going to make much the same point, actually. It's always seemed to me that in the short period pulsars, the ones with the simple, rather narrow pulse profiles, you're only seeing part of the whole thing. In other words, quite often if you look at the different frequencies another component comes up somewhere. In the short period ones you're only seeing a fraction of the polar cap. You still get the elongated beam effect, but I'm not sure it has to be as extended in the latitudinal direction as you're saying.

NARAYAN: It doesn't matter how much of the polar cap you're seeing. We are using the observed pulse width, which tells us immediately the dimension in one direction. And we're using the polarization to say how much away from the pole you are in the other direction. And that's consistent with 100 degrees of latitude and 20 degrees of longitude.

BACKER: It's the derivative of the angle.

NARAYAN: Yes, I presented the total swing, but you could look at the derivative of the angle of polarization and it gives you the same results: 100 degrees is the sort of angle we get for the latitudinal dimension. And the other thing is that if you think of one part of a hollow cone and say the interpulse is from the other half, then one expects a frequency dependence of separation. And this can be ruled out because of the observed frequency <u>independence</u> of separation.

STINEBRING: I think you're overinterpreting the data in a couple of cases although I think this is really an exciting step forward. On PSR 1937+214 you mentioned that the total polarization swing was less than the 120 degrees that you'd expect, but the 120 degrees is purely statistical and especially given the very narrow pulse width of 1937 I'm not surprised that the polarization swing is quite a bit less.

BACKER: Again it's the derivative.

NARAYAN: The derivative is telling you that it's at least 20 degrees off the pole and maybe it's even 40 degrees off.

STINEBRING: Since it's been mentioned a couple of times, I want to put to rest the idea that the 6 millisecond pulsar has an interpulse. I think that that's not a correct interpretation.

NARAYAN: Well, I talked with Val [Boriakoff] again yesterday and he said that maybe at high frequencies it has. Maybe we should put it in the question mark category.

STINEBRING: I would put it in the two question mark category. And then finally, and I think that Alex Wolszczan and Jim Cordes can speak to this better than I can, but I think that the cross-talk between the main pulse and the interpulse in 1937 is a preliminary result, especially because we seem to have some cross-talk between the off-pulse and the main pulse. Especially I think the polarization swing does not fit well your hybrid one-pole model in 1937.

NARAYAN: I wouldn't really say that. There is a problem, and that is that the interpulse has too much of a [position angle] slope. That is the only problem that I see. You can always correct the main pulse to interpulse angle with a 180 [sic] degree shift from what I could see of your data. And that would be almost identical to what you have in 0950+08. Go all the way, then shift by 180 degrees since that is just a redefinition of the polarization, and then you can go to the interpulse. The only problem I see is with the slope of the interpulse. That is a bit of a problem.

MANCHESTER: The position angle swing at the edge of the polar region is much slower than it is at the center. That could give the appearance of it being further from the pole.

NARAYAN: Right. If the main pulse is offset from the center for some reason. The assumption here is that the peak of the main pulse is in the same meridian as the magnetic pole. If it's on one side, yes, that certainly could give you a small swing. But then we have all the other evidence, and it all adds up.

MILLISECOND PULSARS AND THE LOCATION OF THE SOLAR SYSTEM BARYCENTER

M. Prószyński*

Space Telescope Science Institute, Baltimore

ABSTRACT

The possibility of using millisecond pulsars to more accurately determine the location of the solar system barycenter is discussed. Two sets of the light-travel time corrections (necessary to refer pulse arrival-time data to the solar system barycenter) are obtained; one from the old MIT PEP311 ephemerides and the second from the most recent JPL DE200/LE200 ephemerides. The comparison of these two sets gives a rough estimate of the possible uncertainties in the location of the solar system barycenter and in pulsar parameters that are derived from pulse arrival-time data.

INTRODUCTION

Not very long after the regular timing observations of pulsars began, Mulholland (1971) remarked that the day may come when the uncertainties in the location of the solar system barycenter would begin to be important for the reduction of pulsar data. We have had to wait more than ten years for this to happen, that is, for the first millisecond pulsar to be discovered.

In order to refer the arrival times of the pulsar's pulses to the solar system barycenter, three effects connected with the earth's orbital motion need to be accounted for—three 'correction' terms must be added to the topocentric arrival times. They are: the light-travel time correction, the relativistic clock correction and the dispersion delay correction (the last one is needed only in the case of radio observations). The light-travel time correction is given by $(\vec{r}_1 + \vec{r}_2) \cdot \vec{n}/c$, where $\vec{r}_1$ is a vector from the solar system barycenter to the center of the earth, $\vec{r}_2$ is a vector from the center of the earth to the observing site, $\vec{n}$ is a unit vector in the direction to the pulsar, and c is the velocity of light. The vector $\vec{r}_1$ is obtained from the planetary ephemerides and is a major source of error ($\vec{r}_2$ is known to a higher accuracy than $\vec{r}_1$). Even a small error in the assumed location of the solar system barycenter affects the light-travel time correction; it does not affect noticeably the two remaining correction terms.

PLANETARY MASSES

The uncertainty in the location of the solar system barycenter is mainly due to uncertainty in the masses of outer planets. An error in the assumed mass of any

* On leave from N. Copernicus Astronomical Center, Warsaw

given planet will show up in arrival times of pulsar's pulses as a sinusoidal term with period equal to orbital (sideral) period of that planet and with amplitude of

$$\Delta\left(\frac{m}{M_o}\right)\frac{a}{c}\sin i,$$

where $\Delta(m/M_o)$ is the uncertainty in the ratio of the planet's mass to that of the sun, a is the major semi-axis of the planet's orbit, and i is the angle between a vector pointing towards the pulsar and the vector normal to the orbital plane. (The semi-major axis of a planet's orbit is usually known with much higher accuracy than the planet's mass.)

The question to answer is whether the millisecond pulsar PSR1937+21 may be useful in the detection of such periodic terms. The pulsar (which is probably an old, recycled neutron star) is likely to spin-down smoothly, and a typical error in the determination of the pulse arrival time is expected to be close to 1 microsecond, or even slightly less than that (Backer, Kulkarni, and Taylor 1983). It should be noted, however, that in order to detect such a term in the pulse arrival times of a *single pulsar*, the observations must continue for at least an interval of time equal to one orbital period of the planet. This requirement could be relaxed if more such good clocks were discovered. The reason for this is as follows. The values of the pulsar's rotation frequency and its time derivative are obtained by fitting a spin-down model to the pulse arrival-time data. This corresponds to the subtraction of the best-fitting square polynomial from any complicated pattern that may be present in the data (*e.g.*, from a sinusoid, or from a superposition of a number of sinusoids). Of course, if the data cover less than the full cycle of a sinusoid, at least a part of it will be absorbed into the values of frequency and frequency derivative; the remaining part will show up in timing residuals as a superposition of the third, fourth and higher order polynomial terms. As long as there is only one so accurate pulsar, there is no way of deciding whether such terms, if present, are intrinsic to the pulsar spin-down or rather are due to errors in the reduction of the data to the solar system barycenter. The binary millisecond pulsar PSR1953+29 is not very useful for this purpose since any such periodic term would most likely be absorbed into the solution for its binary orbit.

A sinusoidal term of an amplitude of 1 microsecond corresponds to an error in m/M_o of 3.1×10^{-2} for Mercury, 1.1×10^{-3} for Venus, 4.1×10^{-3} for Mars, 4.0×10^{-7} for Jupiter, 7.4×10^{-7} for Saturn, 2.4×10^{-6} for Uranus, and 1.3×10^{-6} for Neptune ($\sin i = 1$ is assumed). The masses of terrestrial planets are known to much better accuracy (Babcock and Chandler 1984; Standish 1984). For the earth such a term cannot be distinguished from the undetectably small offset in the orientation of axes of the coordinate system in which planetary motion is defined. The uncertainties in masses of outer planets are, however, larger than the values quoted above (Babcock and Chandler 1984; Standish 1984). It is also worth noting that the presence of a few most massive planetoids, if not accounted for, would introduce sinusoids with amplitudes of the order of 1 microsecond.

EPHEMERIDES

Several planetary and lunar ephemerides have been produced in the past two decades by fitting appropriate models to existing lunar and planetary data. At the beginning these were radar ranging data combined with conventional optical data. Recent ephemerides also include much more accurate laser ranging and spacecraft tracking measurements.

An estimate of the uncertainty in the location of the solar system barycenter can be obtained by comparing different planetary ephemerides. Unfortunately, the modern ephemerides are based to a large extent on the same sets of measurements, *e.g.*, spacecraft tracking data; they are not completely independent of each other. One can worry, therefore, that if there are any systematic errors in the ephemerides, such a comparison may not disclose them; the real uncertainty may be greater than the differences between ephemerides. A very rough (and conservative) estimate of the possible uncertainty can be obtained by comparing the modern ephemerides with the old ones.

Being interested in the timing of the millisecond pulsar PSR1937+21, I compare not the ephemerides themselves, but rather the light-travel time corrections calculated for this pulsar on their basis. For this purpose I use: the MIT PEP311 ephemerides (Ash, Shapiro, and Smith 1967), and the JPL DE200/LE200 ephemerides (Standish 1982). The MIT PEP311 ephemerides, now seventeen years old, have been those most commonly used in past years for the reduction of pulsar timing data, while the JPL DE200/LE200 ephemerides are the most recent of all ephemerides so far released by JPL. In fact the latter are the JPL DE118/LE62 ephemerides (which themselves were referenced to the equator and equinox of 1950.0) after rotation onto the mean equator and dynamical equinox of J2000.0 (Standish 1982).

Figure 1 shows the difference between the values of $\vec{r}_1 \cdot \vec{n}/c$ as calculated for the millisecond pulsar PSR1937+21 from the MIT and JPL ephemeris tapes.* The wavy pattern of the curve in Figure 1 can be decomposed into a 'secular' trend and a sinusoid with a one-year period. The 'secular' trend results from the differences in the adopted masses of outer planets and is effectively a superposition of a few sinusoids with periods of 11.9 years, 22.5 years, etc. The yearly sinusoid is due to a small offset in the orientation of axes of the coordinate systems used in both ephemerides. The periodic terms due to differences in adopted masses of terrestrial planets are not visible here, being overshadowed by the above two; they are a few orders of magnitude smaller.

It is apparent that the timing position of the millisecond pulsar PSR1937+21 obtained from the MIT PEP311 ephemerides will differ from that obtained from the JPL DE200/LE200 ephemerides. A fit of the standard spin-down model (a square polynomial with terms allowing for determination of timing position) to the 2-year-long segment of the curve shown in Figure 1 (to the data between 1983.0 and 1985.0) gives for this particular pulsar

$$\alpha_{MIT}(1950.0) = \alpha_{JPL}(1950.0) - 0.122 \text{ seconds of arc},$$

$$\delta_{MIT}(1950.0) = \delta_{JPL}(1950.0) + 0.178 \text{ seconds of arc}.$$

The presence of the 'secular' term causes a small shift in the values of the pulsar rotation frequency and the frequency time derivative obtained with the help of both ephemerides; such a shift is impossible to detect since the 'true' values of the frequency and its derivative are not known to us. Third, fourth and higher order components of the 'secular' term may, however, show up in the pulse arrival-time residuals (Figure 2).

* The J2000.0 position of the PSR1937+21 has been obtained from the 1950.0 one by applying the same matrix transformation as used to obtain the DE200/LE200 ephemerides from the DE118/LE62 ephemerides (Standish 1982).

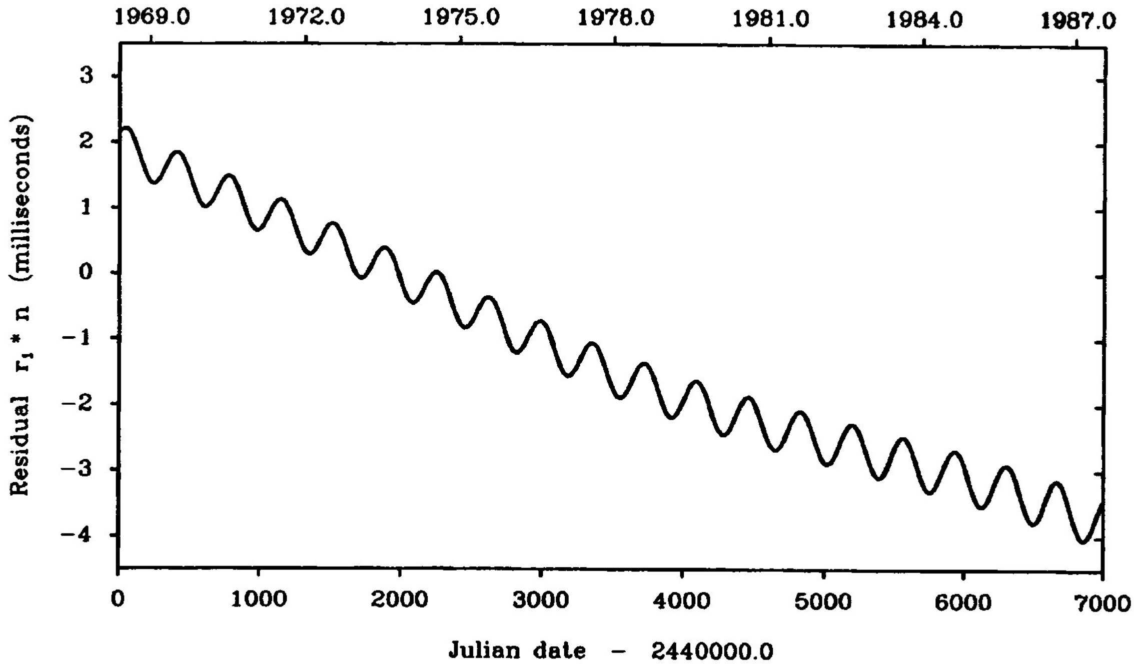


Figure 1 The difference between light-travel time corrections calculated for the millisecond pulsar PSR1937+21 from the MIT PEP311 and JPL DE200/LE200 ephemeris tapes.

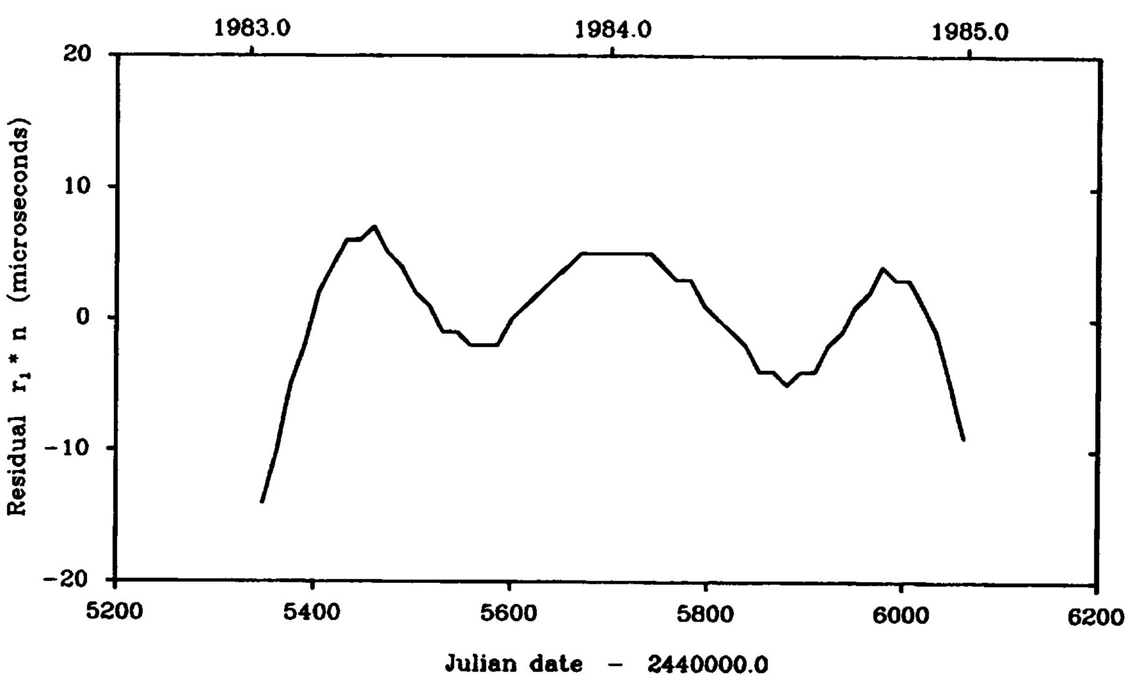


Figure 2 The residual pattern resulting after the best-fitting model (consisting of the square polynomial and the position term) is subtracted from the 2-year-long segment of the curve in Figure 1.

RELATIVISTIC CLOCK CORRECTION

The relativistic clock correction is a difference between the proper time on the earth and the coordinate time in the barycentric frame of reference. It can be decomposed into: a major sinusoidal term with a period of exactly one year and the higher harmonics of it, and several sinusoidal terms with much smaller amplitudes and with periods equal to synodic periods of outer planets (Moyer 1981a, 1981b). Here again, the presence of this major term cannot be distinguished from the offset in the orientation of axes of the coordinate system in which planetary motion is defined. However, all the other terms and the higher harmonics of the yearly term can easily be detected.

ACKNOWLEDGMENTS

I would like to thank R.W. Babcock, J.F. Chandler, I.I. Shapiro and E.M. Standish for discussions on the present state of the art in planetary ephemerides.

REFERENCES

Ash, M.A., Shapiro, I.I., and Smith, W.B. 1967, *Astr. J.*, **72**, 150-167.
Babcock, R.W., and Chandler, J.F. 1984, private comunication.
Backer, D.C., Kulkarni, S.R., and Taylor J.H. 1983, *Nature*, **301**, 314-315.
Moyer, T.D. 1981a, *Cel. Mech.*, **23**, 33-56.
Moyer, T.D. 1981b, *Cel. Mech.*, **23**, 57-68.
Mulholland, J.D. 1971, *Ap. J.*, **165**, 105-107.
Standish, E.M., Jr. 1982, *Astron. Ap.*, **114**, 297-302.
Standish, E.M., Jr. 1984, private comunication.

DISCUSSION OF PROSZYNSKI'S PAPER

VAN DEN HEUVEL: Do I understand that if the mass of Venus is off by 0.44% that you get a 4 microsecond amplitude?

PROSZYNSKI: 1 microsecond amplitude.

DAVIS: Unfortunately Mike [Proszynski] and I checked the mass that was used in the PEP 311 ephemeris from MIT and it was virtually identical to the mass used in the most recent JPL ephemeris.

STINEBRING: But it's not possible that they're both wrong?

PROSZYNSKI: You [Backer, et al.] have a data span of about 18 months. I have fitted two years of data and subtracted this yearly sinusoid and got an amplitude of 20 microseconds. I do not give my head for 20 microseconds, but it was something like that. Where does it come from? When you fit the data you subtract the linear trend and the quadratic term and you see the third order, fourth order, and so on. And if the fourth order is the largest you will see it.

DAVIS: I would have to ask someone familiar with ephemerides whether a 0.5% correction to the mass of Venus is feasible at this time.

TAYLOR: I would think not. Once you've got a satellite running around the planet I would think you would know the mass pretty well.

DAVIS: Maybe Don [Backer] would like to say something about the comparison between the VLA and timing positions.

BACKER: The position of 1937 was derived from VLA maps with very careful astrometry with an accuracy of about 0.05 arc seconds. And at the present time the timing position, with this exquisite timing accuracy of a microsecond, corresponds to a positional accuracy of less than a milliarcsecond. So taking the timing position as the standard and comparing it to the VLA position, we find agreement at the 1 to 1.5 sigma level which is really excellent agreement. As far as the discrepancy goes between the ensemble of pulsars that has been observed by Fomalont, Goss, Manchester, and Lyne, the biggest difference is a constant offset of the timing positions derived using the MIT ephemeris. The offset is less between VLA positions and timing positions derived using the JPL ephemeris. The difference between the positions from the two different ephemerides is just about the right magnitude--don't ask me about the sign. It is not unexpected that the two different ephemerides have a zero-point difference in the origin of their coordinate systems of a couple of tenths of an arcsecond. One further comment on this discrepancy. The errors that are obtained in radar ranging to the various planets during the intervals that they are doing ranging is about three orders of magnitude below what you're showing here: it's tens of nanoseconds, not tens of microseconds.

PROSZYNSKI: But these are just of the terrestrial planets and not of the outermost ones. And these introduce displacements of the barycenter.

BACKER: I think it would still affect radar ranging of the inner planets.

KULKARNI: Does this mean there's a new planet out there?

X-RAY EMISSION FROM FAST PULSARS

Andrew F. Cheng

Johns Hopkins University, Applied Physics Laboratory, Laurel, MD 20707

ABSTRACT

Mechanisms for soft x-ray emission from fast pulsars are considered. Synchrotron radiation from plasma winds powered by a radio pulsar can yield observable fluxes at kiloparsec distances, for pulsar spindown energy loss exceeding $\sim 10^{34}$ erg s^{-1}. Unpulsed x-ray emission which is observed to be spatially extended must arise far outside the light cylinder. Such emission can be explained by synchrotron radiation from a pulsar wind which is confined by an external medium. A theory of ram pressure confinement is reviewed and applied to several objects including 1937 + 214. If unpulsed point source emission is observed, the emission may also arise much closer to the pulsar, at several c/Ω, if the wind is relativistically hot, its Lorentz factor is not too great, and it is not far from equipartition. The models for soft x-ray emission from pulsar winds appear to be consistent with observations of unpulsed x-rays from fast pulsars.

INTRODUCTION

Several radio pulsars have been detected as soft x-ray sources. Einstein observations indicate that only the youngest fast pulsars, like Crab and 1509-58, can give pulsed x-rays, but a much larger class of fast pulsars, including these two, can give unpulsed x-rays. Unpulsed x-rays have been detected from the Vela pulsar and from several pulsars $\sim 10^6$ yr old, including 0355 + 54, 1929 + 10, 1055 - 52, 0950 + 08, and 1642 - 03. The upper limit to the x-ray pulsed fraction is < 3% for 1055 - 52 and < 1% for Vela. Unpulsed x-ray emission from million year old fast pulsars apparently arises from synchrotron nebulae powered by the pulsars (Helfand 1982; Cheng and Helfand 1983). Indeed, synchrotron nebulae may also have been detected around Vela and 1509 - 58, since there are nonthermal emission regions spectrally distinct from the supernova shell emission around both of these pulsars (Harnden 1983; Seward and Harnden 1982). If the Crab Nebula is now included, then every radio pulsar so far detected as an x-ray source has an emission component which can be interpreted as a synchrotron nebula.

These observations suggest that fast pulsars, by which is meant pulsars with spin-down energy loss exceeding 10^{34} erg s^{-1}, generally power synchrotron nebulae which are observable in soft x-rays out to kiloparsec distances. This suggestion has important implications for supernovae and pulsar formation. For example, it would imply that none of five historical shell supernovae made fast pulsars, since no central x-ray sources were detected in any of them (Cheng and Helfand 1983). Indeed, no central x-ray sources were detected in the vast majority of shell supernova remnants, suggesting that these are not associated with pulsars. On the other hand, filled supernova remnants do typically have central x-ray sources suggestive of fast pulsars (Becker et al. 1982). Most of these may be unobservable as pulsars because their beams are not aimed at the earth.

The synchrotron nebulae proposed to account for unpulsed x-rays from radio pulsars generally contain average magnetic and particle pressures far in excess of the static pressure of the interstellar medium (Cheng 1983). Thus the synchrotron nebulae are more properly considered as magnetized plasma winds powered by the pulsars. Cheng (1983) has analyzed a simple, spherical model for a hot, relativistic plasma wind from a radio pulsar. Such a wind is assumed to carry away the entire spindown energy loss of the pulsar beyond some minimum radius r_o estimated as several light cylinder radii. It is probable that no strong electromagnetic wave at the pulsar rotation frequency can propagate near the light cylinder of any observed radio pulsar and that such waves are violently unstable (Kennel and Pellat 1976; Leboeuf et al. 1982). The pulsar plasma wind can become relativistically hot owing to pair creation, magnetic reconnection, or violent instability of the pulsar strong wave.

The next section reviews a theory for x-ray emission from pulsar plasma winds, and the final section applies the theory to several pulsars including the millisecond pulsar 1937 + 214.

SYNCHROTRON RADIATION FROM PULSAR PLASMA WINDS

Cheng (1983) has calculated the rate of synchrotron radiation from simple models for hot, adiabatic, relativistic plasma winds from pulsars, assuming a power law particle energy spectrum. Two cases were considered: unconfined winds expanding into a vacuum, and winds confined by an external medium. In an unconfined wind, most of the synchrotron radiation is produced very near the minimum radius r_o because of rapid adiabatic expansion. The angular diameter of such an x-ray source would be far too small to be resolvable, since r_o is only a few light cylinder radii. Unpulsed x-ray emission which is observed to be spatially extended can never be produced by an unconfined pulsar wind. On the other hand, confinement of a pulsar wind can cause a strong shock to be driven back into the wind, and heating of the plasma by the shock can cause synchrotron radiation far outside the light cylinder. Synchrotron radiation from confined pulsar winds can therefore give spatially extended, unpulsed x-ray emission such as observed from all of the radio pulsar x-ray sources (with the probable exception of 1929 + 10 which has an angular diameter less than about ten arc seconds).

In very young pulsars, the pulsar plasma wind can be confined by supernova ejecta, as in the Rees and Gunn (1974) and Kennel and Coroniti (1982) models of the Crab Nebula. In million year old pulsars, however, a different confinement mechanism is needed. Cheng (1983) suggested confinement by the ram pressure of the interstellar medium as seen in the reference frame of a rapidly moving pulsar. Most radio pulsars have proper velocities exceeding 100 km s^{-1}, so for a synchrotron nebula pressure $P_T \sim 10^{-9}$ erg cm^{-3}, a modest interstellar density

$$\rho_H \sim 6\, P_{T,-9}\, v_7^{-2} \text{ amu cm}^{-3} \qquad (1)$$

is sufficient.

For the unconfined pulsar wind model, the x-ray flux density is (Cheng 1983)

$$F_\nu = 1.2 \times 10^{-34} \frac{\mathrm{keV}}{\hbar\nu} \Gamma_o^{-1} \dot{P}_{-15}^{7/4} P^{-23/4} I_{45}^{7/4} d_{\mathrm{kpc}}^{-2} \left(\frac{\Omega r_o}{c}\right)^{-1/2} g(\sigma)\xi \frac{\mathrm{erg}}{\mathrm{cm}^2\,\mathrm{s\ hz}} \tag{2}$$

where P is period in seconds, $\dot{P}_{-15}$ is in 10^{-15} ss^{-1}, I_{45} is in 10^{45} gm cm^2, and $\Gamma_o >> 1$ is the Lorentz factor of bulk motion near the minimum radius r_o. Also d_{kpc} is the distance in kpc (interstellar extinction is not yet included). The quantity $g(\sigma) = \sigma^{3/4}(1 + \sigma)^{-7/4}$ where $\sigma = B^2/(4\pi\Gamma_o^2(P' + \rho'))$ is the ratio of Poynting flux to particle energy flux near r_o. Finally ξ is the fraction of the plasma energy density accounted for by the radiating charges. A ν^{-1} spectrum has been assumed, as observed from the Crab Nebula and consistent with 1055-52 (Cheng and Helfand, 1983).

For a ram pressure confined pulsar wind model, the soft x-ray flux density is (Cheng 1983)

$$F_\nu^e = 0.91\ F_\nu \Gamma_o \left(\frac{r_o}{r_s}\right)^{1/2} \frac{V}{r_s^3} (1 + \sigma) \tag{3}$$

where r_s is the radius of the shock driven into the pulsar wind (the "reverse shock") and V is the volume of the emitting region. The reverse shock radius r_s is found by balancing the interstellar ram pressure with the total pressure behind the reverse shock

$$\frac{\Omega r_s}{c} = 1.7 \times 10^5\ I_{45}^{1/2} P^{-5/2}\ \dot{P}_{-15}^{1/2}\ \rho_H^{-1/2} v_7^{-1} \tag{4}$$

The volume V can be estimated very crudely by using the approximate relation for flow velocity in the emitting region, $v_r \sim r^{-2}$ in the hydrodynamic limit, and recalling that $v_r = c/3$ behind the reverse shock in this limit. Then the scale length of the emitting region is $\sim r_s\ (c/3v)^{1/2}$ where $v \sim 10^7$ cm s^{-1} should be comparable to the pulsar proper velocity. Thus the volume is very crudely estimated as

$$V r_s^{-3} \simeq 10^5\ v_7^{-3/2} \tag{5}$$

Cheng (1983) did not use this estimate for V, but used instead the observed size of the 1055 - 52 nebula for comparison with observations of 1055 - 52 only.

The x-ray flux density from a ram pressure confined wind, using (4) and (5) in (3), becomes

$$F_\nu^e = 1.1 \times 10^{-34} \frac{\mathrm{keV}}{\hbar\nu} \dot{E}_{30}^{3/2} \left(\frac{\sigma}{1+\sigma}\right)^{3/4} \xi\ d_{\mathrm{kpc}}^{-2}\ \rho_H^{1/4} v_7^{1/2} \frac{V}{10^5 r_s^3} \frac{\mathrm{erg}}{\mathrm{cm}^2\,\mathrm{s\ hz}} \tag{6}$$

where $\dot{E}_{30}$ is the spindown energy loss rate $I\Omega\dot{\Omega}$ in 10^{30} erg s^{-1}.

Equations (2) and (6) are now integrated from 0.1 to 4 keV for comparison with Einstein observations. For the unconfined wind model

$$F_x = 1.1 \times 10^{-16} I_{45}^{7/4} P^{-23/4} \dot{P}_{-15}^{7/4} d_{kpc}^{-2} f_u \text{ erg cm}^{-2}\text{s}^{-1} \qquad (7a)$$

$$f_u = \Gamma_o^{-1} \xi g(\sigma) (\Omega r_o/c)^{-1/2} \qquad (7b)$$

is obtained. Here f_u collects the unknown wind parameters, which however satisfy the constraints $\Gamma_o \gg 1$, $\xi < 1$, $g(\sigma) < 0.303$, and $(\Omega r_o/c) > 1$, so $f_u \ll 1$ is expected. For the confined wind model

$$F_x^e = 0.99 \times 10^{-16} \dot{E}_{30}^{3/2} d_{kpc}^{-2} f_c \text{ erg cm}^{-2}\text{s}^{-1} \qquad (8a)$$

$$f_c = \xi \sigma^{3/4} (1+\sigma)^{-3/4} \rho_H^{1/4} v_7^{1/2} (V/10^5 r_s^3) \qquad (8b)$$

where f_c collects unknown wind parameters for the confined case. Again $\xi < 1$ and $\sigma^{3/4}(1+\sigma)^{-3/4} < 1$, but the remaining factors in f_c may exceed unity. It is noteworthy that f_c of (8b) is independent of Γ_o, so in principle f_c can be much greater than f_u.

The x-ray fluxes predicted by (7) and (8) can now be compared with Einstein observations of million year old fast pulsars and the millisecond pulsar 1937 + 214. The periods, period derivatives, and distances are taken from Manchester and Taylor (1981). The observed soft x-ray fluxes corrected for interstellar extinction (Helfand 1982; Cheng and Helfand 1983) are 3.7×10^{-12} erg cm^{-2}s^{-1} (for 1055 - 52), 5.8×10^{-13} erg cm^{-2}s^{-1} (for 0355 + 54), 4.8×10^{-13} erg cm^{-2}s^{-1} (for 1642 - 03), 1.2×10^{-13} erg cm^{-2}s^{-1} (for 1929 + 10), and 1.6×10^{-13} erg cm^{-2}s^{-1} (for 0950 + 08). A conversion factor 1.6×10^{-11} erg cm^{-2} per IPC count was assumed and the same extinction law was used in all cases. For the millisecond pulsar 1937 + 214, an upper limit to the x-ray flux is available from an Einstein HRI observation (Becker and Helfand 1983). For a 5 kpc distance, the x-ray flux from 1937 + 214 is less than 3×10^{-12} erg cm^{-2}s^{-1}, after correcting for interstellar extinction. A $\dot{P}_{-15} = 10^{-4}$ was assumed for 1937 + 214.

These values for the x-ray fluxes, periods, period derivatives, and distances, together with $I_{45} = 1$, can be used in equations (7) and (8) to determine the pulsar wind parameters f_u and f_c. Table I presents the resulting values of f_u and f_c for six pulsars. PSR 1929 + 10 is considered only in the unconfined wind model, because it is very nearby ($d_{kpc} = 0.08$) and it is an HRI point source. PSR 0950 + 08 is considered in both models since an HRI map is not available. PSRs 1055 - 52 and 0355 + 54 are considered only in the confined wind model since they are both already observed as spatially extended. PSR 1642 - 03 is inferred to be an extended source from the absence of an HRI detection (Helfand 1982) and is also considered in the confined wind model only.

Table I shows that for all unconfined wind model candidates the parameter $f_u \ll 1$ as required by the model. Indeed, $f_u \simeq 10^{-3}$ for PSR 1929 + 10, which is the strongest unconfined wind candidate, suggesting that $\Gamma_o < 10^2$ and that σ is not too far from unity. These may be useful constraints on pulsar magnetosphere models.

Table I also shows that the parameter f_c is typically much less than unity, indicating that the confined pulsar wind model can easily generate the observed soft x-ray fluxes. It is noteworthy that if PSR 1642 - 03 is omitted, then f_c for the remaining four confined wind candidates may vary by less than an order of magnitude. Equation (8b) shows that f_c does not depend strongly on ρ_H, but can depend strongly on pulsar wind properties.

Finally, Table I shows that the millisecond pulsar 1937 + 214 can be accommodated within the models for x-ray synchrotron emission from pulsar winds, despite the extreme values of P and $\dot{P}$. There is a suggestion that the f_u and f_c values for 1937 + 214 are abnormally low, although it should be recalled that uncertainties due to the distance and the correction for interstellar extinction may exceed an order of magnitude. Unusually low values for f_u and f_c in 1937 + 214 may arise from an abnormally low density of electron-positron pairs. Indeed Alpar et al. (1982) have already suggested an abnormally low pair density for 1937 + 214 in order to permit the relativistic plasma frequency to drop below the radio frequency within the light cylinder, as is required for coherent radio emission in some polar cap pulsar models (Cheng and Ruderman 1980).

SUMMARY

Models for x-ray synchrotron radiation from pulsar plasma winds appear to be consistent with observations of unpulsed x-ray emission from fast pulsars. Indeed equation (8) for the unpulsed x-ray flux from a confined pulsar wind becomes

$$F_x^e = 3 \times 10^{-13} \left(\frac{I\Omega\dot{\Omega}}{10^{34} \mathrm{erg\ s^{-1}}}\right)^{3/2} d_{kpc}^{-2} \frac{f_c}{3\times 10^{-3}} \mathrm{erg\ cm^{-2} s^{-1}}$$

neglecting interstellar extinction. It is suggested that fast pulsars with spindown energy loss exceeding 10^{34} erg s^{-1} can generally be expected to be observable in unpulsed soft x-ray emission out to kiloparsec distances, owing to synchrotron radiation from pulsar winds.

Acknowledgement:

This work was supported in part by the National Science Foundation under Grant AST-8319270.

REFERENCES

Alpar, M. A., A. F. Cheng, M. A. Ruderman, and J. Shaham 1982, Nature, 300, 728.

Becker, R. H. and D. J. Helfand 1983, Nature, 302, 688.

Becker, R. H., D. Helfand and A. Szymkowiak 1982, Ap. J., 255, 557.

Cheng, A. F. 1983, Ap. J., 275, 790.

Cheng, A. F. and D. J. Helfand 1983, Ap. J., 271, 271.

Cheng, A. F. and M. A. Ruderman 1980, Ap. J., 235, 576.

Harnden, R. 1983, B.A.A.S., 15, 1006.

Helfand, D. J. 1982, in I.A.U. No. 101, Supernova Remnants and Their X-Ray Emission.

Kennel, C. and F. V. Coroniti 1982, UCLA Preprint PPG-670.

Kennel, C. and R. Pellat 1976, J. Plasma Phys., 15, 335.

Leboeuf, J. et al. 1982, Phys. Rev. A, 25, 1023.

Manchester, R. and J. H. Taylor 1981, Ap. J., 86, 1953.

Rees, M. and J.Gunn 1974, MNRAS, 167, 1.

Seward, F. and R. Harnden 1982, Ap. J., 256, L45.

TABLE 1

Radio Pulsar	Unconfined Wind f_u	Confined Wind f_c
0950 + 08	6×10^{-2}	1×10^{-3}
1929 + 10	1×10^{-3}	
1937 + 214	$< 5 \times 10^{-4}$	$< 7 \times 10^{-4}$
1055 - 52		6×10^{-3}
0355 + 54		2×10^{-3}
1642 - 03		2×10^{-1}

The parameters f_u and f_c are defined in equations (7) and (8) respectively.

DISCUSSION OF CHENG'S PAPER

ALPAR: Is there reason to believe that the ram pressure of the interstellar medium is small near 1929+10?

CHENG: Yes, there is considerable evidence that the interstellar medium density within 100 parsecs of the sun is abnormally low.

KULKARNI: What model do you use for the ISM?

CHENG: No model. I just have a density that I put into the formula.

KULKARNI: What's the density that you use?

CHENG: A number on the order of 1 cm^{-3}.

KULKARNI: Does the HRI have arcsecond resolution? If so, you should see an asymmetry in the pictures.

CHENG: Ten arcsecond resolution. There are, I think, only two HRI pictures, and they are both asymmetric. For 1642-03 there is an IPC point source but no HRI detection, which was interpreted by David Helfand as indicating spatially extended emission on the order of 90 arcseconds. Since there is no HRI picture in that case you don't know whether it is asymmetric or not. The other objects I'm including are the Vela nebula, the 1509-58 nebula [MSH15-5(2)] and the Crab nebula, all of which show varying degrees of asymmetry.

KULKARNI: I think the interstellar medium density is an important parameter. 1 cm^{-3} on the average is right, but when you're looking at sub-parsec scales...

CHENG: I agree. Maybe there are pulsars you might expect to see for which you don't see any X-rays and that could be the explanation.

TAYLOR: I'm wondering if the anomalous number that you get for 1642-03 is related to the distance to that source, because values for its distance have changed by a factor of 4 over the years.

CHENG: That could well be. I would be happy if that were true.

TAYLOR: Do you know what value you used?

CHENG: The one in your most recent paper, the 1981 value.

TAYLOR: I think that's the correct value to use.

BACKER: Another comment about 1642 is that it also has peculiar interstellar scattering properties, as if you have a strong wind that piles up the medium.

REYNOLDS: I want to know what you assumed about the particle spectrum. I would expect that the X-ray synchrotron spectrum is dominated by synchrotron losses. Is that true?

CHENG: The calculation I did neglected that. It's just an adiabatic wind. You have to pick your parameters so that the total synchrotron luminosity comes out way less than the wind luminosity.

REYNOLDS: So you assume that the injection spectrum is E^{-2}. The other point is that you can easily get around this problem of not seeing the X-ray nebula around young pulsars by just having them not produce 10 erg electrons, which is what you need. I just have to point out that Chris McKee and I produced a model almost exactly like this for the compact radio source in the galactic center in 1980.

CHENG: I was not aware of it.

STINEBRING: This may be nothing more than saying that fast pulsars tend to have interpulses, but I was struck when I saw your list that 5 of those 8 pulsars have interpulses and, in particular, PSR 1055-52, a very interesting pulsar, is the only pulsar besides the Crab and PSR 1937+214 whose interpulse is comparable in strength to its main pulse.

CHENG: Yes, and 1055 also has a precursor, isn't that correct?

STINEBRING: Yes, it does.

MANCHESTER: Some people might question that nomenclature.

CHANMUGAM: What happens when the pulsar slows down? Where does the energy go? Do you still have a shock front?

CHENG: You will still have a wind, and three will still be a shock. It's just a question of how much X-ray energy will be generated. If the pulsar gets too old X-rays may drop down to undetectable levels. But there still should be a wind, and thre still will be a shock. One possibility is that the emission will move to a lower frequency range. Three are a lot of details that have been swept under the rug. For example, the question of whether you can make 10 erg electrons or not.

BACKER: Have you thought about models generated by orbits of a main sequence star where there's more mass at a higher density?

CHENG: I hadn't thought about it. It's another possibility.

PROSZYNSKI: Regarding PSR 1642-03. In the catalog of 1981 the distance to this pulsar is the old one, the larger one.

MANCHESTER: No, that's the new one. The old one was small.

BORIAKOFF: There is an observation by a Russian group, the reference escapes me right now, that PSR 0950+08 has a little Crab-like remnant around it--in the radio range, around 100 MHz.

HANKINS: That same observation was made by Gopal-Krishna at Ooty at 327 MHz during a lunar occultation.

GAMMA-RAY EMISSION FROM FAST PULSARS

Kenneth Brecher*

Boston University, Boston, MA 02215 and NASA/GSFC, Greenbelt, MD 20771

ABSTRACT

It is suggested that many, perhaps all, of the heretofore unidentified COS-B gamma-ray sources are fast pulsars. If the incoherent synchrotron emission mechanism at the speed-of-light cylinder is effective up to gamma-ray energies ($\approx$100 MeV), then a population of old (>10^6 years), weak magnetic field ($B < 10^{10}$ gauss), high angular velocity ($\omega > 10^3$ sec^{-1}) pulsars may account for a number of properties of these sources.

INTRODUCTION

Some 25 discrete gamma-ray sources have been detected by the COS-B gamma-ray satellite (Bignami and Hermsen, 1983). Of these sources, three have already been identified with pulsars (Crab, Vela, PSR 1953+29), all of which have relatively short pulse periods (33, 89 and 6 ms, respectively). Two other sources have been identified with the quasar 3C273 and with the ρ Oph cloud. Little is known of the properties of the remaining 20 unidentified sources.

To confuse matters further, some sources seen by COS-B were not seen by, for example, the SAS-2 satellite, and sources detected at gamma-ray energies by other balloon and satellite detectors, such as Cyg X-3, were not reported by COS-B. Nonetheless, though it is reasonable to suggest that gamma-ray emission from some sources is probably associated with properties intrinsic to binary star systems such as mass transfer (Cyg X-3 ?), several other sources clearly involve the emission from single neutron stars (as in the cases of the Crab and Vela pulsars). Unfortunately, the one known case which might argue strongly for an association between fast pulsars and the unidentified COS-B gamma-ray sources (the 6.1 ms pulsar PSR 1953+29 lying in the error box of the COS-B source 2CG065+00) may be only a chance positional coincidence. Still, the following remarks may offer further support for continued searches for fast radio pulsars within the gamma-ray source error boxes.

LIGHT CYLINDER SYNCHROTRON EMISSION

To date, no complete theory of emission of radiation from pulsars exists. The fact that the Crab pulsar emits double pulsed radiation at radio, infrared, optical, x-ray and gamma-ray energies, whereas the Vela pulsar does not emit so-far observed x-rays, and has single pulsed radio but double pulsed optical and gamma-ray emission, continues to confound detailed complete models of pulsar radiation, numerous publications notwithstanding. However, the incoherent synchrotron emission model from the speed of light cylinder proposed by Pacini (1971) to account for optical emission from the Crab pulsar has proved to be singularly successful: it

*NASA-NRC Senior Resident Research Associate at Goddard Space Flight Center, on leave from Boston University, 1983 - 1984.

predicted, successfuly, the optical luminosity of the Vela pulsar, as well as the long term optical luminosity decrease of the Crab pulsar. We therefore blindly proceed with an application of this model to the higher energy emission from pulsars in the spirit that further correct predictions will justify an otherwise rather speculative extension of the basic model.

Withough repeating in detail the arguments of Pacini (1971), it suffices to note that almost independent of the exact nature of the energy loss mechanism from pulsars, the total energy loss rate is related to the pulsar surface magnetic field B, angular velocity ω , and radius R by

$$\frac{dE}{dt} \equiv L = \alpha \frac{B^2R^6\omega^4}{c^3}, \quad \text{where } \alpha \simeq 1 . \quad (1)$$

The energy loss is in the form of particles, magnetic dipole radiation, and free infrared through gamma-ray radiation. For particles flowing out through a dipole magnetic field, incoherent synchrotron radiation results near the speed-of-light cylinder with a luminosity $L_{inc\ sync}$ given by

$$L_{inc\ sync} = L_{rad} \propto B^4\omega^n , \quad \text{where } n \simeq 10. \quad (2)$$

The main point is that the radiation loss rate in this model is incredibly strongly dependent on the angular velocity ω, less strongly dependent on the magnetic field strength B, and more weakly dependent on the other parameters of pulsars. Equations (1) and (2) imply that $L_{rad} \propto L^2\omega^2$. Thus for a given total energy loss rate, the higher the angular velocity, the greater the proportion of energy is put into free radiation vis-a-vis particle and magnetic dipole energy loss. Also, since the "lifetime" of a pulsar $\tau \equiv E_{rot}/L = I\omega^2c^3/B^2R^6\omega^4$, where $I \simeq MR^2$ is the moment of inertia of the pulsar, one has $\tau \propto 1/B^2\omega^2$. That is, for a given age τ, the higher the ω, the greater the fractional energy loss to incoherent synchrotron radiation. Thus for an older population of pulsars (say $\tau > 10^6$ years), those with higher angular velocity will predominate provided they are also the ones which have weaker magnetic fields.

COMPARISON WITH OBSERVATIONS

We may compare the above two relations with observations made at gamma-ray energies for the Crab and 6.1 ms pulsars. Using the published values of the period and first period derivative for the 6.1 ms pulsar, Boriakoff, Buccheri and Fauci (1983) found that $(L_{rad}/L)_{Crab} = 1.5 \times 10^{-5}$, and $(L_{rad}/L)_{6.1} = 6.7 \times 10^{-5}$. Using equations (1) and (2) above, one expects $(L_{rad}/L)_{6.1} / (L_{rad}/L)_{Crab} \simeq 5$: astonishingly good agreement between observation and theory! Unfortunately, V. Boriakoff (this meeting) has now reported an upper limit on $\dot{P}$ a factor of about 14 below the value used above, resulting in a now order of magnitude discrepancy. However, considering the possible variability in allowed values of n in equation (2) above (perhaps ranging from 9 to 11), and the large difference in angular velocities, agreement to better than an order of magnitude in the exponent probably consitutes a triumph of the theory!

In Table 1 below, we list the properties of a number of "unusual" pulsars (those with high ω and/or weak B). These 8 pulsars are also plotted on the B-ω plane in Figure 1, along with the region occupied by all of the other known radio pulsars. Included also are several scaling

TABLE 1

Pulsar	P(ms)	$\dot{P}$ (10^{-15})	B(G)	$\omega(s^{-1})$
PSR 1937+214	1.56	.0001	3.0×10^{8}	4026
PSR 1953+29*	6.13	<.042	$<1.6 \times 10^{10}$	1025
PSR 053+21	33.1	422	4.0×10^{12}	189
PSR 0540-69†	50.2	479	5.0×10^{12}	126
PSR 1913+16*	59	.0086	2.3×10^{10}	106
PSR 0833-45	89.2	125	3.5×10^{12}	70.4
PSR 0655+64*	195.6	.0015	1.7×10^{10}	32
PSR 1952+29	426.7	.002	3.0×10^{10}	14.7

* binary pulsars
† x-ray pulsar lying in SNR 0540-69.3 in the Large Magellanic Cloud

lines. Sources with ages less than 1000 years would appear in the upper right hand corner of the plot. At present, we know only of the Crab pulsar in this region, and based on supernova statistics, do not expect many more. A dotted line labeled $\tau = 10^{6}$ years marks the region above which sources are 10^{6} or less years old. Finally, the solid line labeled $L_{inc\ sync}$ = constant results from taking n = 10, and normalizing to the Vela pulsar. Sources very much weaker than this, at typical distances of a few kiloparsecs, would not have been detectable by the COS-B satellite.

DISCUSSION

The present discussion does not address the question of the origin of pulsar magnetic fields or angular velocities. In an earlier discussion (Brecher and Chanmugam, 1978) it was suggested that only strongly magnetized neutron stars could shed their angular momentum by mass-loss braking at formation. It is natural, therefore, to consider a population of pulsars born with weak magnetic fields which, in the absence of any other mechanism for rapid loss of angular momentum, would be left with high angular momenta. Such objects would be found in the lower right portion of the B-ω plane shown in Figure 8. Provided that the magnetic fields continue to survive outside the star for 10^{7} -10^{8} years, we would expect these sources to radiate predominantly as incoherent synchrotron radiation sources. Whether or not this radiation appears at energies much above the optical region is unclear. However, the discovery of further fast pulsars in COS-B error boxes would certainly lend observational support to this hypothesis.

REFERENCES

Bignami, G.F. and Hermsen, W. 1983, Ann. Rev. Astr. Ap., 21, 67.
Boriakoff, V., Buccheri, R., and Fauci, F. 1983, Nature, 304, 417.
Brecher, K. and Chanmugam, G. 1978, Ap. J., 221, 969.
Pacini, F. 1971, Ap. J. (Letters), 169, L17.

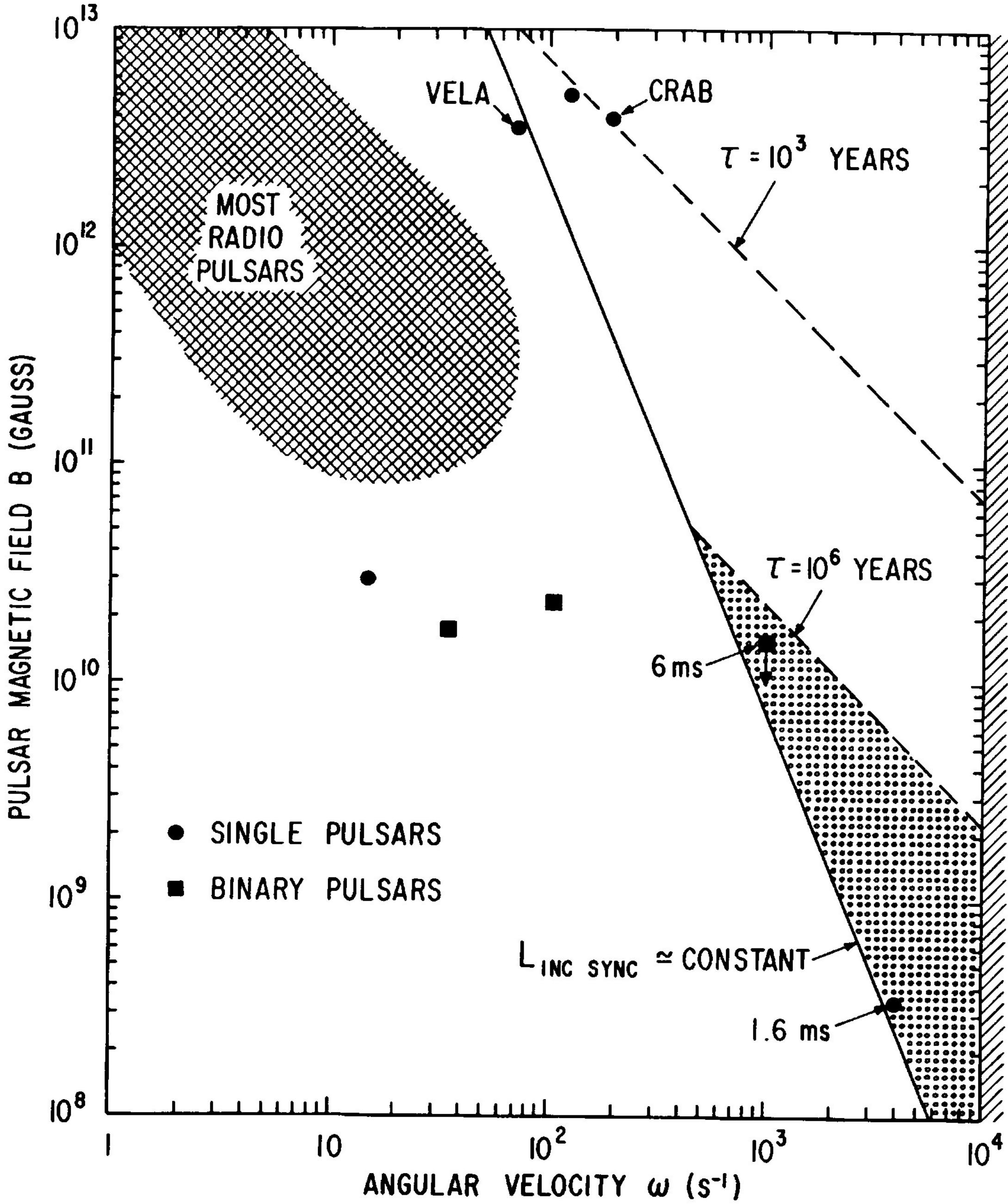


Figure 1. Plot of angular velocity ω vs surface magnetic field B for pulsars, assuming $I = 10^{45}$ gm-cm^2 and $B = 3 \times 10^{19}(P\dot{P})^{1/2}$. With the exception of the plotted points, all known radio pulsars lie in the cross-hatched region at the upper left. Old, fast, weak field pulsars radiating strong fluxes of incoherent synchrotron radiation from their light cylinders lie in the dotted region at the lower right. This is the suggested region on the B-ω plane containing the largest number of gamma-ray emitting pulsars.

DISCUSSION OF BRECHER'S PAPER

TAYLOR: Could you tell us again, Ken, what is the factor by which the gamma ray flux from PSR 1953+290 is comfortably above the energy loss rate based on the new $\dot{P}$ upper limit.

BRECHER: It's 10^4 times larger than the energy loss rate. I'm sorry, I shouldn't have gone by that so fast. I heard remarks yesterday that made me nervous. It's this comparison that I just gave you that bothered a number of people. It's that $\dot{E}$ in the gamma rays over $\dot{E}$ is 0.5×10^{-5} for PSR 1953+290. It's way down. I think what bothered people is that for the Crab this ratio was a little bigger, but I don't think that is significant.

TAYLOR: Well, there's plenty of energy there if you put it all into gamma rays.

BUCCHERI: OK, but you are using an upper limit as if it is the right value.

BRECHER: I was honest, though. I said I chose the optimistic value of 3.5 kiloparsecs, but if you want me to use 7 kiloparsecs instead you have another factor of 4 and now you're off by a factor of 12.

BACKER: You mean putting $\dot{P}$ on the magic line in the resurrection scenarios.

BRECHER: Yes. I'm lucky giving my talk today since I can use a lower limit for $\dot{P}$. This talk might disappear next month.

REYNOLDS: I think, just intuitively, that if you're able to make gamma rays at all that you should make brilliant X-ray sources.

BRECHER: That's why I mentioned Vela.

REYNOLDS: No, not pulsed X-rays. I mean an X-ray nebula.

BRECHER: I haven't thought about that. I'll only remark that it should be old. There shouldn't be any confining medium around except for the ambient interstellar medium. That's a good point.

VAN DEN HEUVEL: Could you give me the observational data indicating that Cygnus X-3 is really a gamma ray source? You said that COS-B did not see it.

BUCCHERI: We finished combining all the data from Cygnus X-3 last month and we don't find any source at that position.

VAN DEN HEUVEL: And the other evidence is from ground-based observations?

BRECHER: No, it's from SAS-3. They saw it as a strong source. They still believe it, don't they?

BUCCHERI: Yes, but the statistical significance is at least 10 times less than COS-B.

VAN DEN HEUVEL: There are so few photons in gamma rays that I always get a little bit worried. You mentioned yourself this 160 minute [solar] periodicity, which was a terrible thing to have happen.

BUCCHERI: Yes, but I have to comment: you mentioned that there was this claim, but you didn't mention that the COS-B collaboration disclaimed this finding.

VAN DEN HEUVEL: I may have already mentioned that there is a new claim of a 59-second periodicity [in 2CG195+4] that the COS-B group has disclaimed, but that will be published in Nature anyway.

BRECHER: They are going to publish that? I didn't want to get into it.

VAN DEN HEUVEL: My understanding is, yes, it has already been accepted. But I understand from Dr. Buccheri that it is very unbelievable.

BRECHER: Can I make a remark about unbelievability. Being a theorist, I have never fully appreciated the world of gamma ray observers because they always have disagreements, and as you say there are not many photons.

BUCCHERI: But it's very simple. You have only to base your conclusions on the data.

BRECHER: I was talking with Dave Thompson, and he said you always have to face the data.

BUCCHERI: But you have to look at the data, not only talk with people.

BRECHER: This is a remark, since you brought up the gravitational coupling through the sun. This is from Littlewood's Mathematician's Miscellany. I highly recommend that people read it. Professor X, I won't name names, finds gravitational waves under these conditions. But there is a suggestion that there is a mistake in the work. Clearly, any mistake generates gravitational waves. Let me just make a remark for the observers, lest you laugh too hard. Charles Darwin had a theory that once in a while one should perform a damn-fool experiment. It always fails, but when it does come off it's terrific. Darwin played the trombone to his tulips. The result of this particular experiment was negative.

LOW FREQUENCY VARIABILITY OF PULSARS - IMPLICATIONS FOR TIMING OF MILLISECOND PULSARS

*Roger Blandford and Ramesh Narayan**
Theoretical Astrophysics ,California Institute of Technology
Pasadena, CA 91125, U.S.A.

ABSTRACT

Rickett, Coles and Bourgois (1984) have argued that long-term (months to years) variation in pulsar flux is caused by fluctuations in the interstellar electron density on length scales $\sim 10^{13-16}$ cm. We show that there should then be correlated fluctuations in the pulse arrival time, pulse width, and angular size. PSR 1937+21 is suitable for detecting some of the new effects. We estimate the timing noise and pulse width variation in this pulsar assuming a power-law spectrum for the electron density fluctuations, normalized using scintillation data.

INTRODUCTION

The intensity variation of pulsars over time scales of months to years is usually considered an intrinsic effect. Recently, however, Rickett, Coles and Bourgois (1984) have shown on the basis of earlier work by Sieber (1982) that the effect could be convincingly explained as a propagation effect, caused by fluctuations in the interstellar medium on length scales of $\sim 10^{13-16}$cm.

Let us for convenience make a thin screen approximation. Because of the scattering by small scale ($\sim 10^{10}$cm) inhomogeneities (the ones invoked for

*On leave from : Raman Research Institute, Bangalore 560080, India

scintillation), an observer receives radiation from a circular patch of radius σ (angular radius $\theta = \sigma/L$) on the screen (fig. 1a). Now consider phase fluctuations on the wavefront on length scales $\gtrsim\sigma$. The single Fourier component considered for concreteness in fig. 1b converges rays at point C, leading to an enhanced flux F, and tends to defocus at A and E. The effect is due to refraction and can be understood on the basis of geometrical optics. For any reasonable spectrum of inhomogeneities, the maximum focusing/defocusing is produced by waves with $q \sim 2\pi\sigma^{-1}$ and hence the flux fluctuations at the observer screen have a spatial coherence length $\sim\sigma$. If the earth moves through this pattern with speed v ($\sim$100kms^{-1}), the time scale for intensity variations is $T_{ref} \sim \sigma/v$.

FLUCTUATIONS IN OTHER OBSERVABLES

We now show that fluctuations are expected in a variety of other pulsar parameters. The flux at C is enhanced because rays are received from a larger area on the screen (spot radius $>\sigma$), and so we expect the image size and shape to fluctuate on a timescale $\sim T_{ref}$, the fluctuations being correlated with the flux variations. This should be measurable using VLBI in favorable cases. If there is anisotropy in the electron density fluctuations, then the spot would be predominantly elongated perpendicular to the long axis of the blobs. The reported elongation perpendicular to the galactic plane of the non-thermal source at the galactic center at radio wavelengths (Lo 1984, private communication) could be evidence for the blobs being stretched out in the galactic plane.

Pulse arrival times have two sources of fluctuations. Firstly, because rays from the outer regions of the spot have a larger distance to travel ($\sim\sigma^2/2Lc$), fluctuations in spot size affect the arrival time of the pulse centroid. Secondly, the fluctuations in the phase front at the screen directly affect the group velocity of the radiation (fig. 1b). For reasonable choices of the spectrum of inhomogeneities, this second noise contribution increases monotonically as a function of the duration of observation. Combining the two effects, the arrival time fluctuates due to both effects for timescales up to $\sim T_{ref}$, but is dominated by group velocity effects beyond T_{ref}. There are similarly fluctuations in the pulse width, high flux being associated with increased pulse width.

Consider now the intermediate points B and D in fig.1b, where the rate of change of the flux, $|dF/dT|$, is a maximum. At these points the apparent position of the source is shifted by an amount that is correlated with dF/dT. This could be tested using VLBI. The "prisms" at B and D also disperse radiation of different frequencies, causing drift in frequency of the scintillation patterns (Hewish 1980). This is yet another fluctuation that is expected to be correlated with fluctuations in dF/dT and position.

All the above phenomena are reasonably broad-band and have decorrelation bandwidths $\Delta\nu \sim \nu$.

OBSERVATIONS ON PULSARS

We thus find that the suggestion of Rickett *et al.* (1984) has a wealth of observational implications. We have developed a formalism (described in detail elsewhere), based on a thin screen approximation and assuming that the refractive bending is smaller than σ/L, which quantifies the above effects in terms of the power spectrum $Q(q)$ of the electron density fluctuations. We have calculated auto- and cross-correlations of the various quantities in both time and observing frequency. Since all observables are expressed in terms of one function $Q(q)$, there are numerous consistency relations that can be checked. Alternatively, if the picture is confirmed by such tests, one could "invert" the observations to estimate $Q(q)$ in a range of q ($\sim 10^{-14}$cm^{-1}) hitherto inaccessible.

PSR 1937+21 would be suitable for monitoring timing and pulse width fluctuations. We take C_N^2 (eg Rickett 1977) for this pulsar to be $1.4\times10^{-4}m^{-6.67}$, as suggested by the measured scintillation decorrelation bandwidth of 6.3 kHz at 430 MHz (Cordes and Stinebring 1984), and assume a Kolmogorov spectrum, $Q(q) \propto q^{-\alpha}$, $\alpha = 11/3$. We then estimate the amplitude of the flux and pulse width fluctuations to be $\delta F/F \sim .09\lambda^{-17/30}$ and $\delta\tau \sim 9\lambda^{23/6}\mu s$, where λ is in meters. The timescale for variation is $T_{ref} \sim \lambda^{11/5}v_7^{-1}$yr, where the pulsar velocity is $100v_7$kms^{-1}. The pulse arrival time should fluctuate with amplitude $\delta t \sim 24\lambda^2(v_7T)^{5/6}\mu s$ where T(yr) is the time over which the observations are made (see also Armstrong 1984). The timing accuracy in PSR 1937+21 is presently better than $1\mu s$ at $\lambda = 21$cm and is shortly expected to become significantly better (Taylor 1984, private communication), and so the fluctuations δt and $\delta\tau$ should be measurable, particularly at longer wavelengths.

The assumption of a Kolmogorov spectrum generally predicts smaller intensity fluctuations than actually seen (eg Cole *et al.* 1970, Helfand *et al.* 1977). It is possible that α is not 11/3 but close to or even greater than 4. The magnitudes of all fluctuations are then predicted to be much greater than the above estimates, and therefore easier to observe.

Armstrong (1984) has pointed out that efforts to set limits on the stochastic background of gravitational radiation using the timing of PSR 1937+21 will soon be limited by the timing noise due to dispersion fluctuations and suggested that simultaneous monitoring of the pulsar dispersion measure could eliminate this source of noise. We find that there is also a contribution to timing noise $\sim\delta\tau$ from geometrical path length effects. Monitoring of pulse width and flux variations could help remove a substantial fraction of this noise.

REFERENCES

Armstrong, J.W. 1984, *Nature*, **307**, 527.

Cole, T.W., Hesse, H.K. and Page, C.G. 1970, *Nature*, **225**, 712.

Cordes, J.M. and Stinebring, D.R. 1984, *Ap. J.*, **277**, L53.

Helfand, D.J., Fowler, L.A. and Kuhlman, J. V. 1977, *Astr. J.*, **82**, 701.

Hewish, A. 1980, *M.N.R.A.S.*, **192**, 799.

Rickett, B.J. 1977, *Ann. Rev. Astr. Ap.*, **15**, 479.

Rickett, B.J., Coles, W.A. and Bourgois, G. 1984, *Astr. Ap.*, in press.

Sieber, W. 1982, *Astr. Ap.*, **113**, 311.

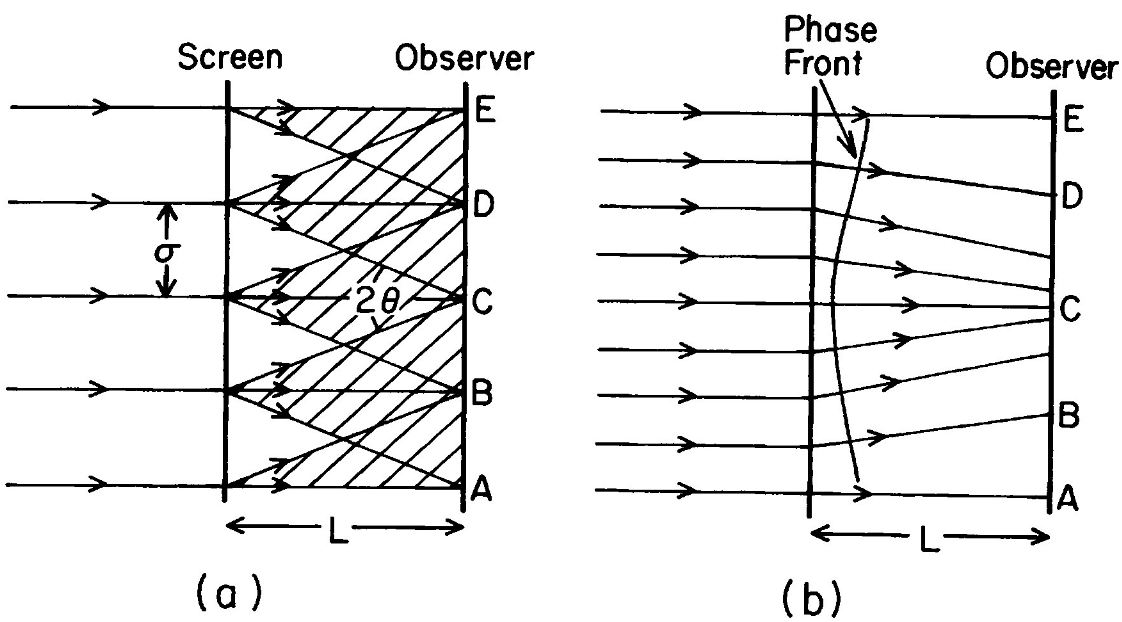


Figure 1. (a) The radiation from a distant source is scattered by small fluctuations in the screen into a beam of half-angle θ, which therefore measures the apparent angular size of the source. (b) Effect of a long wavelength phase fluctuation on the screen. Only the central ray from each point is displayed. The flux, angular size, pulse width and arrival time of pulse centroid are affected by the bending of the rays. Note that the pulse is retarded when the phase is advanced, as indicated by the arrows on the right.

DISCUSSION OF PAPER BY BLANDFORD AND NARAYAN

ALPAR: Suppose there was a distortion in the medium, powered by some strong source. Would you be able to pick this up by systematic effects of this type in pulsars situated around the source?

NARAYAN: You are thinking of some large scale distortion, on the order of a few hundred parsecs? I don't know. The sizes we are talking about here are 10^{13} - 10^{14} centimeters, very much sub-parsec. We don't know the origin of these fluctuations. They may be just the clumping of electron density. They may be from supernova shocks. Or they may be contributions from HII regions. But I don't know whether you can really correlate different pulsars. I don't think these fluctuations are correlated over such large distances. I would think that all sources could be handled as probing independent bits of the interstellar medium.

BACKER: All pulsars seen behind the Gum Nebula or an H II region would show correlated effects.

NARAYAN: They would have large effects, but they may not be correlated.

DAVIS: I noticed when Barney Rickett was down in Arecibo last fall, he commented on the correlation between dS/dt and $d\nu/dt$ and actually took some data for that purpose. I don't know what the results were.

LYNE: Barney is still working on it. He just proposed some new observations to try and sort it all out.

KULKARNI: When you talked about correlation with flux, couldn't that get confused with the diffraction effects of normal scintillation?

NARAYAN: The flux I am talking about here is an average flux, averaged over much greater than a scintillation time scale. You have to choose pulsars with short scintillation time scales.

KULKARNI: So you are suggesting that we go to low frequencies.

NARAYAN: That's right. In fact if you observe at 35 MHz you will see good effects [laughter].

BORIAKOFF: There's one pulsar that has had in the past drifts in both directions simultaneously.

NARAYAN: I think Jim [Cordes] was telling me that he has a number of such examples. They are very natural in this picture. Because as this wave moves, sometimes the phase gradient will be in one direction, sometimes in the other. And so you really expect drifts that go in both directions.

BACKER: At the same time at various frequencies? Instantaneously?

CORDES: Yes.

BORIAKOFF: It looks like a herringbone pattern.

NARAYAN: Now that's a tough one [laughter]. It's not consistent with this Kolmogorov picture, but it could be consistent with a spectrum that's steeper than 4. Then we can expect a small number of blobs contributing to the situation, and you could expect to see these crossed patterns.

BACKER: Needs three beams.

NARAYAN: That's right, at least three beams.

MANCHESTER: Jim Roberts has been modelling this stuff in Sydney. Jim Cordes is aware of that. He's just using scattering theory and not involving refraction explicitly.

STINEBRING: As far as the correlation of time scale with dispersion measure goes, if you put the actual velocities in rather than using the 100 km/sec that Sieber used in his original paper, the correlation becomes less good.

NARAYAN: I see. That's a bad one.

Further Observations of the Eight Hour Binary Pulsar PSR 1913+16

J. M. Weisberg and J. H. Taylor

Joseph Henry Laboratories, Physics Department
Princeton University, Princeton, NJ 08544

ABSTRACT

Timing measurements of the binary pulsar PSR 1913+16 now permit determination of the system's orbital elements and component masses to high precision. The pulsar and companion masses are 1.42 $\pm$ 0.03 and 1.40 $\pm$ 0.03 solar masses, respectively. The measured orbital period derivative is 1.00 $\pm$ 0.04 times the rate of orbital decay expected from emission of gravitational radiation. This agreement requires the equivalent energy density of a cosmic background of gravitational waves, with periods in the range $\sim$10 to 10^4 y, to be less than half that required to close the universe.

Introduction

The eight-hour binary pulsar PSR 1913+16 has proven to be an outstanding astrophysical laboratory (Taylor, Fowler, and McCulloch 1979; Taylor and Weisberg 1982; Weisberg and Taylor 1984). Timing measurements of the pulsar have been particularly fruitful in two main areas: first, the determination of the orbital elements and component masses of the system to high accuracy; and secondly, as a probe of gravitational radiation. Our observations have been made at the Arecibo Observatory over a nine-year time span, and consist of average pulse profiles measured near either 430 or 1400 MHz. The root-mean square uncertainties of pulse arrival times obtained in the most recent data are approximately 20 μs. Measurements of pulse arrival times are used as input for a multi-parameter least-squares fit for a number of quantities including the celestial coordinates of the pulsar, its spin frequency and derivative, and the orbital elements. In the fitting procedure we use the timing model of Blandford and Teukolsky (1976), as modified by Epstein (1977, 1979) and Haugan (1984).

Determination of Orbital Elements and Component Masses

In order to specify the masses of the stellar components and the orbital elements, one needs a set of seven measured quantities. Five of these, which might be called the "classical" orbital elements, can be determined from a Newtonian analysis of first-order Doppler variations of the pulsar period with orbital phase. These parameters and their uncertainties are listed at the top of Table 1.

Table 1. Orbital parameters of PSR 1913+16.

	(a) "Classical" parameters		
$a_p \sin i$	(light s)	2.34185	$\pm$ 0.00012
e		0.617127	$\pm$ 0.000003
P_b	(s)	27906.98163	$\pm$ 0.00002
ω_0	(deg)	178.8643	$\pm$ 0.0009
T_0	(JED)	2442321.4332084	$\pm$ 0.0000012
	(b) "Relativistic" parameters		
$<\dot{\omega}>$	(deg y^{-1})	4.2263	$\pm$ 0.0003
γ	(s)	0.00438	$\pm$ 0.00012
$\dot{P}_b$	(s s^{-1})	(-2.40	$\pm$ 0.09) $\times 10^{-12}$
$\sin i$		0.76	$\pm$ 0.14

As a result of the tightly bound, high-speed orbit, various relativistic phenomena are measurable in this system as well. The mean rate of periastron advance, $<\dot{\omega}>$, is now determined to better than 0.01% accuracy. The variation in time dilation and gravitational redshift around the orbit, which we parametrize as γ, leads to an additional several milliseconds of variation in pulse arrival times. This term is now measured with 2% accuracy. A third relativistic measurable, the gravitational propagation delay, arises from passage of the pulsar signals through the companion's gravitational field. The expected variation in delay around the orbit — of order tens of microseconds — depends strongly on orbital inclination. Therefore this term is parametrized as the geometric quantity $\sin i$, where i is the angle between the orbital plane and the plane of the sky. Successful measurement of $\sin i$ is made difficult by the small magnitude of the propagation delay and its large covariance with some of the other fitted parameters. In addition, there are other small post-Newtonian effects that must be included in the timing model to achieve the required accuracy (Haugan 1984). We believe that our present timing model is reliable at the $\sim$1 μs level, and that the propagation delay term has been measured with 20% accuracy.

The five classical orbital elements, together with the relativistic measurables $<\dot{\omega}>$, γ, and $\sin i$, comprise a redundant set of parameters describing the orbiting system. It is interesting to use this set of eight quantities to solve for two important parameters, the pulsar and companion masses m_p and m_c. The measured values of $<\dot{\omega}>$, γ, and $\sin i$ can be related to the classical elements and component masses as follows, yielding three equations in the two unknowns m_p and m_c:

$$\dot{\omega} = 3\,(P_b \,/\, 2\pi)^{-\frac{5}{3}}\,(1-e^2)^{-1}\,(m_p+m_c)^{\frac{2}{3}}$$

$$=2.11287\left(\frac{m_p+m_c}{M_\odot}\right)^{\frac{2}{3}} \quad \deg\ y^{-1} \tag{1}$$

$$\gamma = e\,(P_b \,/\, 2\pi)^{\frac{1}{3}}\, m_c\,(m_p+2m_c)\,(m_p+m_c)^{-\frac{4}{3}}$$

$$= 0.002936\left(\frac{m_c}{M_\odot}\right)\left(\frac{m_p+2m_c}{M_\odot}\right)\left(\frac{m_p+m_c}{M_\odot}\right)^{-\frac{4}{3}} \quad s \tag{2}$$

$$\sin i = (a_p \sin i \,/\, m_c)\,(P_b \,/\, 2\pi)^{-\frac{2}{3}}\,(m_p+m_c)^{\frac{2}{3}}$$

$$= 0.509\left(\frac{m_c}{M_\odot}\right)^{-1}\left(\frac{m_p+m_c}{M_\odot}\right)^{\frac{2}{3}} \quad . \tag{3}$$

Figure 1 shows the region of parameter space consistent with the measured value of each parameter. At present, the rather large uncertainty in the $\sin i$ term does not provide much additional constraint on the masses. Nevertheless, it is significant that the measured value is fully consistent with the much tighter limits imposed by $<\dot{\omega}>$ and γ. Thus, $\sin i$ provides independent evidence that all important phenomena that might affect the timing model have been correctly taken into account.

The component masses can be estimated by doing a least-squares fit to the three relativistic parameters, their estimated errors, and their covariances. The result is $m_p = 1.42 \pm 0.03\ M_\odot$ and $m_c = 1.40 \pm 0.03\ M_\odot$. The pulsar mass measurement provides the most precisely known value of a neutron star's mass. The very similar companion mass argues that it, too is a neutron star, in agreement with evolutionary considerations [see the contribution by van den Heuvel (1984) in this volume, and references therein].

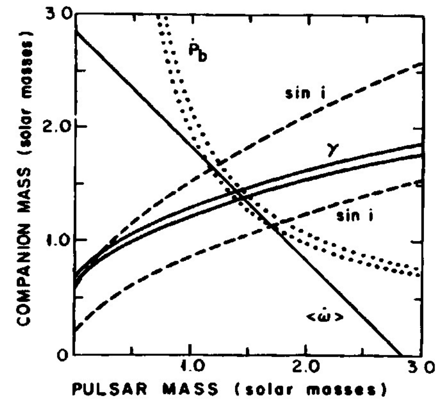


Figure 1. - Solid and dashed lines give constraints placed on the stellar masses by measured values of $<\dot{\omega}>$, γ, and $\sin i$. Dotted curves give the mass constraints if the measured orbital period derivative, $\dot{P}_b$, is attributed to gravitational radiation damping. All four measurements are consistent with pulsar and companion masses near the Chandrasekhar limit, 1.4 $M_{\odot}$.

PSR 1913+16 and Gravitational Waves

General relativity predicts that a gravitationally bound system such as PSR 1913+16 will emit gravitational waves. The resulting energy loss should lead to an orbital period decrease whose value depends on the orbital elements and component masses as follows:

$$\dot{P}_b = -\frac{192\pi}{5}(P_b / 2\pi)^{-\frac{5}{3}}(1-e^2)^{-\frac{7}{2}}(1+\frac{73}{24}e^2+\frac{37}{96}e^4)\, m_p\, m_c\, (m_p+m_c)^{-\frac{1}{3}} \quad . \qquad (4)$$

The value of $\dot{P}_b$ calculated from equation (4) and Table 1 is (-2.403 $\pm$ 0.002) $\times\ 10^{-12}$ s s^{-1}. The measured value of $\dot{P}_b$, obtained from the least squares fit to arrival times, is (-2.40 $\pm$ 0.09) $\times\ 10^{-12}$. This agreement of prediction and observation to within 4% provides strong evidence that the system is emitting gravitational radiation, and that general relativity provides a satisfactory framework to describe it.

Psr 1913+16 is also useful as a *detector* of very long wavelength gravitational waves (Mashhoon, Carr, and Hu 1981; Bertotti, Carr, and Rees 1983). The passage of waves with period longer than the total span of observations would manifest itself as an extra contribution to the orbital period derivative $\dot{P}_b$. If one accepts the validity of the general relativistic quadrupole formula, which leads directly to equation (4), then an upper limit to deviations of $\dot{P}_b$ from the expected value can be converted to an upper limit on the energy density of long-period gravitational waves. The binary pulsar thus makes very long wavelength gravitational radiation accessible to observation for the first time.

If observations exist over an interval T and the pulsar distance is L, then Ω_{GW}, the fraction of closure density in gravitational radiation in the period range $T < P < L$, is given by (Bertotti *et al.* 1983)

$$\Omega_{GW} < \frac{1}{2}\left[\frac{\delta \dot{P}_b}{P_b H}\right]^2 = \frac{1}{2} h^{-2} \left[\frac{\delta \dot{P}_b / P_b}{10^{-10}\ \mathrm{y}^{-1}}\right]^2 , \tag{5}$$

where $\delta \dot{P}_b$ is the measured deviation (or upper limit of the deviation) of $\dot{P}_b$ from the expected value, H is the Hubble constant, and $h = H / (100\ \mathrm{km\ s^{-1}\ Mpc^{-1}})$. The present upper limit on $\delta \dot{P}_b$ already requires that $\Omega_{GW} < 0.5\ h^{-2}$.

Measurements over the next decade should decrease the uncertainty in $\dot{P}_b$ by a factor of five or more. Thus, if agreement with the expected value of $\dot{P}_b$ still persists, the limit on Ω_{GW} would decrease to $\sim 0.02\ h^{-2}$. Beyond this level, it is expected that uncertainties in the pulsar's galactic motion will place a limit on further improvements.

References

Bertotti, B., Carr, B. J., and Rees, M. J., 1983. *Mon. Not. Roy. Astron. Soc.*, **203,** 945.

Epstein, R., 1977. *Astrophys. J.*, **216,** 92. Epstein, R., 1979. *Astrophys. J.*, **231,** 644.

Haugan, M. P., 1984. In preparation.

Mashhoon, B., Carr, B. J., and Hu, B. L., 1981. *Astrophys. J.*, **246,** 569.

Smarr, L. L., and Blandford, R., 1976. *Astrophys. J.*, **207,** 574.

Srinivasan, G., and van den Heuvel, E. P. J., 1982. *Astron. Astrophys.*, **108,** 143.

Taylor, J. H., Fowler, L. A., and McCulloch, P. M., 1979. *Nature*, **277,** 437.

Taylor, J. H., and Weisberg, J. M., 1982. *Astrophys. J.*, **253,** 908.

Weisberg, J. M., and Taylor, J. H., 1984. *Phys. Rev. Lett.*, **52,** 1348.

DISCUSSION OF WEISBERG'S PAPER

BACKER: What is the reason for the observational uncertainty in $\dot{P}$?

WEISBERG: Well, of course we're assuming that the quadrupole formula is correct. The pulsar's galactic motion, which presumably we ought to be able to estimate fairly well, leads to a $\dot{P}/P$ of 10^{-13} per year. Our present uncertainty in $\dot{P}/P$ is 10^{-10}. Its proper motion leads to an uncertainty of around 10^{-11} per year. But now with our improved ephemeris we ought to be able to measure the proper motion a little better. But notice that we have to know the actual speed. Speed requires a knowledge of the distance as well, and the distance is not known more accurately than, say optimistically, 20%.

STINEBRING: With regard to being able to measure long-wavelength gravity waves much better than in PSR 1913+16: can you be sure that in estimating the orbital eccentricity or the masses of the stars there isn't a contamination by gravity waves? Say, for example, that there is a gravity wave passing right now. Can you be sure that this source of error wouldn't have the same effect as introducing a spurious $\dot{P}$ as in the isolated pulsar case?

WEISBERG: No, I don't think so. The signature of the orbital elements has a much different time scale than what you would expect from a passing gravity wave.

GOSS: What are your current thoughts, Joel, about the optical identification of the companion?

WEISBERG: Well, over the last few years no one that I know of has made any progress in identifying the candidate star. The candidate star is very close to the position of PSR 1913+16. If it were associated with the system, it seems like it would have to be a helium star on the basis of its brightness. But we don't see any way that there could be a helium star in the system, given the determination of the orbital elements, because a helium star should cause an advance of periastron and, conceivably, some part of the orbital period decrease. And the fact that all of our parameters are consistent now, in fact they are doubly over-determined, on the assumption that the stars are two point masses, suggests to us very strongly that the star is not connected with the system. So, we believe that it is probably a chance superposition. It's too faint to get a spectrum, which would let you check if there is a changing Dopplier shift. Of course that would be the ideal test.

DAVIS: Is the character of your residuals such that you are truly noise limited in your measurements?

WEISBERG: Yes, the residuals go down as the square root of the number of observations, so we still benefit from increased signal-to-noise.

HAGFORS: Is it possible to detect the presence of plasma in the system by the presence of annual, if you like, time delays in the data?

WEISBERG: Yes, what we would look for would be the frequency dependence. In fact it would be very similar to the gravitational propagation delay--it would be largest when the pulsar is behind the companion. But we had relatively high-quality 430 MHz data, although not as good as our 1400 MHz data, but of course dispersion is much bigger at 430 MHz. Anyway, we placed rather strong limits on any stellar wind from the companion.

REYNOLDS: You must be able to put a phenomenal limit on the presence of a third star in this system. Is there any chance that a very long period binary could mimic the behavior of a passing gravitational wave?

WEISBERG: No, we can rule that out very definitely.

VAN DEN HEUVEL: Has any one ever tried to calculate the interaction of the magnetic fields of two orbiting neutron stars?

WEISBERG: Well, the speed of light cylinder is much smaller than the orbital separation for PSR 1913+16. And again, we feel that the overdetermined system fits so well with a gravitational radiation explanation that any other effects are very minor.

VAN DEN HEUVEL: What is the component separation?

WEISBERG: About one solar radius at periastron.

PULSAR POWERED RADIO SUPERNOVAE
AND THE EARLY EVOLUTION OF PLERIONS

R. Bandiera

European Southern Observatory, Garching (FRG)

F. Pacini

Arcetri Astrophysical Observatory, University of Florence (Italy)

M. Salvati

Istituto di Astrofisica Spaziale, Frascati (Italy)

ABSTRACT

We discuss the nature of Radio Supernovae assuming that their activity is due to the presence of a very fast internal pulsar. We then try to establish a direct evolutionary link between Radio Supernovae and plerions using the theory of pulsar powered Supernova Remnants.

INTRODUCTION

There is a common agreement on the fact that all Crab-like Supernova Remnants (SNR), the so-called plerions (Weiler and Panagia 1980), emit mainly by synchrotron radiation, and that the required magnetic field and relativistic particles are provided by a central pulsar. A theory has been developed (Pacini and Salvati 1973, henceforth PS), which derives the evolution of synchrotron luminosity on the basis of the time behaviour of the particle distribution and the magnetic field.

In the frame of this theory, one would predict a large flux of non-thermal radiation, beginning shortly after the Supernova explosion, and lasting for a time of the order of the pulsar initial slowing-down time scale. Newly discovered strongly variable radio sources at the sites of recent extragalactic Supernovae, the so-called Radio Supernovae (RSN) (see Weiler et al. 1983 for a review), show in fact a behaviour similar to that expected for proto-plerions. This prompted us to check in more detail whether a genetic connection between RSN's and plerions is a tenable hypothesis.

ORIGIN AND DETAILS OF THE MODEL

Basically two models were presented to explain the RSN data. While both agree that the radio flux is due to synchrotron emission, different origins of the magnetic field and the relativistic particles are proposed: the first (Chevalier 1982) invokes a turbulent production, when the ejecta interact with the circumstellar matter; according to the latter, instead, the engine is a central pulsar (Pacini and Salvati 1981, Shklovskii 1981).

We have based our computations on the latter model, and followed the treatment outlined by PS: the pulsar feeds energy to the remnant by magnetic dipole radiation (or an equivalent mechanism); this energy goes partly into magnetic field, and partly into fast particles, which in turn are subject to synchrotron losses. Furthermore we have introduced some improvements:

i) We have taken into account synchrotron reabsorption in the very early life of the source. However we have neglected possible free-free absorption from external ionized matter: this is justified when strong instabilities affect the envelope and break it up into filaments.

ii) In the case of a very fast pulsar, we have included gravitational radiation losses: this allows us to be consistent with typical SNR energies. We have parametrized such losses as function of a constant quadrupolar moment (Bandiera et al. 1983).

iii) Here too we have restricted ourselves to the case of a power-law spectrum for the injected particles; unlike PS, however, the high energy cutoff now depends on the maximum potential drop in the pulsar magnetosphere. According to Goldreich and Julian (1969), it goes as the square of the pulsar rotation frequency.

iv) In order to allow a direct comparison with old plerions, we need to follow the evolution up to the Sedov phase. Even though we omitted a fully dynamical treatment, we have simulated the effect of the interstellar matter by assuming that it is swept up in a thin shell.

The basic parameters on which our model depends are:

i) P_o: the initial pulsar period. For an object like PSR0531 it is 17 ms, while it can reach about 1 ms in the case of a maximally rotating neutron star.

ii) ε: the equatorial ellipticity, regulating the gravitational losses. It is important only for fast pulsars, for which we have chosen $\varepsilon = 10^{-4}$.

iii) v_o: the initial expansion velocity of the remnant. The quoted standard value is 10^9 cm s^{-1}; while for the Crab $v_o = 1.5\ 10^8$ cm s^{-1}.

iv) γ: the particle spectral index at the injection. In our treatment, we need $\gamma < 2$: for the Crab the radio spectrum implies $\gamma = 1.5$.

We have then fixed the remaining parameters as follows: the moment of inertia and the magnetic dipole are taken from PSR0531; the maximum energy of the injected particles is scaled with Crab; the energy lost by the pulsar is equally shared between magnetic field and relativistic particles; and, finally, a standard interstellar density (1 cm^{-3}) is taken. A more detailed discussion of the model is given in Bandiera et al. (1984).

THE RADIO BEHAVIOUR

We have found it convenient to classify the models into four general categories, according to the initial pulsar period (Slow: P_o = 10–20 ms; Fast: P_o = 1 ms), and to the initial expansion velocity (Slow: $v_o = 10^8$ cm s^{-1}; Fast: $v_o = 10^9$ cm s^{-1}). Also of importance is the injection spectral index: we have chosen it in such a way as to get a reasonable compromise between radio evolution and X-ray properties. Fig.1 compares the theoretical light curves at 6 cm for the following models:

FF) P_o = 1 ms (and $\varepsilon = 10^{-4}$); $v_o = 10^9$ cm s^{-1}; and $\gamma = 1.4$.

SF) P_o = 20 ms; $v_o = 10^9$ cm s^{-1}; and $\gamma = 1.8$.

SS) P_o = 17 ms; $v_o = 1.5\ 10^8$ cm s^{-1}; and $\gamma = 1.5$.

with some actual measurements or upper limits for RSN's; the observations are labeled with the Supernova name, while the asterisk marks the present time position of the Crab. Only the most stringent available upper limits are shown individually, while the others are represented by the hatched area. The references to the data shown are listed in Bandiera et al. (1984).

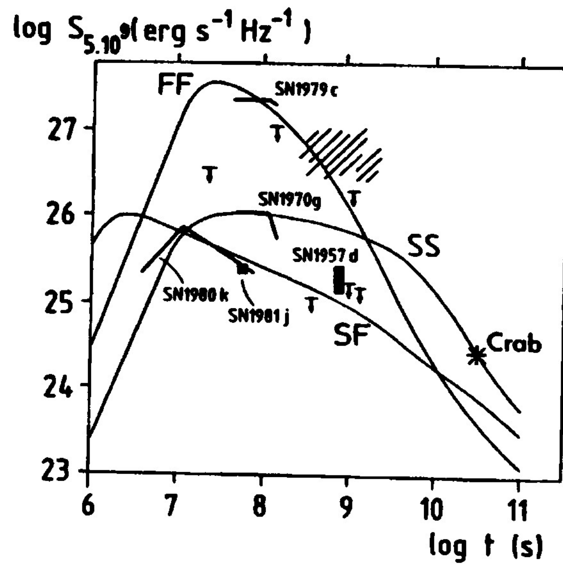


FIG.1

The radio evolution can be typically divided into three phases: the early flux rise is due to a decreasing synchrotron opacity; then a phase of almost constant luminosity lasts for a time comparable with the pulsar slowing-down time scale; later on, there is a marked flux decrease, since the declined injection rate cannot any more balance adiabatic and radiation losses. The curves labeled FF and SF approximate the data on SN1979c and SN1980k, respectively. Curve SS, instead, has been fitted to the present time flux and slope of the Crab, and is intended to prove the continuity between RSN's and fully developed plerions from the standpoint of "typical" peak fluxes. The agreement with the flat portion of the light curve of SN1970g has to be regarded as accidental; indeed a shock model, rather than a plerionic one, would explain more naturally the subsequent abrupt decline. No clearly established example of case FS is available yet; however if the nuclear radio source in M 82 (Kronberg and

Biermann 1983) were interpreted as an RSN undetected in the optical, its properties would be suggestive of an FS plerion.

THE SURFACE BRIGHTNESS-DIAMETER RELATIONSHIP

A classical way of comparing theory and observation in the field of SNR's is the relationship between the radio surface brightness Σ and the diameter D. Independently of the assumed model, the Σ-D is meaningful if all the objects represent different evolutionary stages corresponding to identical initial conditions. We know this is not the case for plerions - take for instance the peculiar expansion velocity of the Crab - hence the following considerations must be applied to the entire class, rather than to single objects. Weiler and Panagia (1980) showed that the dependence of Σ on D is shallower for plerions than for standard SNR's, due to the presence of a late energy input: this is suggestive of a long pulsar lifetime, which in turn implies a relatively slow initial rotation.

Fig.2 compares theoretical Σ-D relations with observations of uncontroversial plerions (Weiler and Panagia 1980); while SN1980k extrapolates satisfactorily to the whole class, the model fitted to SN1979c gives too short a pulsar lifetime and too steep a dependence. In fact, SN1979c stands out as an exceptional occurrence and less energetic events appear more common.

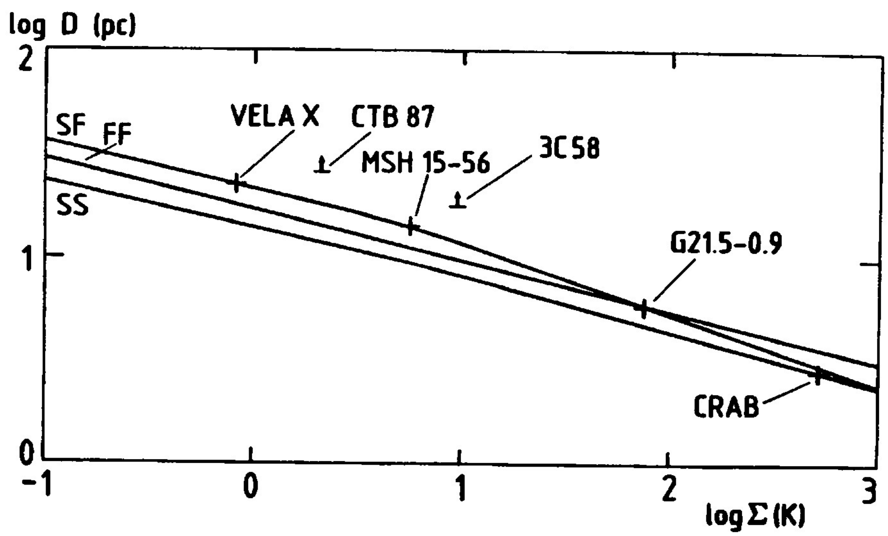


FIG.2

CONCLUSIONS

Using a model for pulsar powered SNR's we were able to establish a plausible genetic link between RSN's and plerions, and to draw the following conclusions:

RSN's and plerions can be seen as two different phases in the evolution of a pulsar powered SNR.

In the majority of cases, a pulsar like PSR0531 is sufficient to explain the properties of RSN's.

A millisecond pulsar is more appropriate for explaining the most energetic cases, as SN1979c. However the comparison with known plerions indicates that such cases are rather exceptional.

REFERENCES

Bandiera, R., Pacini, F., Salvati, M. 1983, Astr. Ap. **126**, 7

Bandiera, R., Pacini, F., Salvati, M. 1984, Ap. J. (in press)

Chevalier, R. A. 1982, Ap. J. **259**, 302

Goldreich, P., Julian, W. H. 1969, Ap. J. **157**, 869

Kronberg, P. P., Biermann, P. 1983, IAU Symp. No. 101, Supernova Remnants and their X-ray Emissions, eds. J. Danziger and P. Gorenstein (Dordtrecht, Reidel)

Pacini, F., Salvati, M. 1973, Ap. J. **186**, 249

Pacini, F., Salvati, M. 1981, Ap. J. **245**, L107

Reynolds, S.P., Chevalier, R. A. 1984, Ap. J. **278**, 630

Shklovskii, I. S. 1981, Pis'ma Astr. Uh. **7**, 479 (Sov. Astr. Lett. **7**, 263)

Weiler, K. W., Panagia, N. 1980, Astr. Ap. **90**, 269

Weiler, K. W., Sramek, R. A., van der Hulst, J. M., Panagia, N. 1983, IAU Symp. No. 101, Supernova Remnants and their X-ray Emissions, eds. J. Danziger and P. Gorenstein (Dordtrecht, Reidel)

DISCUSSION OF BANDIERA'S PAPER

GOSS: There are at least two groups at the VLA that are looking into this last point at the moment. They are doing a survey of low-latitude sources, looking for 10 arcsecond separations, throwing away double sources.

BANDIERA: OK, that's good to know about.

PSR 1953+29 - POSSIBLE EXPLANATION OF THE LARGE PERIOD DERIVATIVE

L. A. Nowakowski

Dartmouth College, Hanover, NH 03755

ABSTRACT

This paper attempts to explain larger $\dot{p}$ observed in PSR 1953+29 than expected from the spin-up theory in terms of the simultaneous magnetic field decay and counter-alignment, occuring on different time scales. We also show that this pulsar may evolve to period and period derivative similar to the majority of other known pulsars if its initial p and $\dot{p}$ were similar to present ones and counter-alignment is assumed.

INTRODUCTION

Two newly discovered millisecond pulsars with very low period derivatives (Backer et al.,1982,1983, Boriakoff et al.,1983, Ashworth et al.,1983) are belived to be the remnants of close binary systems, spun-up to short periods by accretion from the companion star (Alpar et al.,1982, Helfand et al.,1982, Paczynski, 1983). If so, their initial period and period derivatives should follow the relations (e.g. Alpar et al. 1982 and references therein):

$$p = p(B,\ R,\ M,\ \dot{m}) \tag{1}$$

$$\dot{p} = \dot{p}(p,\ M,\ \dot{m},\ I) \tag{2}$$

where B is the surface dipole magnetic field, R is the radius of the star, M is its mass, $\dot{m}$ is the accretion rate and I is the moment of inertia of the neutron star. This implies that spun-up neutron stars that are (or were) members of the binary systems, should start their evolution in the log p - log $\dot{p}$ diagram from (or below) the line described by the initial conditions of Equations (1) and (2). Three other pulsars which are membesrs of such systems, and also PSR 1937+21 (for which there is no direct evidence supporting its past binary nature), seem to follow these relations quite well. If the millisecond pulsars evolve according to the simple magnetic braking with constant or decaying magnetic field, they would never reach the region in the p - $\dot{p}$ diagram where nearly 300 other pulsars are situated (see Fig.1 of Alpar et al.,1982). We show here that this may be not the case, at least for PSR 1953+29, if counter-alignment occurs during the evolution. We discuss possible observational consequences of this process and present arguments that may help to understand the present position of the PSR 1953+29 in the p-$\dot{p}$ diagram, which differs from that predicted from the spin-up theory.

MAGNETIC FIELD DECAY AND COUNTER-ALIGNMENT

Observations suggest, that the magnetic field in pulsars decreases on a timescale τ_B < 10 Myr (e.g. Lyne et al., 1982, Manchester et al., 1974). There are also arguments indicating that counter-alignment of the magnetic axis may occur on another timescale τ_α (Macy, 1974, Flowers, Ruderman, 1977, Nowakowski, 1983b). Each of these processes gives another type of the evolutionary track in the p - $\dot{p}$ plane (see Nowakowski 1983 a,b for a brief review). We assume here that both processes take place at the same time. In such a case the braking torque increases as the angle between the axes increases and the pulsar period can be written as:

$$p = \Bigg\{ p_0^2 + \frac{\tau_B\, p_0 \dot{p}_0}{\cos^2\alpha_0} (1 - \exp(-2t/\tau_B)) \tag{3}$$

$$+ \frac{\tau_\alpha \tau_B\, p_0 \dot{p}_0}{2\cos^2\alpha_0} \sum_{j=0}^{N} \frac{(-1)^j (2\alpha_0)^{2j}}{(2j)!(\tau_\alpha + 2j\tau_B)} (1 - \exp(-2t(\tau_\alpha + 2j\tau_B)/(\tau_\alpha \tau_B)))\Bigg\}^{1/2}$$

and the period derivative is:

$$\dot{p} = p^{-1} K \exp(-2t/\tau_B) \cos^2(\alpha_0 \exp(-2t/\tau_\alpha)) \tag{4}$$

(see Nowakowski, 1983 b for details). The above equations have been used to calculate the evolutionary tracks for PSR 1953+29. We have tested many different pairs of τ_α and τ_B and we present several examples of our results in Figs 1 and 2, where letters a-h denote pairs (τ_α , τ_B): $(10^3, 10^6)$, $(10^3, 10^7)$, $(10^4, 10^6)$, $(10^4, 10^7)$, $(10^7, 10^6)$, $(10^7, 10^7)$, $(10^3, 10^8)$, $(10^6, 10^8)$. Our results show, that time variations of the effective dipole moment, caused by simultaneous counter-alignment and decay of the magnetic field, result in a rapid increase of the period derivative when τ_α is short. Below we discuss some possible observational consequences of such a scenario for PSR 1953+29.

RESULTS OF THE CALCULATIONS

In our calculations we have used two values of $\dot{p}$: its present upper bound ($\dot{p} < 5.8 \cdot 10^{-16}$ s·s^{-1} , Boriakoff et al., 1983) and that which follows from the spin-up theory ($\dot{p} = 3.6 \cdot 10^{-19}$ s·s^{-1}, see Alpar et al., 1983, Nowakowski, 1984 for more details). Fig.1 presents evolutionary tracks starting from p and $\dot{p}$ close to their present values. This case seem to be interesting, since all tracks after some time go into that region of the diagram, where we have all other pulsars. Rapid counter alignment [$\tau_\alpha = 10^3$ years, with $\alpha_0 = 89°$, where $\alpha = \sin((\vec{m}\cdot\vec{\omega})/(m\omega))$] results in a large jump upwards, which ends in the vicinity of the Crab pulsar. Then the track reverses its direction and goes down, crossing the cluster of all other pulsars in the diagram. On the first part of the track the pulsar should have $\ddot{p}>0$, while $\ddot{p}<0$ should be observed on the second part, which begins close to the Crab, which has

$\ddot{p}<0$. In case of longer τ_* the tracks go into the cluster after $t > 5*10^4$ years, after initial drop (tracks e,f and h in Fig.1), during which $\ddot{p}$ should be negative. Then $\ddot{p}$ becomes positive, as it is observed in some pulsars within this region (Gullahorn, Rankin, 1978,1982). In the second case (p and $\dot{p}$ predicted from the spin-up - Fig.2) two interesting features can be seen: first - for $\tau_* = 10^3$ and 10^4 years, $\dot{p}$ may evolve to its present value after $t \sim 5*10^3$ or $5*10^4$ years, respectively. Second - after initial jump the tracks go down and after $t > 10^7$ years the pulsar may be found in the vicinity of another binary pulsar, PSR 1913+16 (tracks b, d). This is possible, however, also for slow counter-alignment (track f).

DISCUSSION

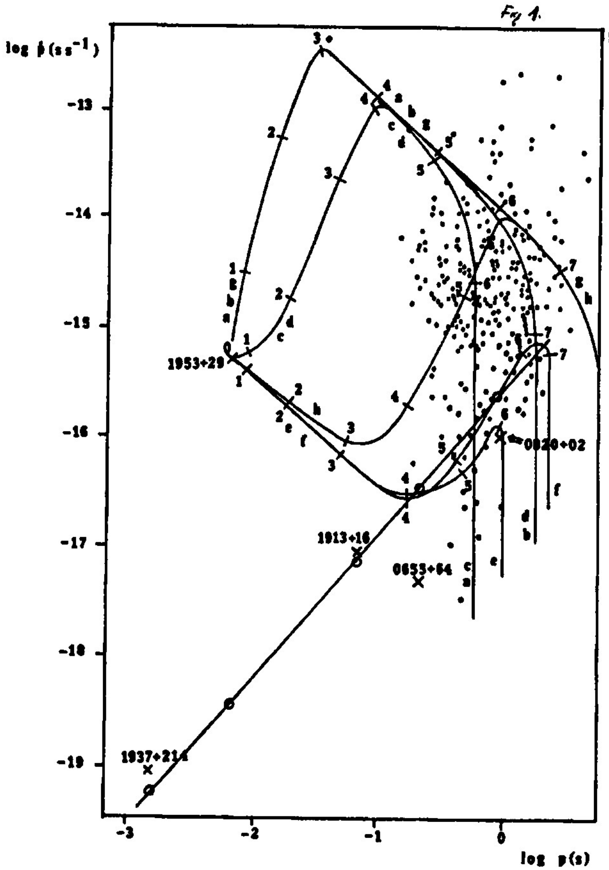
From the physical point of view it seems possible that pulsars may undergo counteralignment during their evolution (Macy,1974, Flowers, Ruderman, 1977). If so, younger pulsars should be nearly aligned and it is possible that we see the same beam of radiation twice as the main and interpulse (Narayan, Vivekanand, 1983). Recent polarization measurements of PSR 1937+214 do not exclude this model (Stinebring, Cordes,1983). We do not know however, if similar configuration may be assumed for PSR 1953+29, until polarization measurements are carried out. We have tentatively assumed that it may be so. Pulsar ages are usually estimated from a formula $\tau = p/2\dot{p}$ which applies only to the magnetic braking with constant effective dipole moment and if $p_o^2=0$ (in case of counter-alignment this estimator should not be used, Nowakowski, 1984). Many authors agree that τ may be regarded only as an upper limit of the real age and try to find better age estimators. Recently the age of PSR 1953+29 has been estimated from the comparison of the neutron star cooling calculations with estimations of the X-ray luminosity of a pulsar. The result is $t > 3*10^3$ years (Helfand et al., 1983), compared to $\tau = 1.5*10^5$ years. It is interesting to note, that our calculations indicate similar age, provided that $\tau_* = 10^4$ years and $\dot{p}$ equals its theoretical (spin-up) value (see track d in Fig.2). Measurements of the second derivative of the period, together with polarization measurements would give the most convincing arguments that might support our picture of the evolution.

This work is supported in part by NSF Grant AST-8217236.

REFERENCES

Alpar,M.A.,Cheng,A.F.,Ruderman,M.A.,Shaham,J.:1982, Nature 300,p.728
Ashworth,M.,Lyne,A.G.,Smith,F.G.,:1983, Nature 301,p.313
Backer,D.C.,Kulkarni,S.R.,Heiles,C.,Davis,M.M.,Goss,W.M.,:1982, Nature 300,p.615
Backer,D.C.,Kulkarni,S.R.,Taylor,J.H.,:1983, Nature 301,p.314
Boriakoff,V.,Buccheri,R.,Fauci,F.,:1983, Nature 304,p.417
Flowers,E.,Ruderman,M.A.,:1977, Astrophys. J. 215,p.302
Gullahorn,G.E.,Rankin,J.M.,:1978, Astron. J. 83,p.1219
Gullahorn,G.E.,Rankin,J.M.,:1982, Astrophys. J. 260,p.520
Helfand,D.J.,Ruderman,M.A.,Shaham,J.,:1983, Nature 304,p.423

Lyne,A.G.,Anderson,B.,Salter,M.J.,:1982, Monthly Notices Roy. Astron. Soc. 201,p.503
Macy,W.W.M.,:1974, Astrophys. J. 190,p.153
Manchester,R.N.,Taylor,J.H.,Van Y.Y.,:1974, Astrophys. J. 189,L119
Narayan,R.,Vivekanand,M.,:1983, Astrophys. J. 274,p.771
Nowakowski,L.A.,:1983a, Astron. Astrophys. 118,p.29
Nowakowski,L.A.,:1983b, Astron. Astrophys. 127,p.259
Nowakowski,L.A.,:1984, 164th Meeting AAS,Baltimore (unpublished)
Paczynski,B.,:1983, Nature 304,p.421
Stinebring,D.J.,Cordes,J.M.,:1983, Nature 306,p.349



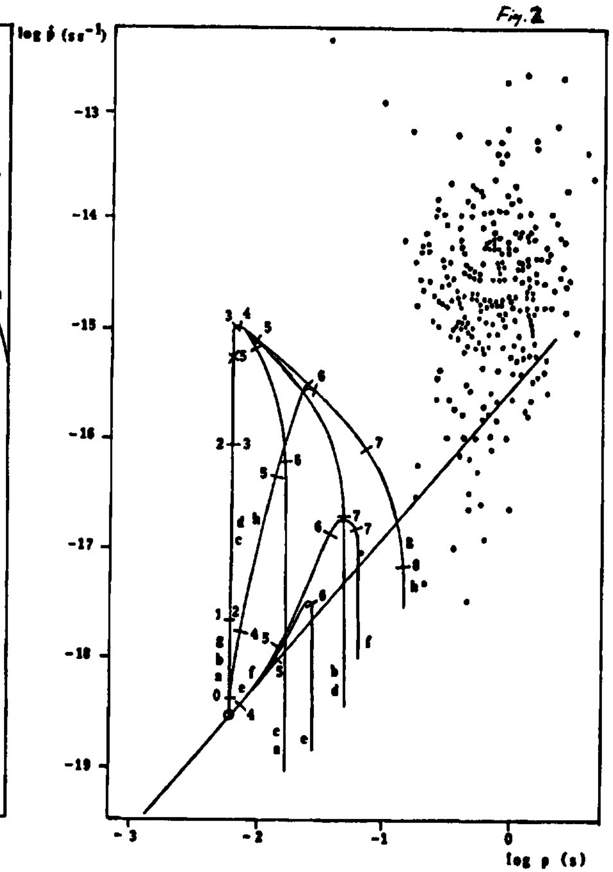


Fig.1. The evolutionary tracks of PSR 1953+29 for several pairs of τ_α and τ_β (see text). Numbers along each track denote the age counted from p_o and $\dot{p}_o$. ($\dot{p}_o = 5\cdot10^{-16}\,ss^{-1}$). Three other binary pulsars and the one-millisecond pulsar are also indicated; O indicate their calculated positions (spin-up) from the Equations 1 and 2, while × - observed.

Fig.2. Same as Fig.1 but $\dot{p}_o = 3.6\cdot10^{-19}\,ss^{-1}$ (theoretical value)

PULSAR MULTI-COMPONENT PROFILES:

A PHENOMENOLOGICAL MODEL

M. Prószyński*

Space Telescope Science Institute, Baltimore
and
Max-Planck Institut für Radioastronomie, Bonn

ABSTRACT

Pulsar radio emission is suggested to be confined to a number of narrow beams irregularly placed in the vicinity of the pulsar magnetic axis. The beams are assumed to originate from different streams of plasma that flow away from the region close to the polar cap. This requires that the sources responsible for generating these streams operate only at some points of the polar cap. The number of observed components in the pulsar's integrated profile does not depend predictably on the observer's location with respect to the pulsar rotation axis. Due to the radius-to-frequency mapping, the beams of radiation associated with a given stream, but corresponding to different frequency bands, are not coaxial. It may happen, therefore, that components observed at low frequencies disappear at higher frequencies, and vice versa. Finally, it is suggested that narrow, widely spaced components may result from a non-dipolar structure of the magnetic field near the star's surface.

THE MODEL

The separation of components in the integrated profiles of many pulsars increases with decreasing radio frequency. This phenomenon is usually explained by postulating that different frequencies are emitted (or enhanced) at different heights above polar cap. For the dipolar configuration of the magnetic field, to be in agreement with what is observed, lower frequencies have to be emitted farther from the star's surface (Komesaroff 1970). Simultaneous observations of single pulses at two radio frequency bands showed a correlation between appearances of pulses at both bands (Bartel and Sieber 1978; Bartel *et al.* 1981). A complete cessation of emission (pulse nulling) was observed to occur simultaneously at both frequency bands in the case of PSR 0809+74 (Bartel *et al.* 1981). Similar observations of a pulsar exhibiting mode-switching showed that the switch between profiles occurs at both frequencies at the same moment (Bartel *et al.* 1982). All this implies that, within the framework provided by the family of polar cap models, subpulse emission should be attributed to the streams of plasma rather than to any individual group of emitting particles. A hypothetical observer corotating with the star far above polar cap could see 'subpulse' emission continuously, that is, as long as the stream of plasma would continue to flow through the emission region.

If the source generating such a stream, *e.g.*, a spark in the Ruderman and Sutherland (1975) model, is operating at one well confined region on or above the polar cap, then the stream always flows along the same tube of magnetic lines. In such a case, subpulses appear always at the same phase of the integrated profile

* on leave from N. Copernicus Astronomical Center, Warsaw

and a component shows up. If there is only one such source active, an integrated profile consists of only one component. If there are more such stable sources, then more components may result.

For a given stream of plasma, if there is radius-to-frequency mapping, the emission beams corresponding to different frequency bands are not coaxial. Therefore, the spots of emission on the celestial sphere that correspond to the same stream at different frequency bands are displaced from each other. Now, if the above picture of the polar cap with several stabilized sources is correct, and if the field structure in the emission zone is indeed dipolar, then spots at higher frequencies are located on the celestial sphere closer to the magnetic pole than those at lower frequencies. Thus the separation of components should increase with decreasing radio frequency, if two or more components are visible.

THE NON-DIPOLAR MAGNETIC FIELD

So far there is no agreement as to how the pulsar magnetic field originates and how it is maintained (Flowers and Ruderman 1977; Blandford, Applegate, and Hernquist 1983). One is not allowed therefore to assume that a dipole component is responsible for the magnetic field structure very close to the neutron star surface. The main implication from the non-dipolar structure of the field is that the streams generated near the star's surface could, at the beginning, move along much more curved trajectories. Thus they would reach the dipole-dominated region much farther from each other. One can only speculate that, in consequence of complicated field structure, two or more streams could be associated with one source, *e.g.*, the stream could in some sense split before entering the emission region. In that way, one source might be responsible for more than one component; the presence of a correlation between pulse intensities at two widely spaced components could so be explained. Finally, if the emission of high frequencies takes place in the non-dipolar region near the star's surface, the component width as well as separation for high enough frequencies may not follow the prediction of the dipole model.

The consideration of multipole components brings to any model new degrees of freedom, of course. There is no reason, however, why one should expect a purely dipolar field. As noticed by Vivekanad and Radhakrishnan (1980), the presence of a more complicated field configuration near the neutron star surface may provide a mechanism to stabilize the sources of plasma streams at specific locations on (or above) the polar cap.

REFERENCES

Bartel, N., Kardashev, N.S., Kuzmin, A.D., Nikolaev, N.Ya., Popov, M.V., Sieber, W., Smirnova, T.V., Soglasnov, V.A., and Wielebinski, R. 1981, *Astr. Ap.*, **93**, 85-92.

Bartel, N., Morris, D., Sieber, W., and Hankins, T.H. 1982, *Ap. J.*, **258**, 776-789.

Bartel, N., and Sieber, W. 1978, *Astr. Ap.*, **70**, 307-310.

Blandford, R.D., Applegate, J.H., and Hernquist, L. 1983, *M.N.R.A.S.*, **204**, 1025-1048.

Flowers, E., and Ruderman, M.A. 1977, *Ap. J.*, **215**, 302-310.

Komesaroff, M.M. 1970, *Nature*, **225**, 612-614.

Ruderman, M.A., and Sutherland, P.G. 1975, *Ap. J.*, **196**, 51-72.

Vivekanand, M., and Radhakrishnan, V. 1980, *J. Astr. Ap.*, **1**, 119-128.

SUMMARY REMARKS

V Radhakrishnan

Raman Research Institute, Bangalore 560 080, India

Now's a good time to leave for people who have planes to catch or any other good excuse. I know you are both tired and hungry, so I'm only going to make a few remarks. And I'm going to make them simple enough that I understand what I'm saying.

First of all, I am sure I would be expressing everybody's wish if I congratulated all the people involved in the discovery of the millisecond pulsars. To me it's a splendid example of cooperation, and of really struggling for a long time following a sort of detective trail, and none of this stumbling on something in the dark business. And I'm delighted that we haven't heard this terrible word 'serendipity' used once in this meeting here. And just as an illustration of what I mean I would like to show one viewgraph, about the non-accidental nature of this discovery. You don't have to read the whole of this letter from the Editor to Don (Backer), regarding a paper submitted in 1979 actually suggesting that there could be a very fast pulsar in this object (4C21.53); as you see down here, it was rejected, firstly because it was too "speculative", but also because it was "poorly written".

I was personally staggered by the precision with which so many properties of this pulsar (PSR 1937+214) have been measured; its period, pulse number, polarization, etc. Maybe these are easy things to do for people who do them all the time, but I certainly think they are impressive. A good illustration of the point made by Mike (Davis) that the systematic errors were larger than the random ones was the intriguingly good looking sine wave in the timing residuals. I don't understand it, of course, but I would just like to take a bet that there is no rock around this clock, and that it has to be explained away in other terms than something tiny in orbit around the pulsar.

Returning for a moment to Don's overture in E-flat, something I found extremely interesting and which I think holds much promise for the understanding of pulsars in general are the plots which he (Backer) showed with three lines representing the different types of pulses nicely connecting up the periods with the pulse widths. And I think if we can put this together with the polarization models we may eventually get to know what pulsar beams really look like and how they evolve with time.

The 6 millisecond pulsar (PSR 1953+290) is clearly in the same zoo as the first one, but looks a completely different animal. I don't know whether Val (Boriakoff) or other people were disappointed that its period wasn't shorter than the other one's or at worst say 1.7 milliseconds, but personally I'm delighted. I think it has a quite different story to tell. It has a companion. It has little or no polarization. It has ten times less rotational energy, and a field which is presumably higher. I personally believe, call it a religious belief if you like, that all very short period pulsars are a result of their binary histories. I feel that these two pulsars must surely be different, and even though there is only one of each kind, I think they are trying their best to tell us that there are in fact different kinds of binary evolution. As Ed (van den Heuvel) explained to us, you can have different scenarios in which the companion is more or less massive, and which then either disappears or coalesces, etc.

There are two reasons for my great belief in the binary stories. One - as we have seen before - is that most of these (high-spin low-field) objects that are being found are very very close to the "spin-up" line. Let me just show that logB-LogP plot once again since I want to make a second point which I forgot to stress the other day. The position of this spin-up or equilibrium line is <u>independent</u> of the decay time of the magnetic field. That's an important thing to remember; it does not matter whether fields decay or not, you will always end up with this same condition. And I think that it is very sensible to use it as a criterion for seeing whether a given pulsar may have had a spin-up history in a binary system. If you believe it has, one of the consequences is that if you are given a P, then you can predict that the $\dot{P}$ <u>has</u> to be less than a certain value, i.e. $(P/2\dot{P})$ should be greater than 10^7 years. So if you take the 6-millisecond pulsar, $\dot{P}$ better be less than $10^{-17} ss^{-1}$, whatever the observers may think they find, just as in the case of the other pulsar we were able to predict its $\dot{P}$ with confidence well before it was measured correctly.

Another reason why I think we are going to stick with binary histories as far as very short period pulsars are concerned, is that we now have a few cases where the <u>initial</u> periods of normal pulsars are starting to be established as relatively long. We've lived for a long time with only one estimate, the Crab, for which there was this calculation of 17 milliseconds. But there are two others now in supernova remnants, and as you heard, for one of them the estimate is 34 milliseconds (Reynolds, LMC pulsar); for the other one I think we (Radhakrishnan and Srinivasan) came up with an estimate of 70 milliseconds, which we now think is somewhat on the long side. But in general, my guess is that for normal pulsars, you will never find initial periods close to anything like the break-up limit, and that they will tend to be very much longer. And that, in fact, the absence of as many Crab nebulae as you should find around the Galaxy if all pulsars were born spinning very fast, is quite simply because of this.

There are some worrisome things however regarding the binary hypothesis. For example, and I think this was mentioned the other day, if one wants to make a 1.5-millisecond pulsar by accretion and not by coalesence or something similar, you will need a very long time to accrete the required fraction of a solar mass if you are going to respect the Eddington limit. And this time is so long that if you believe that fields decay - even as slowly as 6 million years - then while you are accreting, the field is going to disappear. Remember you have to put in almost all of the energy right at the end; and the field then is what determines the period. So it looks like you simply can't do it. So the other way is to say all right, fields do decay from some high value - because I think the evidence for that is overwhelming - but that they hit the deck at some point like 10^8gauss and they never go below. Conceivably, this is possible in the Flowers and Ruderman model, which I happen to like; when the field in the crust decays so that you can't really hold the field inside together, it turns around like bar magnets trying to cancel each other. And then you could well be left with some small fraction, say 10^{-4} of the original field. But if this is what happens, you have to then ask whether it's going to be the same field for all neutron stars when they get to this stage, whether we can measure them or not, or whether it will differ from case to case. For example, is the 10^{10} gauss field in the 6-millisecond pulsar such a field that is not going to get any lower?

There is also another problem with those scenarios in which the companion is supposed to disappear conveniently. They were described by Shaham and Ruderman (Alpar, Cheng, Helfand, Ruderman, and Shaham) and talked about here by Shaham, and also invoked by me to explain the low velocities observed for some pulsars, which are more or less like the others except that they've been recycled. Apparently, the stability condition for such a thing to happen is not fully established. I was talking with Paczynski just a few days before coming here and he seems to have very serious reservations as to whether such a scenario will work. I mention this since he knows so much about these things. So it may be that the companion cannot be got rid of quietly, although if we could, it would be most useful.

Something that keeps coming up every time as a problem is this business of the magnetic field of Hercules X-1. Whatever you say about anything, someone is sure to jump up and ask how are you going to explain the field of this object. A suggestion in this regard made to me by Ed (van den Heuvel) appealed to me greatly, and I thought it would be nice for everyone to hear it. He said that it doesn't have to be an old neutron star. It could have been a white dwarf that was pushed over the cliff quite recently, and then the rest of the scenario would continue exactly as if it had been an old neutron star. If we can get rid this way of that one object, I think that discussions in future conferences can be pursued more peacefully.

I was personally very impressed by the work on interstellar scattering and all the new things that are coming out of it. A good example is the very neat method described by Andrew (Lyne) where he used scattering observations to learn about the orbit of a system (PSR 0655+64). Also this morning's talk by Narayan (slow scintillation) from which it looks like we may be able to learn a lot about the interstellar medium if we can get some more measurements.

Coming now to yesterday's talks, I was at a bit of a loss with all the heavy theory. But for me it was the first time (Pines' talk) since Vela dropped its first bundle 15 years ago, that I have heard an account in which the explanation of glitches hangs together. Of course, I do not understand the details, but it is clearly a coherent story, it has predictions, and it appealed to me greatly. So may be we do understand what is happening inside neutron stars in terms of pinning and unpinning of vortices and so on.

The other very interesting paper was, of course, the one by Jim (Applegate) on the new way of generating magnetic fields in pulsars. My own private thoughts on this, that I wouldn't dare share with anyone, is that it is a pity you have to resort to help from a dynamo mechanism to finally get the required field; you can't get it just with the surface effects, which would have been much nicer. We also have to live with the Crab for which I find it very difficult to imagine that it didn't really come with its magnetic field. You'd have to make a very special argument that in this case the whole thing worked in ten years or so. It doesn't seem to fit in. So I would still like to believe in fossil fields, an idea that Ganesh (Chanmugam) seems to share with me. Considering that we see eye to eye on (flux) conservation, it is a pity he is opposed to a good thing like recycling.

Coming to the searches (Five minutes left? Now is a good time to cut me off. Chairman: Keep going). The effort and zeal that is being put into the searches is most impressive. I'm sure I'm voicing everybody's <u>hope</u> that when the analyses are complete, there will be many more millisecond pulsars. But now if you ask me, I'm not holding my breath. I suspect that one may not find many. You ask me why? If you take the really interesting objects, then from experience we know that we've had only one Crab, one Vela, one 1913+16, one SS433, etc. All the really spectacular fellows that have taught us more than a big collection of mediocrities, seem to me to come in singles. (Taylor: "You should have told him to sit down two minutes ago".) I said I <u>hope</u> we have many more, but if we don't, then perhaps we should put in the kind of effort into studying these one or two objects, that Joe (Taylor) and his colleagues have on the original binary pulsar, in order to learn as much as we can from it - like this morning's report on the measurement of the gravitational propagation delay (Weisberg and Taylor). As a sort of analogy I'd like to say that if you had just one or two good friends, it's far better to cultivate them deeply than to go charging around madly trying to find as many good guys as you can to form a club. If after all these new searches we fail to find many more, then I suggest that the next workshop here be on FIZZLERS, if we find one, or failing that, on RED HERRINGS to be organized by Miller Goss, since he has assured us he has a good supply.

I have already touched upon some of the work presented this morning, all of which must be fresh in your mind anyway. The only other item I wish to remark on is the business of elongated beams which I think Ramesh (Narayan) has persuaded all of us is here to stay. You can give them corners, or you can round them off, you can stretch the beams a little more, or a little less, but no matter how many people sit on them you are never going to make them round again; and if any pulsar birthrate calculations are to be taken seriously, they better allow for elongation. In the context of the remarks I made a few moments ago on searches for millisecond pulsars, it should also be borne in mind that we are less likely to miss them - because of beaming effects - than normal long period pulsars.

I think I have said enough and I would like to finish - now I'm sure I'm speaking for everybody - by expressing our thanks to Steve and Dan and all of the NRAO staff for their magnificent efforts in making us comfortable here and this workshop such a pleasure to attend.

Search Techniques Session

8 June 1984

About 20 people attended the two hour special session on pulsar search techniques, moderated by Joe Taylor. The following is a summary of the major points that were discussed.

Basic Method

Taylor described the search algorithm used in most current searches. The time series formed by sampling a number of closely spaced frequency channels, typically 8 to 32, are transformed into the frequency domain. Since the number of harmonics expected is approximately the inverse of the duty cycle, there are typically 15 or 20 harmonics with comparable power. Considering a single frequency channel, one looks for harmonically related peaks in the power spectrum, comparing the incoherent sum of one set of harmonics against other, nearby summations. If the sum exceeds a threhold value, typically 3 to 3.5 sigma, further investigation of the raw data is performed. The final step is to go back to the Fourier coefficients and form short (16 point) profiles to see if there is a pulse present.

Kulkarni described the variation of this technique that will be used in the Berkeley fast pulsar search machine. Instead of forming the harmonic sums, they will do the long FFTs directly, setting a slightly lower threshold on peaks in the original power spectrum. He contended that harmonic summing, since it is incoherent averaging, does not improve detectability very much and is very computationally expensive. *Taylor* replied that it did give about a factor of two improvement in detectability, and that this meant you would detect twice as many pulsars -- making it worth the additional effort. *Kulkarni* said that what they lost in detectability they would gain back in integration time.

Lyne described the variation of the standard method used at Jodrell Bank. They sum across the outputs of the filter bank with time delays consistent with a set of dispersion measures. Each dedispersed sum is searched for periodicities by performing long (≈ 1 million point) transforms and looking for the peaks. They need a lot of computing power to perform their long transforms. *Taylor* emphasized that 2-dimensional transforms were very desirable if they could be afforded computationally.

Reporting on the technique used in the Australian searches, *Manchester* emphasized the similarities with Taylor's description. They had developed those techniques while working together on the Molongolo survey.

Boriakoff described the method that he and his collaborators have used in the Arecibo/Cos-B search. They have 30 channels of a filter bank that they sum in pairs to form 15 time series. They do long FFT's on these outputs and sum the power spectra. They don't do any harmonic summing, which he said biases them toward finding pulsars with large duty cycles. The most common situation, he pointed out, is to have about 10 harmonics of roughly equal power, with the second harmonic stronger than the fundamental (because of an interpulse). *Kulkarni* emphasized that this fact reduced the sensitivity of most searches, since the search procedure typically stops at any unsuccessful stage. *Taylor* agreed, saying that they first sum one harmonic, then two, and so forth. *Boriakoff* concluded by reemphasizing that fast pulsars may not have equally strong harmonics.

Discussion

Davis noted that the phase of an interferometer signal stabilizes in the presence of a signal long before the amplitude becomes apparent. He asked if more could be done with the phase information, rather than throwing it away by forming power spectra. *Taylor* said that after their first amplitude filter they look only at the phase information. *Kulkarni* reported that he had looked into the phase issue and found that it biased you toward small duty-cycle pulsars -- because any pulse structure will affect the phase behavior. This was jokingly seen as a way of discriminating against slow, normal duty-cycle pulsars.

Fisher asked for comments on the the Green Bank spectral processor project. Will this instrument be useful for pulsar searching? Should they try to provide the capability to dedisperse multiple dispersion measures simultaneously? Would the high dynamic range being built into the machine be used if searches continued to move toward 1400 MHz and above? The consensus was that the spectral processor would be very useful, as designed, for follow-up observations of newly discovered pulsars. It would also be useful as an interference excising spectrometer for use in pulsar searches. Its ability to do high dynamic range work at low frequencies would be very valuable, since many interesting pulsar phenomena are more pronounced at low frequencies. There were no changes suggested to its overall design.

Boriakoff said that the NAIC group was working on a similar machine. He said that Arecibo experience indicated that such a machine would be used about half the time for searches and half the time for follow-up work. *Taylor* strongly disagreed, contending that the Arecibo pulsar processor had been used almost entirely for follow-up work, mainly because of lack of observatory-level support for the spectrometer mode.

Further discussion of harmonic summing followed. *Dewey* stated that below about 8 harmonics you were better off looking for individual harmonics, as *Kulkarni* had suggested. But her calculations showed that above about 8 equally strong harmonics you did better with harmonic summing. *Lyne* pointed out that harmonic summing became increasingly attractive for long data sequences, since you were then looking for 5 and 6 sigma events rather than the much commoner 3 sigma events.

Davis concurred, pointing out that the SETI people had to require 10 to 12 sigma events in order to keep their false alarm rate reasonable. He urged the pulsar people to share their practical experience with the SETI people, whom he said were doing some very detailed calculations about search strategies, but were not sufficiently grounded in the practical details of searching. He also pointed out that *Backer* had previously noted the similarity between pulsar searching and the nuclear physics problem -- they were both concerned with finding islands of points along a straight line in a 2-dimensional space. Perhaps, it was suggested, R and theta values for all the peaks in the plane could be tabulated. A straight line would show up in a histogram of these values. *Kulkarni* replied that you can't ultimately improve on harmonic summing.

Davis asked what increase in computational effort was implied by going to a full harmonic search for 1 millisecond pulsars (searching, say, 16 harmonics). *Taylor* replied that it would be about 256 times the size of the searches they were now doing. *Stinebring* noted that the accumulated political clout in the room might make it possible to get some amount of supercomputer time for these searches. That might involve combining the efforts of a number of groups. *Fisher* strongly disagreed with this approach, saying that people would inevitably end up administrating in such a project rather than coming up with new and clever ideas. *Manchester* said that 1% of a Cray was not nearly as good for this project as 100% of a Vax. *Kulkarni* remarked that some of the M68000 based machines could run as fast as the Vax, and were well suited to this kind of work. *Stinebring* said that a Vax-class machine was really not big enough for some of the more ambitious search projects, and that he had in mind 100% of a Cray, not 1%.

Fisher continued the discussion by noting that everyone had been assuming computers with a Von Neumann architecture. He thought that parallel processors should be looked at very closely for these kinds of problems, and pointed out that they were presently getting almost no attention within the pulsar search community. *Hankins* seconded this remark, saying that he was very interested in what one could now do in VLSI fabrication. Combining specially fabricated chips in parallel might result in a <u>very</u> powerful search machine.

At this point there was a stampede for the door, as everyone rushed out to find the next millisecond pulsar.

AUTHOR INDEX

<u>Principal author</u>

(Co-author)

Discussion