Summer Student Lecture Notes
1975

PULSARS

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DISCOVERY

For most observations in radio astronomy, the receiver outputs are integrated over long periods of time. In this way, the random noise averages out, and a constant low level signal can be detected. However, in the 1960's, it was known that very compact sources scintillated (twinkled) at low frequencies (100's of MHz) due to irregularities in the interstellar and interplanetary mediums. At Cambridge, a long-term project was undertaken to study these effects. A large array of dipole antennas scanned the sky, sensitive to fluctuations at short time scales. In such observations, pulsed interference is an occupational hazard. Electric motors starting, dirty motor brushes, ignition systems, radio and TV transmitters, radar, lighening, etc. are among the long list of man-made and natural culprits. However, Jocelyn Bell, a graduate student on the project, noted a series of pulses that began to appear with some predictability. They occurred at the same time every day, and had a constant separation in time between adjacent pulses. This strange phenomenon was studied for months, until finally its extraterrestrial origin was confirmed. The pulses always originated from the same position in the sky with respect to the stars, not the Earth. In addition, the period between successive pulses varied as one would expect from the Doppler shift due to the Earth's motion. The scientific world's confrontation with this strange astronomical beast had begun.

POSSIBLE SOURCES

What kind of object could emit such radiation? New pulsars were donstantly being discovered, and the following two characteristics were most disconcerting:

1) Exceptional stability in period - typically measured to better than 1 part in 10^9.
2) Rapid repitition rate - on the order of seconds, with individual pulses only milliseconds long.

The distribution of these sources on the sky showed a definite concentration toward the galactic plane (fig. 1), indicating typical distances of a few kiloparsecs.

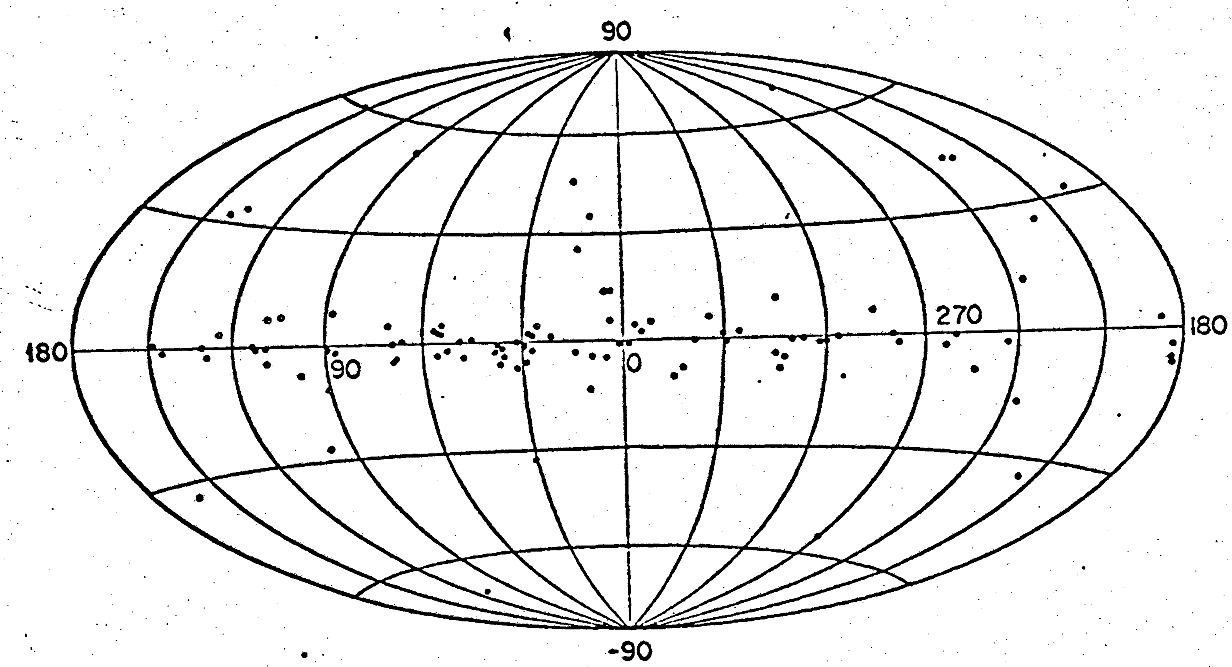

FIG. 1, MAP OF PULSARS IN GALAXY

These few facts placed enormous restriction on possible sources for the radiation. Aside from the quickly discarded LGM hypothesis, we appeared to require a massive rigid object, incapable of being perturbed by the irregularities of the surrounding medium, with an energy output on the order of 10^{30} ergs/sec. The two main proposals involved rotation or vibration of some type of collapsed star. Fig. 2 shows many of the early theoretical proposals.

FIG. 2 Early Theories

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TABLE 2. Pulsar theories

References	Theories
Hewish et al (1)	Radial pulsation of neutron star or white dwarf. Shock-wave excitation
Saslaw et al (63)	Gravitational focusing of radiation from neutron-star binary
Ostriker (64)	Active spot on rotating white dwarf
Hoyle & Narlikar (65)	Reversible collapse of supernova
Burbidge & Strittmatter (66)	Neutron star with satellite, analogous to Jupiter-Io effect
Gold (67)°	Synchrotron-type radiation from density fluctuations in corotating neutron-star magnetosphere
Israel (68)	Repetitive mass loss from neutron star on verge of gravitational instability
Pacini (69)	Neutron star or white dwarf, oblique magnetic rotator
Layzer (70)	New type of condensed star, gravity balanced by magneto-turbulence
McIlraith (71)	Plasma interaction between binary neutron stars
Eastlund (72)	Synchrotron radiation from corotating neutron-star magnetosphere
Black (73)	White-dwarf atmospheric pulsation
Gunn & Ostriker (74)	Particle acceleration in magnetic dipole radiation from spinning neutron star
Chiu et al (75)	Coherent emission from population inversion in quantum magnetic states of rotating and vibrating neutron star
Bertotti et al (76)	Neutron-star oblique magnetic rotator, radiation pressure induced shockwaves
Ginzburg & Zaitsev (77)	Radio emission by induced scattering from plasma waves near neutron-star magnetic poles
Piddington (78)	Interaction between boundary of neutron-star magnetosphere and expanding magnetic shell
Michel & Tucker (79)	Radiation from tangential field discontinuities in plasma outflow from spinning neutron star
Stothers (80)	Radial pulsation of neutron star undergoing mass loss
Dyson (91)	Radiation from neutron-star volcano

White dwarfs were one of the major candidates. These are stars which have largely depleted their nuclear fuel, and are kept from gravitational collapse by electron degeneracy pressure. The neutron star was another viable alternative. This theoretical object (suggested as early as 1932), was assumed to be formed as the byproduct of supernova explosions. This one possible end-point of stellar evolution is the process whereby a red giant begins to collapse, and the matter becomes highly condensed and hot. At some critical point, neutrinos can transfer energy from the extremely dense core, blowing off the outer layers of the star. These result in the commonly known supernova remnants. The core, if it lies within a certain mass range, can remain in this condensed state, where neutrons are the most populous species of particles. Neutron degeneracy prevents further collapse.

Let's take a crude look at the source parameters predicted by these models. White dwarfs could have densities up to about 10^7 g/cm^3, and neutron stars on the order of 10^{14} g/cm^3. For vibrational models, a characteristic time scale can be clacu-lated by saying that the gravitational force at the surfact, $\frac{GM}{R^2}$, is equal to the surface acceleration, $\frac{\partial^2 R}{\partial t^2}$. For harmonic motion, we can let the radius vary as $R\cos(\frac{t}{t_o})$. This gives:

$$t_o \approx (GM/R^3)^{-\frac{1}{2}} \quad .$$

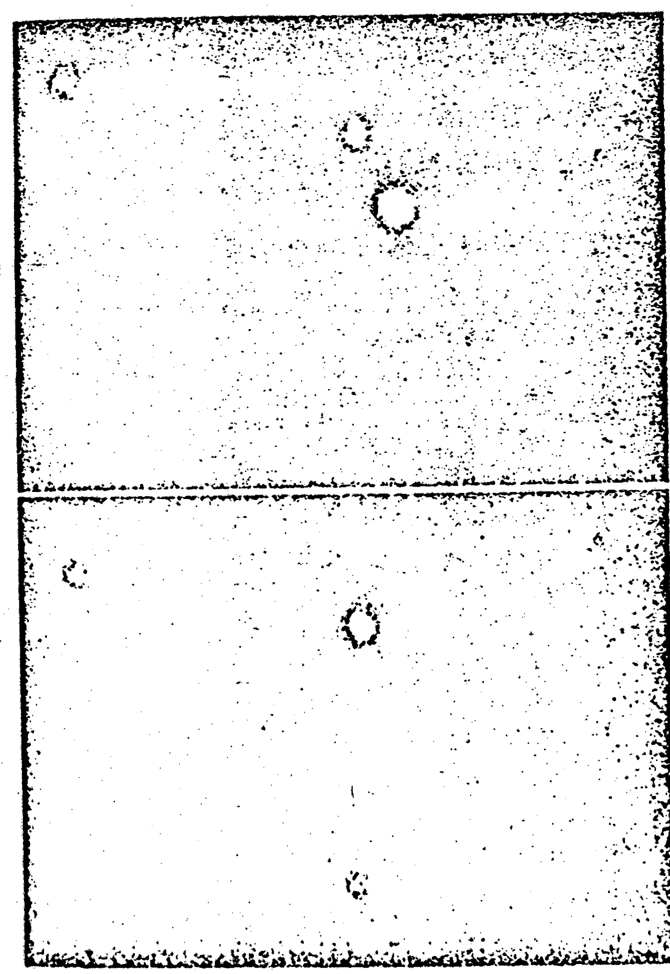
The same approximate time scale applies for rotational models if one equates the centrifugal and gravitational forces at the surface. Thus, periods on the order of a second are possible for white dwarfs, with neutron stars capable of time variations down to a millisecond. As an interesting aside, the sun rotates about once every 26 days. If we allowed it to collapse from 10^5 to 10 kilometers, and conserve angular momentum, its period of rotation would by about 1 msec.

With the discovery of two pulsars with very short periods, (tens of milliseconds) the white dwarf models appeared to be ruled out. In addition, these two pulsars were found near the centers of the Crab and Vela supernova remnants, giving further credence to the neutron star hypothesis. The period of the Crab pulsar is slowly increasing. From models, we can calculate a characteristic age of 1000 years for the pulsar. In 1054 A.D., Chinese astronomers reported the apperance of a "guest star" in the direction where the Crab now appears. It outshone all other stars, and was even visible during the day. Do you believe in magic?

While we're off the track a bit, let's take note of the fact that the Crab pulsar, probably the youngest still known, has some other remarkable characteristics. It is the only pulsar to date with an optical counterpart, and its emission has also been observed in the X and γ ray regions of the spectrum. See the figures below.

Fig.3

Two pictures showing the Crab Nebula pulsar with three field stars. The upper photograph shows the pulsar near maximum light and the lower photograph shows it near minimum. →



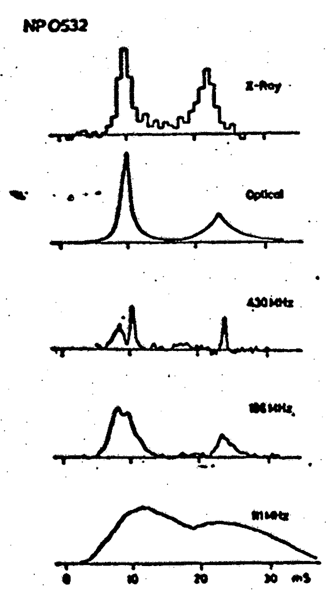


FIGURE 4. Mean pulse envelope of NP 0532 at radio, optical, and X-ray wavelengths.

Tom Gold was the major proponent of the rotating neutron star model. He felt that the enormous energy radiated by pulsars, $\approx 10^{30}$ ergs/sec, could be obtained from the star's rotational energy supply. In addition, by conserving the magnetic flux from the original star:

$$B_{final}R^2_{final} = B_{initial}R^2_{initial}$$

a 1 gauss field (the average over the surface of our sun), would increase to 10^{12} gauss for a neutron star of radius 10 km. This was the order of magnitude magnetic field strength needed to couple the rotational energy and electromagnetic radiation in the models of Gunn & Ostriker and of Pacini. Also, as the pulsar lost rotational energy (through various dissipative forces), it would be expected to slow down. This very gradual but steady increase in period has been observed for a number of pulsars, and the largest value is only on the order of 1 part in 10^{12}. On the other hand, as a vibrating body loses energy, its period would be expected to decrease. This has not been observed.*

Finally, if one calculates the loss in rotational energy from the Crab pulsar due to the observed slowing, we find the value 10^{38} erg/sec . This assumes a neutron star of approximately 1 solar mass with a radius of 10 km. This energy is much greater than that emitted in the radio pulses, but is comparable to the total radiation output from the Crab Nebula. Another clincher for rotation.

*Both the Crab and Vela pulsars have been observed to undergo sudden small decreases in period ("glitches"). These have been attributed (among other things) to small readjustments of the solid crystalline surface of the star - "starquakes". After some relaxation time, the periods continued their regular increase.

PULSE CHARACTERISTICS AND THE EMISSION MECHANISM

The pulse widths imply an emission region with sizes on the order of the distance light could travel in that time. For pulses of 10^{-4} sec duration, this implies and emission region of $3 \cdot 10^{6}$ cm. With fluxes of 10^{30} ergs/sec, this implies blackbody temperatures on the order of 10^{24} ^{o}K or greater, if the emission is incoherent thermal radiation. Particles of this high an energy would not radiate radio waves, but high energy photons ten orders of magnitude beyond what we consider the   ray region. Some type of coherent mechanism (where the particles radiate in phase with one another) is clearly necessary.

The actual details for making the pulses are probably very complex. Some theories envision the pulses arising from bursts on the stellar surface. Others picture a co-rotating magnetic field, with its dipole axis different from the axis of rotation. (see fig. 5). In one of these "oblique-rotator" models, an E field is induced at the surface by the rotating magnetic field. Particles are then accelerated along the field lines, participating in the rotation. At some critical radius, where the velocity of rotation would equal the speed of light, the particles can no longer continue on their original course. It is at this "light cylinder" that many theories place the origin of the radio pulses.

High polarizations (up to 100%) are often seen in individual pulses. Sometimes, a linear polarization is observed to rotate its plane slowly and predictably through the duration of the pulse. The measurement of these phenomena are important for determining the shape of the magnetic field in the emission region.

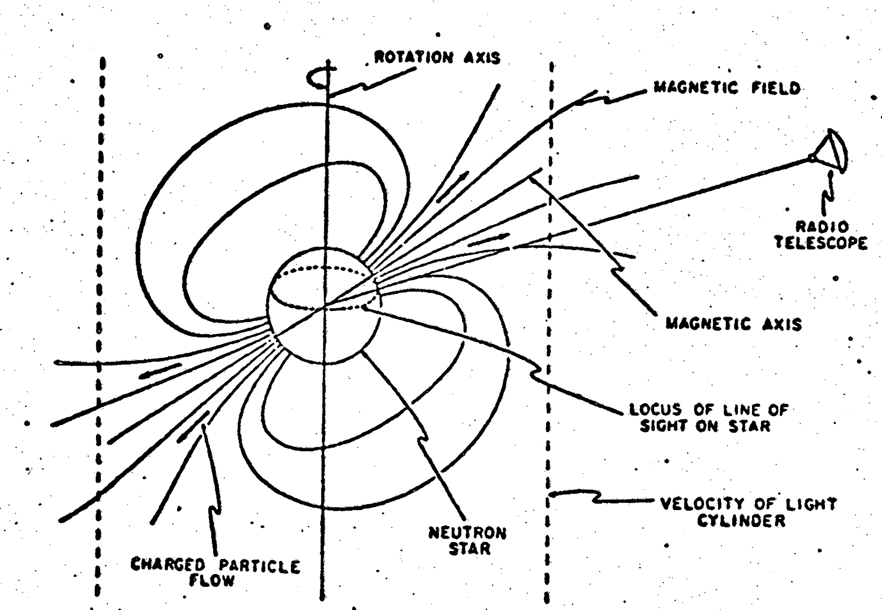


FIG. 5 Schematic of "oblique rotator"

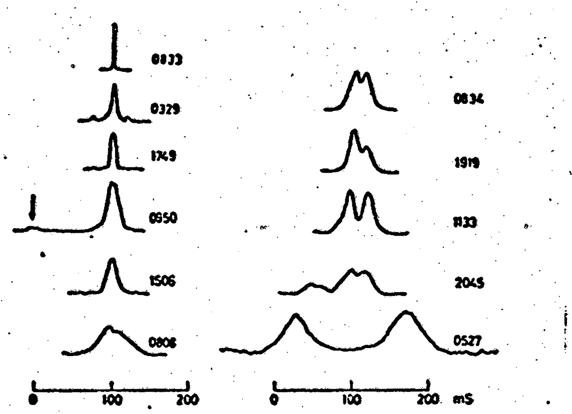
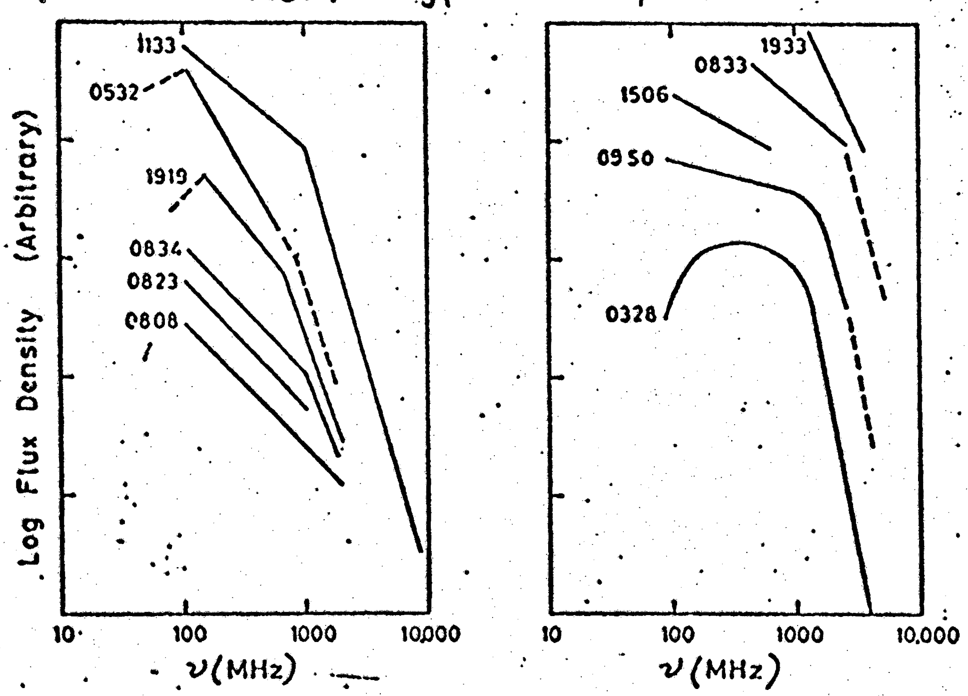


FIG. 6 Typical mean pulse shapes

Pulses also come in a variety of shapes, though for an individual pulsar, the shape is remarkably constant in time. There are sometimes small changes observed at different radio frequencies. Double-pulsed structures are common, as are inter-pulses, well separated from the main pulse. With very good time resolution, fine structure was been observed in some pulsars with time scales less than 100 microseconds. A sample of pulse shapes is displayed in fig. 6.

Typical radio frequency spectra for pulsars are shown in fig. 7. There is usually a straight sloping region between approximately 100 and 1000 MHz, with an index of -1, and sharp cutoffs at lower and higher frequencies. The low cutoff is probably the result of self-absorption by the radiating charges themselves. The high frequency cutoff is most likely an intrinsic property of the radiation mechanism. One way of producing the necessary coherent radiation is by placing the particles in bunches. If these bunches have a minimum size, then there would be a high frequency cutoff to the coherent radiation.

FIG. 7 Typical RF spectra



DISPERSION AND FARADAY ROTATION

The index of refraction of a medium determines the group velocity of electromagnetic waves through it, that is, the rate at which energy (or pulses) are transported. The interstellar medium contains a number of ionized hydrogen atoms, which form a tenuous plasma. From Maxwell's equations we can calculate the index of refraction (and group velocity) for this plasma, simplifying matters by ignoring the negligible magnetic field contribution:

$$\frac{v_{group}}{c} = 1 - \left(\frac{e^2}{2\pi mc^2}\right) \cdot \left(\frac{N_e}{f^2}\right) ,$$

where N_e is the electron density and f is the radio frequency. Since v_{group} depends on f, the medium is called dispersive; that is, an instantaneous pulse over a wide range of radio frequencies will arrive at an observer over a finite length of time.

The dispersion delay (the difference in pulse arrival times) observed between two observing frequencies f_a and f_b is

$$t_d = \frac{e^2}{2\pi mc}\left(\frac{1}{f_a^2} - \frac{1}{f_b^2}\right)\int N_e \, ds ,$$

where the integral is taken over the path between source and observer. The integral is usually expressed for astronomical convenience in terms of parsecs/cm^3, and is called the dispersion measure (DM). The time delay observed between pulses at different radio frequencies can be seen in fig. 8. By matching up individual pulses, one can sometimes find that the time delay may exceed the pulsar period, for widely separated frequencies. Dispersion measures have been observed to range from a few to greater than four hundred pc/cm^3. By determining

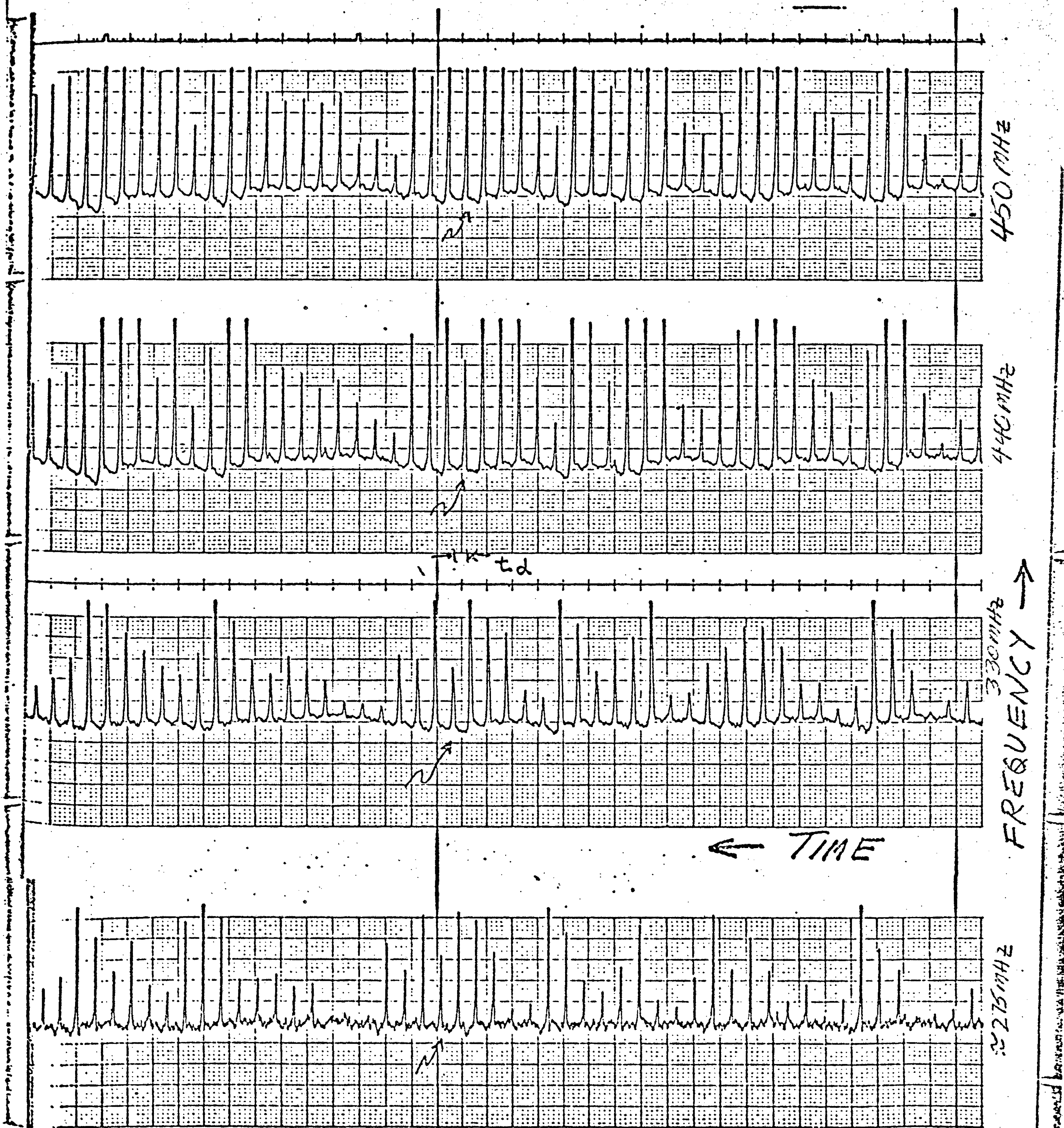


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FIG. 8 Strip chart recordings at several frequencies the dispersion measure to the Crab, whose distance we believe to be between 1.7 and 2 kpc, we can make an estimate of the average interstellar electron density. Using the few pulsars for which this type of estimate can be made yields average electron densities between 0.03 and 0.05 /cm^3. The dispersion is often anomalously high when the line of sight passes through an HII region. Based on the average density values, (which must be treated with caution) we then estimate pulsar distances from their dispersion measures. These leads to a distribution of observed pulsars from less than 100 pc away, perhaps as far as 10 kpc.

We have another means of establishing pulsar distances, and that is through 21 cm absorption. If we look at the 21 cm emission in the direction of a pulsar when it is not pulsing (OFF), we see a line profile originating from one or more of the spiral arms of the galaxy (ideally). When the pulsar is ON, we see an increase at all frequencies from the pulsar emission. However, some absorption also takes place along the line of sight, and by differencing the two profiles, (see fig. 9) we may be able to determine whether or not absorption has taken place in a given spiral arm. Using the (model dependent) distance to the spiral arm, we can then place upper and/or lower limits on the pulsar distance. These measurements are difficult ones, and the technique has been used successfully on only a fraction of the known pulsars.

Linearly polarized radiation through a plasma is rotated by an angle

$$\Delta\theta \propto \frac{1}{f^2} \int N_e B \, ds \quad ,$$

where B is the component of the magnetic field along the line

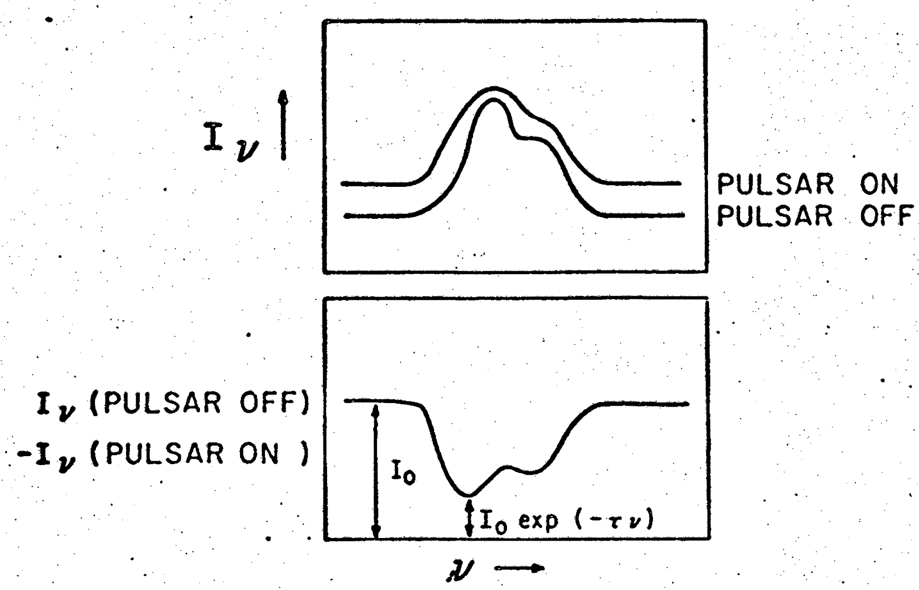

FIG. 9 Absorption Profile Schematic

of sight. By measuring the dispersion measure and the Faraday rotation, one can obtain an estimate of the average interstellar magnetic fields. These measurements yield values on the order of 10^{-6} gauss (plus and minus - towards and away from us), and have been used to map the magnetic field structure of our neighborhood of the galaxy.

OBSERVATIONS OF PULSARS

I am just going to briefly mention some of the new techniques which arose from the need to study pulsars. Observations have been made on both single dishes and interferometers. A technique known as signal averaging is often used to enhance the signal from a pulsar of known period. In this way, we can average together the signal from many pulses, while eliminating the random noise contribution when the pulse is off.

Because of dispersion, pulsars are also smeared in time within the finite bandwidth of the receiver. However, the larger the bandwidth, the higher the signal-to-noise. Therefore, many channels, each with a small bandwidth, are often used. These may be added together, on-line or off-line, inserting appropriate delays between channels to compensate for the dispersive delay. This "de-dispersing" helps to reveal some of the finer features of pulse shape and polarization which would otherwise be smeared out.

Power spectrum analysis is another tool of the pulsar observer. It is useful when searching for new pulsars, or when the period is not accurately known. This type of analysis divides the incoming signal into separate channels based on the power at each repitition frequency. It can be done electronically, or digitally, off-line. The noise output from a receiver is usually white (equal at all frequencies) with a sharp increase at frequencies greater than a few seconds due to variations in the receiver. Pulsars, with their regular repitition rate, appear as spikes in the power spectrum at the fundamental and harmonic frequencies.

To study the effects of interstellar scintillation and scattering, observations have also been made simultaneously at two different observatories. Correlations between the amplitude fluctuations of individual pulses have been used to estimate the size and speed of interstellar clouds.

So much for a taste.

TODAY

Again- just briefly, three areas of current interest in the study of pulsars.

Timing - with such accurate periods, and slow rates of change, pulsar timing is a state of the art affair in terms of accurate clocks. However, these measurements are extremely important Without them, the "glitches" which give us such valuable clues as to the composition of the neutron star would have gone unnoticed. In addition, if we can accurately measure the second derivative of the period, that is, the rate of deceleration, we may be able to understand the forces that are slowing the pulsar down. Current possibilities (of varying probabilities) are quadrupole gravitational or magnetic radiation losees, dipolar magnetic losses, stellar wind drag, etc.

Proper Motions - with the Interferometer here at NRAO, Backer and Sramek have been measuring the proper motions of a number of pulsars. Knowledge of their speeds will help us to pin down a number of questions about the origins (location , ejection velocities, associations with other objects) of these exotic beasts.

Binary Pulsar

Though many stars occur in binary paris (especially O and B stars, the supposed progenitors of pulsars), until recently, no pulsars had been detected in binary systems. This may arise naturally because of the violent nature of their formation. However, Hulse and Taylor have recently discovered, using the Arecibo 1000 ft. dish, a pulsar in a binary system, with an orbital period of about 8 hours, and an orbital radius on the order of a solar radius. Neither member of the pair can be yet seen optically; they are probably about 5 kpc away in the crowded galactic plane. The binary nature was evident from the characteristic Doppler shift of the pulsar repitition frequency. However, it took a bit of masterful detective work to untangle the unexpected period changes which accompanied the discovery of this pulsar. If problems such as the tidal interactions, mass transfers, and the like, between the two components, this system may prove to be a fertile testing ground for general relativity.

With the recent search at Arecibo, the number of pulsars is now near 140. A list of the 105 known as of 8/13 is shown in the table at the end of the notes, along with some of their characteristic parameters.

I have not discussed many of the interesting features of the study of pulsars. These include scintillation and scattering, cosmic ray production, neutron star structure, intrinsic pulse-to-pulse variations, optical and X-ray observations ....
These may be pursued in the various references (and further bibliographies) mentioned below.

Review

A. Hewish 1970, Ann. Rev. As. Ap., **8**, p. 265.

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YERVANT TERZIAN CRSR AND NAIC CORNELL UNIVERSITY *PULSARS* AUG. 7,1973 TOTAL NUMBER= 105 PAGE 1

PULSAR DESIGNATION	PULSAR	R.A. H.M.S.	DECL. DEG. ' "	L II DEG.	B II DEG.	PERIOD (SEC)	EPOCH (J.D.24+)	1/2 PULSE WIDTH (MSEC)	DISPERSION MEASURE (PARSEC/CM3)	PERIOD CHANGE (NSEC/DAY)	APP. AGE P/(DP/DT) (YRS)
P0031-07	MP0031	0 31 36	-07 38 26	110.4	-69.8	0.9429507566	40690	51.0	10.89	0.0366	7.1E+07
P0105+65	PSR0105+65	1 05 00	65 50	124.6	3.3	1.283651	41554	(29)	30		
P0138+59	PSR0138+59	1 38	59 45	129.1	-2.3	1.222949	41544	35	34.5		
P0153+61	PSR0153+61	1 53 00	61 55	130.5	0.2	2.351615	41554	(43)	60		
P0254-54	MP0254	2 54 24	-54	270.9	-54.9	0.4476	(41347)	10	10		
P0301+19	PSR0301+19	3 01 45	19 23 36	161.1	-33.2	1.38758356	41347	27	15.7		
P0329+54	CP0329	3 29 11	54 24 38	145.0	-1.2	0.71451864244	40622	6	26.776	0.177	1.1E+07
P0355+54	PSR0355+54	3 55 00	54 05	148.1	0.9	0.156380098	41701	3.5	57.0		
P0450-18	MP0450	4 50 22	-18 04 14	217.1	-34.1	0.548935369	41536	19	39.9		
P0525+21	NP0525	5 25 52	21 58 18	183.8	-6.9	3.7454934468	40957	181.0	50.8	3.461	2.9E+06
P0531+21	NP0531	5 31 31	21 58 55	184.6	-5.8	0.0331296454	41221	3	56.805	36.526	2.5E+03
P0540+23	PSR0540+23	5 40 10	23 28	184.4	-3.3	0.245965189	41701	10	72		
P0611+22	PSR0611+22	6 11 15	22 32	188.7	2.4	0.334918981	41701	6	96.7	4.84	1.9E+05
P0628-28	PSR0628-28	6 28 51	-28 34 08	237.0	-16.8	1.244414895981	40242	(50)	34.36	0.217	1.6E+07
P0736-40	MP0736	7 36 51	-40 35 18	254.2	-9.2	0.374918324	40221	22	100	<1.728	>5.9E+05
P0740-28	PSR0740-28	7 40 48	-28 15 16	243.8	-2.4	0.166750167	41027	8	80		
P0809+74	CP0809	8 09 03	74 38 10	140.0	31.6	1.2922412852	40689	41.3	5.84	0.0138	2.5E+08
P0818-13	MP0818	8 18 06	-13 41 23	235.9	12.6	1.23812810726	41006	22	40.9	0.1820	1.9E+07
P0823+26	AP0823+26	8 23 51	26 47 18	197.0	31.7	0.530659599042	40242	5.9	19.4	0.144	1.0E+07
P0833-45	PSR0833-45	8 33 39	-45 00 11	263.6	-2.8	0.0892187479	40307	2	63	10.823	2.3E+04
P0834+06	CP0834	8 34 26	06 20 47	219.7	26.3	1.27376349759	40626	23.7	12.90	0.587	5.9E+06
P0835-41	MP0835	8 35 34	-41 24 54	260.9	-0.3	0.76698	(41347)	20	120		
P0904+77	PSR0904+77	9 04	77 40	135.3	33.7	1.57905	(40222)	<80			
P0940-55	MP0940	9 40 40	-55 30	278.5	-2.1	0.664365	(41835)	30	145		
P0943+10	PP0943	9 43 20	10 05 33	225.4	43.2	1.097707	40519	50	15.35		
P0950+08	CP0950	9 50 31	08 09 43	228.9	43.7	0.25306504317	40622	8.8	2.965	0.0198	3.5E+07
P0959-54	MP0959	9 59 51	-54 37	280.1	0.3	1.436551	40553	50	90		
P1055-51	MP1055-51	10 55 49	-51 40	286.0	7.0	0.1971	(41347)		<30		
P1112+50	PSR1112+50	11 12 49	50 46	155.1	60.7	1.65643810	41594	18	9.2		
P1133+16	CP1133	11 33 28	16 07 33	241.9	69.2	1.18791116405	40622	27.7	4.834	0.323	1.0E+07
P1154-62	MP1154	11 54 45	-62 08 36	296.7	-0.2	0.40052	(41347)		270		
P1221-63	PSR1221-63	12 21 40	-63 47	300.0	-1.3	0.216475	(41835)		92		
P1237+25	AP1237+25	12 37 12	25 10 17	252.2	86.5	1.38244657195	40626	49.9	9.254	0.0825	4.6E+07
P1240-64	MP1240	12 40 20	-64 07 12	302.1	-1.6	0.38850	(41347)	60	220		
P1323-62	PSR1323-62	13 23 42	-62 03	307.1	0.3	0.529854	41733		313		
P1354-62	PSR1354-62	13 54 10	-62 13	310.5	-0.6	0.455780	41733		400		
P1359-50	MP1359	13 59 43	-50	314.5	11.0	0.690	(40585)	20	20		
P1426-66	MP1426	14 26 34	-66 09 54	312.3	-6.3	0.7874	(41347)	10	60		
P1449-65	MP1449	14 49 22	-65	315.3	-5.3	0.180	(40282)	(5)	90		
P1451-68	PSR1451-68	14 51 29	-68 32	313.9	-8.6	0.263376764	(40545)	25	8.6	<0.259	>2.8E+06
P1508+55	HP1508	15 08 04	55 42 56	91.3	52.3	0.73967787630	40626	10.3	19.60	0.433	4.7E+06
P1530-53	MP1530	15 30 23	-53 30	325.7	1.9	1.368852	40553	25	20		
P1541+09	AP1541+09	15 41 14	09 38 43	17.8	45.8	0.7484483	(41347)	63	35.0		
P1556-44	MP1556	15 56 12	-44 31 30	334.5	6.4	0.25705	(41347)				
P1557-50	PSR1557-50	15 57 05	-50 36	330.7	1.6	0.192598	(41835)		270		

PULSAR DESIGNATION	PULSAR	R.A. H.M.S.	DECL. DEG. ' "	L II DEG.	B II DEG.	PERIOD (SEC)	EPOCH (J.D.24+)	1/2 PULSE WIDTH (MSEC)	DISPERSION MEASURE (PARSEC/CM3)	PERIOD CHANGE (NSEC/DAY)	APP. AGE P/(DP/DT) (YRS)
P1558-50	PSR1558-50	15 58 46	-50 49	330.7	1.3	0.864192	41733		165		
P1601-52	PSR1601-52	16 01 58	-52 56	329.7	-0.6	0.657953	41733		35		
P1604-00	MP1604	16 04 38	-00 24 41	10.7	35.5	0.42181607579	41005	15	10.72	0.0265	4.4E+07
P1641-45	PSR1641-45	16 41 09	-45 51	339.2	-0.2	0.454963	41733		449		
P1642-03	PSR1642-03	16 42 25	-03 12 30	14.1	26.1	0.38768877965	40622	3.7	35.71	0.154	6.9E+06
P1700-32	PSR1700-32	17 00 00	-32 40	351.7	5.4	1.211786	41852		103		
P1700-18	MP1700-18	17 00 56	-18	4.0	14.0	0.802	(41347)		<40		
P1706-16	MP1706	17 06 33	-16 37 21	5.8	13.7	0.65305045437	40622	12	24.99	0.550	3.3E+06
P1717-29	PSR1717-29	17 17 10	-29 32	356.5	4.3	0.620449	41554	(32)	45		
P1718-32	PSR1718-32	17 18 40	-32 05	354.5	2.5	0.477154	41554	(35)	120		
P1727-47	MP1727	17 27 50	-47 42 18	342.6	-7.6	0.829683	40553	30	121		
P1730-22	PSR1730-22	17 30 15	-22 29	4.0	5.8	0.8716815	41853		45		
P1742-30	PSR1742-30	17 42 45	-30 43	358.5	-1.0	0.367421	(41835)		84		
P1747-46	MP1747	17 47 56	-46 56 12	345.0	-10.2	0.742349	40553	20	40		
P1749-28	PSR1749-28	17 49 49	-28 06 00	1.5	-1.0	0.562553168299	40127	6	50.88	0.705	2.2E+06
P1813-26	PSR1813-26	18 13 10	-26 50	5.2	-4.8	0.592889	41823		90		
P1818-04	MP1818	18 18 14	-04 29 03	25.5	4.7	0.59807262183	40622	10.3	84.48	0.545	3.0E+06
P1819-22	PSR1819-22	18 19 50	-22 53	9.4	-4.3	1.874398	41554	(76)	140		
P1822-09	PSR1822-09	18 22 40	-09 36	21.4	1.3	0.768948	41554	11	19.3		
P1826-17	PSR1826-17	18 26 15	-17 54	14.6	-3.3	0.307128	41554	(59)	207		
P1831-03	PSR1831-03	18 31 00	-03 40	27.7	2.3	0.686675	41554	(32)	235		
P1831-04	PSR1831-04	18 31 40	-04 31	27.0	1.8	0.2901091	41850		68		
P1845-01	OP1845-01	18 45	-01 27	31.3	0.2	0.659475	(41192)	(80)	90		
P1845-04	JP1845	18 45 10	-04 05 32	28.9	-1.0	0.59773452	40998	20	141.9		
P1846-06	PSR1846-06	18 46 07	-06 43	26.7	-2.4	1.451323	41554	(38)	152		
P1857-26	MP1857	18 57 44	-26 04 49	10.5	-13.5	0.612204	41026	25	35		
P1858+03	JP1858	18 58 40	03 27 02	37.2	-0.6	0.655444	40754	(170)	402		
P1900-06	PSR1900-06	19 00 30	-06 35	28.5	-5.6	0.431985	41554	(14)	180		
P1900+01	PSR1900+01	19 00 50	01 34	35.8	-1.9	0.7293016	41850		228		
P1906+00	PSR1906+00	19 06 45	00 05	35.1	-3.9	1.0169443	41849		111		
P1907+02	PSR1907+02	19 07 20	02 56	37.7	-2.7	0.494914	41554	(11)	190		
P1907+10	PSR1907+10	19 07 30	10 55	44.8	1.0	0.2836387	41851		144		
P1910+20	PSR1910+20	19 10 20	20 55	54.0	5.0	2.232964	41815		84		
P1911-04	MP1911	19 11 15	-04 45 59	31.3	-7.1	0.82593366503	(40624)	8.0	89.41	0.351	6.5E+06
P1915+13	OP1915+13	19 15 25	13 50 00	48.3	0.6	0.1946255	41274	15	94		
P1917+00	PSR1917+00	19 17 15	00 18	36.5	-6.1	1.272254	41554	(27)	85		
P1918+19	PSR1918+19	19 18 50	19 43	53.9	2.7	0.821039	41850		140		
P1919+21	CP1919	19 19 36	21 47 17	55.8	3.5	1.33730115212	40690	31.2	12.43	0.116	3.2E+07
P1920+21	PSR1920+21	19 20 36	21 08	55.3	3.0	1.077917	41850		220		
P1929+10	PSR1929+10	19 29 52	10 53 03	47.4	-3.9	0.22651703833	40625	5.3	3.176	0.100	6.2E+06
P1933+16	JP1933+16	19 33 32	16 09 58	52.4	-2.1	0.35873542051	40690	8.0	158.53	0.519	1.9E+06
P1944+17	MP1944	19 44 38	17 58 44	55.3	-3.5	0.4406179	(40618)	30	16.3		
P1946+35	JP1946	19 46 35	35 28 36	70.6	5.0	0.717306	40659	21	129.1		
P1953+29	JP1953	19 53 00	29 15 03	66.0	0.7	0.426676	40754	13	20		
P2002+30	JP2002	20 02 35	30	67.7	-0.7	2.111206	40756	15	233		

PULSAR DESIGNATION	PULSAR	R.A. H.M.S.	DECL. DEG. ' "	L II DEG.	B II DEG.	PERIOD (SEC)	EPOCH (J.D.24+)	1/2 PULSE WIDTH (MSEC)	DISPERSION MEASURE (PARSEC/CM3)	PERIOD CHANGE (NSEC/DAY)	APP. AGE P/(DP/DT) (YRS)
P2016+28	AP2016+28	20 16 00	28 30 31	68.1	-4.0	0.55795339053	40689	13.9	14.16	0.0129	1.2E+08
P2020+28	PSR2020+28	20 20 33	28 44 30	68.9	-4.7	0.343400790	41348	6.7	24.6		
P2021+51	JP2021	20 21 25	51 45 08	87.9	8.4	0.52919531221	40626	6.6	22.580	0.263	5.5E+06
P2045-16	PSR2045-16	20 45 47	-16 27 48	30.5	-33.1	1.96156682076	40695	79.0	11.51	0.945	5.7E+06
P2106+44	PSR2106+44	21 06 30	44 30	86.9	-2.0	0.414371	41845		129		
P2111+46	JP2111	21 11 33	46 31 42	89.0	-1.3	1.01468444509	41006	29	141.4	0.0620	4.5E+06
P2148+63	PSR2148+63	21 48 40	63 15	104.1	7.4	0.380141895	41701	15	125		
P2154+40	PSR2154+40	21 54 56	40 02 30	90.5	-11.4	1.52526334	41532	52	71.0		
P2217+47	PSR2217+47	22 17 46	47 39 48	98.4	-7.6	0.53846737844	40624	7.9	43.52	0.239	6.2E+06
P2223+65	PSR2223+65	22 23 30	65 22	108.7	7.0	0.682532	41833				
P2255+58	PSR2255+58	22 55 46	58 54	108.8	-0.7	0.368241	41554	13	148		
P2303+30	AP2303+30	23 03 34	30 43 49	97.7	-26.7	1.575884410	41006	26.0	49.9	0.2514	1.7E+07
P2305+55	PSR2305+55	23 05 00	55 26	108.6	-4.2	0.475063	41554	(27)	45		
P2319+60	JP2319	23 19 42	60 08	112.0	-0.6	2.25648387	41536	68	96		
P2324+60	PSR2324+60	23 24 00	60 55	112.9	0.0	0.2336518	41851		120		