Summer Student Lecture Notes 1971

PULSARS

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Late in 1967 astronomers at Cambridge, England discovered pulsars. They were found by a graduate student who was studying interstellar scintillation with a large array operating at low frequencies. Initially four pulsars were found in this way. Since that time the number of known pulsars has grown to 57 and observations have provided much information on the processes involved.

The basic properties of pulsars are as follows:

1. Intense short duration pulses with a duty cycle of about 5%.
2. Great regularity in the pulse repetition rate.
3. Not quite erratic variation in the pulse amplitude.

See Figure 1

All the observed pulsars are within our galaxy, and many of them are at distances large compared to the thickness of the galactic disk. This is shown by the clustering of pulsars along the galactic plane.

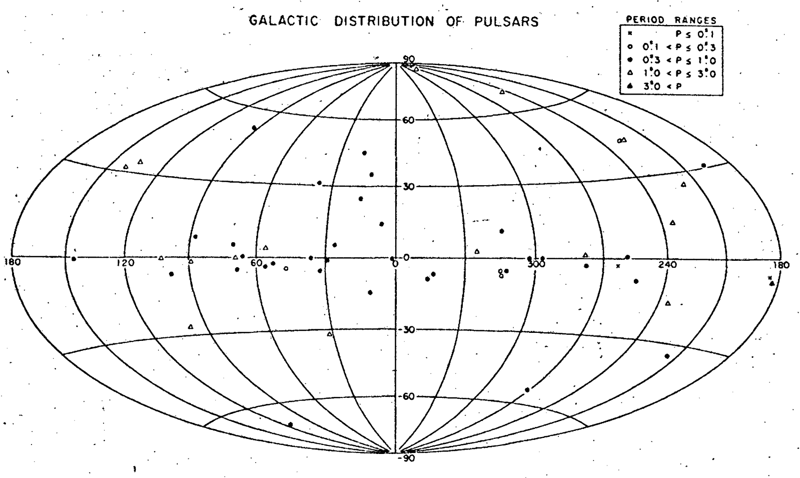

Figure 2

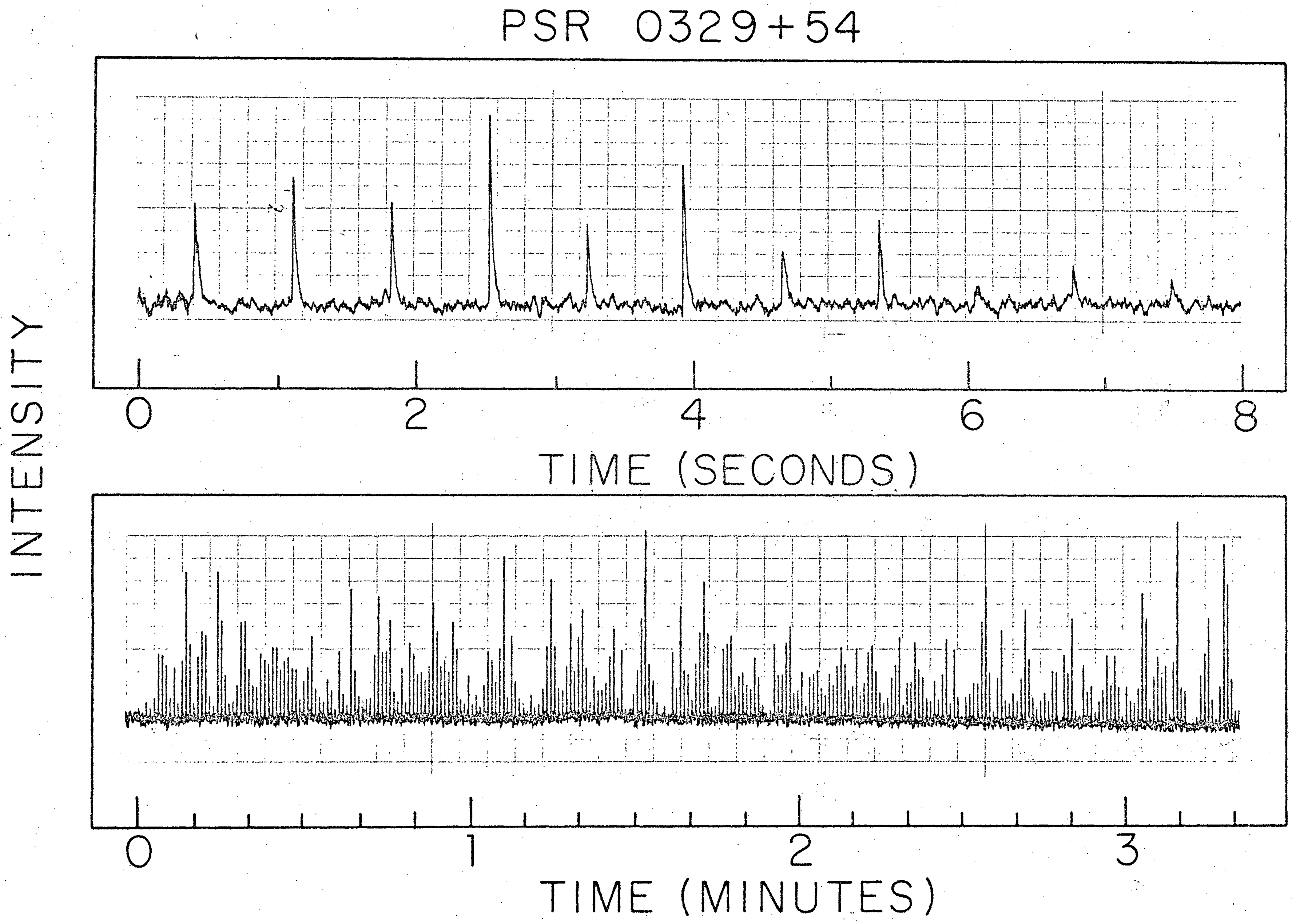

Figure 1

The interstellar medium has an important effect on pulsar radiation—dispersion. Lower frequency radiation propagates with a smaller velocity and so arrives later. This effect allows us to measure the integrated electron density in the line of sight to the pulsar by observing the difference in arrival times for pulses at different frequencies. The dispersion measure for a given pulsar is defined by

$$DM = \int_{\text{path}} n_e \, d\ell = 2.41 \times 10^{-16} \left(\frac{t_i - t_j}{\nu_i^{-2} - \nu_j^{-2}} \right)$$

where n_e = electron density (cm^{-3})
$d\ell$ = element of path (pc)
t_i, t_j = arrival time (sec) of pulse at frequency ν_i, ν_j (Hz).

As pulsars have a very stable period, the signal/noise ratio of observations can be improved by averaging together many pulses. The mean pulse profile obtained in this way remains the same for a given pulsar but differs greatly from one pulsar to another. Observations with orthogonal feeds show

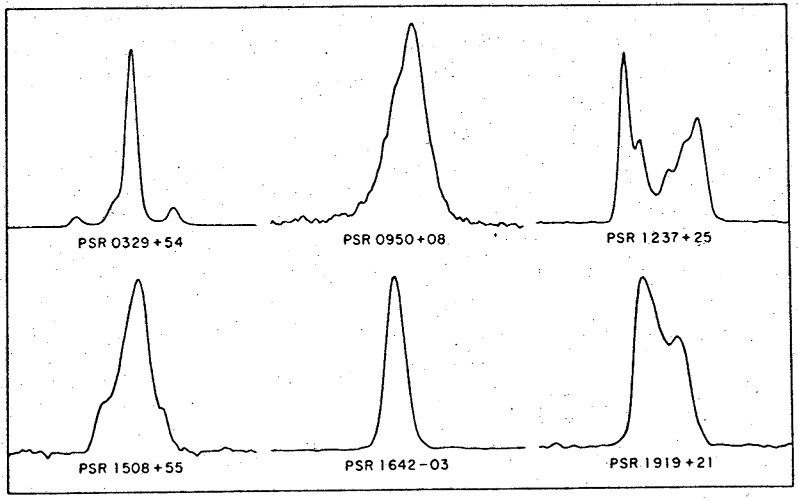

Figure 3

that the pulses are often highly linearly polarized with systematic variations of the polarization parameters across the pulse. As these mean pulse profiles do not differ from day to day, they must be determined by the emitting regions at the pulsar and not by propagation effects.

Single pulse observations show that the pulse often has very narrow spikes of emission, in some cases as narrow as 100 μs. Variations in intensity this short put strong limits on the size of the emitting region, as the region cannot be much larger than the distance light would travel during the rise of the spike. For 100 μs the limiting size is about 30 km.

Observations of successive individual pulses have also shown that, for several pulsars, series of subpulses drift steadily across the main pulse. In all cases where the drift is seen clearly, the subpulses move backwards through the mean profile. This effect can introduce a periodic variation into the pulse amplitude. Power spectrum analysis can be used to find the periodic components in the pulse amplitude variations. So far they have been found in about one-third of the known pulsars. Scintillation effects in the interstellar medium produce irregular fluctuations in the pulse intensity. After scattering by clouds of interstellar gas some of the radiation interferes constructively producing strong pulses, while some interferes destructively producing weak pulses.

See Figure 4

Scintillation also affects the spectrum of the pulsar radiation. Some frequency ranges are enhanced by the constructive interference while some others

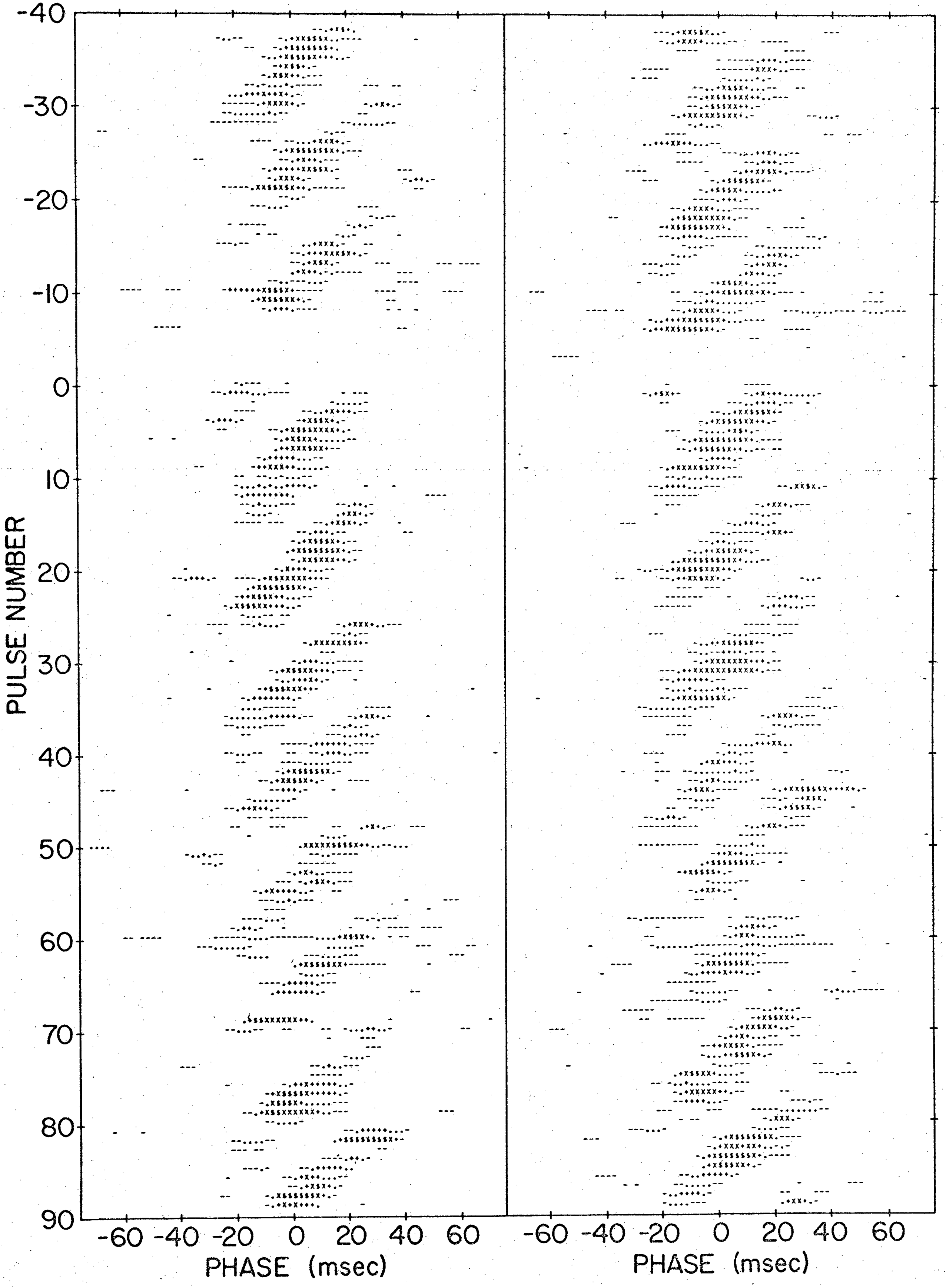
PULSE NUMBER
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
-60
-40
-20
0
20
40
60
PHASE (msec)
PHASE (msec)

Figure 4

are depressed. The enhanced bands tend to last for several minutes and then die out with a new band appearing at a different frequency.

If the power averaged over all scintillation effects is measured at a number of frequencies, the overall spectrum of the radiation can be determined. In all cases the power is less at higher frequencies; however the falloff is faster in some pulsars than in others. These measurements are complicated by the fact that the mean pulse intensity at a given frequency can often vary by large amounts, sometimes greater than an order of magnitude, over periods of a few weeks.

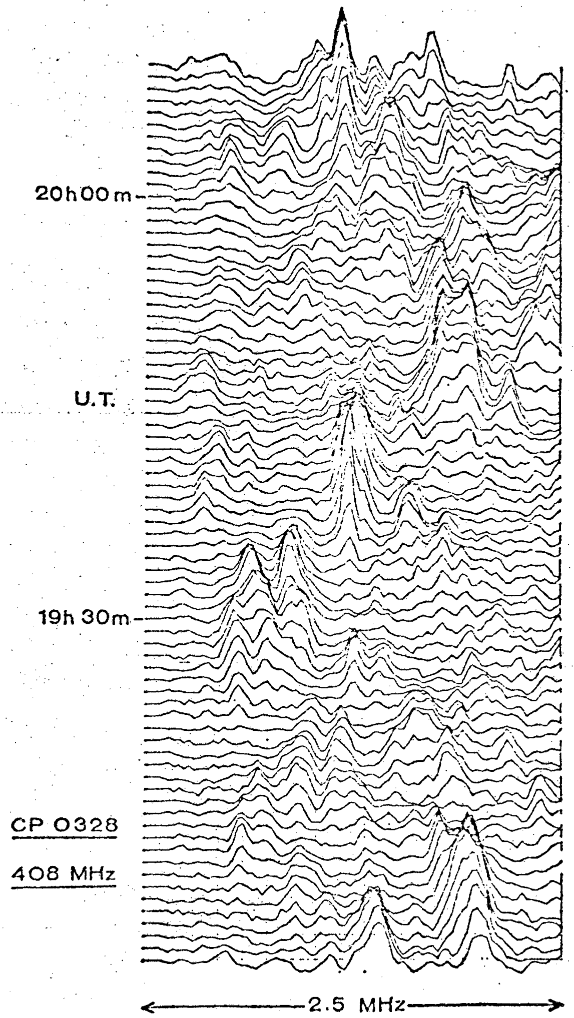

Fig. 1. Successive mean pulse spectra from *CP* 0328 at 408 MHz at intervals of about 50 s. The frequency resolution is 60 kHz and the spectra include the effect of the receiver pass-band.

Timing

The most noteworthy thing about pulsars is their extremely stable pulse repetition rate. Observations have shown that in most pulsars the period is slowly increasing. For example, the Crab Nebula pulsar (which has the shortest known period) had a period of

$$0^{s}.033\ 099\ 324\ 10 \pm 0^{s}.000\ 000\ 000\ 05$$

at 00^h on June 27, 1969, and a rate of increase of period of

$$422.66 \times 10^{-15} \text{ s/s or } 36.518 \text{ ns/day.}$$

Generally those pulsars with the shortest period have the fastest rate of slow-down. To obtain these very accurate periods and period derivatives the pulsar must be observed for a long period. Times of pulse arrival calculated using an assumed period are compared with those observed and new parameters are calculated so that the differences between the calculated and observed values are minimized. If the period has a significant rate of change the residuals form a parabola and the period first derivative can be calculated from the shape of the parabola.

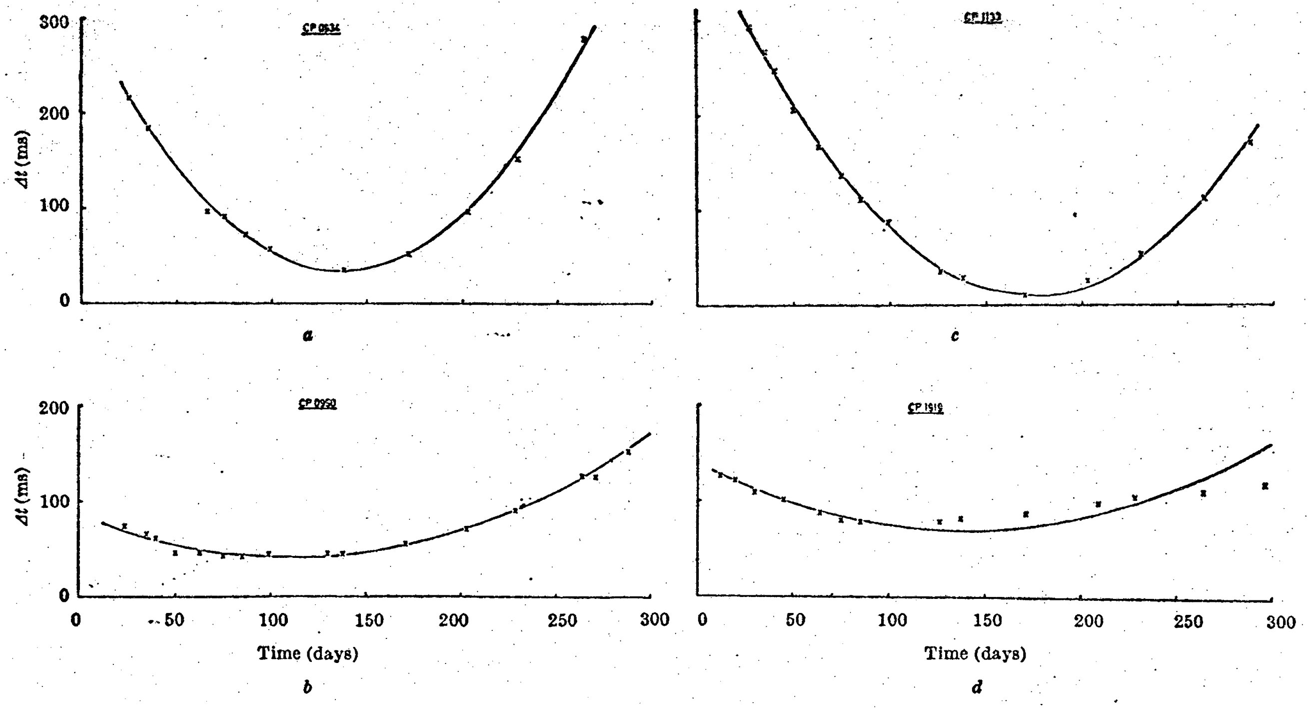

Fig. 1. Difference Δt between measured and predicted arrival times for four pulsars: (*a*) *CP* 0834, (*b*) *CP* 0950, (*c*) *CP* 1133, (*d*) *CP* 1919. The initial date is Julian Day 2439900·5 (February 14, 1968).

Pulsars are not always so predictable. During March 1969 the period of the Vela pulsar suddenly decreased by about 200 ns, and then resumed its regular increase. Since then the Crab Nebula pulsar has also suffered similar but smaller jumps.

The pulsar in the Crab Nebula has been the most intensively studied and is the most interesting for a number of reasons.

1. It has the shortest known period and the largest known rate of change of period.

2. It is the only known pulsar associated with an optically visible object--the Crab supernova. The pulsar in Vela is the only other for which the pulsar-supernova association is reasonably certain.

3. It is the only pulsar from which pulses of visible light have been observed.

4. Similarly, it is the only one from which pulsed X-rays and γ-rays have been observed.

Models

Of the many models proposed for pulsars only one, the rotating neutron star, appears to fit all the observational data. In this model the pulsed nature of the radiation is accounted for by a narrow beam from thestar sweeping past the observer as the star rotates--the so-called lighthouse effect. The material of the star must be very dense to prevent the star bursting apart at the high rotational velocities observed. It is thought that neutron stars have about the same mass as the sun, but a diameter of only about 10 km; that is, a density of 100,000,000 tons/cm^3.

Neutron stars are thought to be the condensed remnant of a star, formed following a supernova explosion. As the magnetic field remains frozen in during the collapse of the star, the magnetic field of a neutron star will be very large--about 10^{12} gauss at the surface of the star. In general the magnetic axis will not coincide with the rotation axis, so we have the "oblique rotator" model for pulsars.

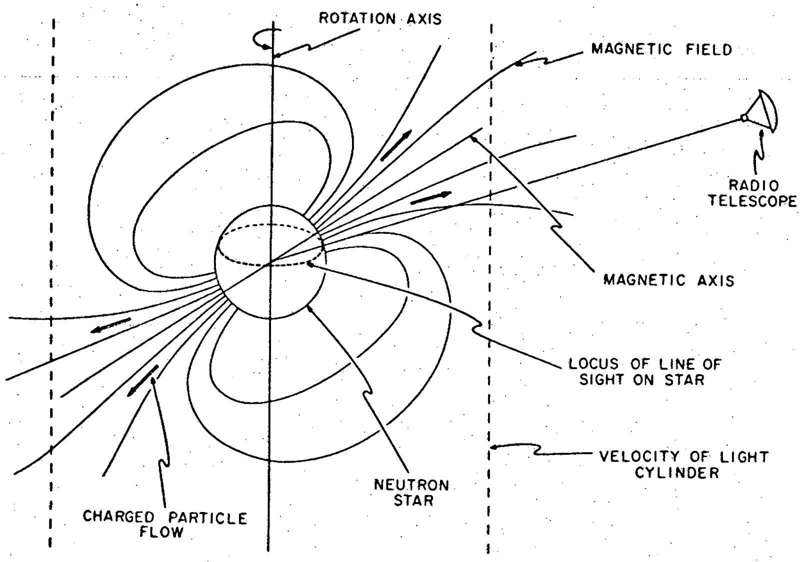

Figure 5

The pulsed emission from the pulsar must be generated within the "velocity of light cylinder"; that is, the cylinder aligned along the rotation axis at which the tangential velocity due to rotation equals the velocity of light. Beyond this surface the magnetic field and plasma cannot co-rotate with the star. Observations of polarization changes across the pulse indicate that the emission probably originates close to a magnetic pole. Because of the curvature of the field line, ultra-relativistic particles moving out from the pole along a field line radiate a narrow beam at radio frequencies in the direction of their instantaneous velocity. If the particles are gyrating round the field lines they will also radiate optical synchrotron radiation. Coherent processes are required to account for the pulse intensities observed.

This model explains the very stable pulse repetition rate and the slow increase in period. Because of dissipation of energy in various radiation processes the rotation is gradually slowing down, resulting in a slow increase in period. The period jumps seen in the Vela and Crab pulsars are thought to be due to a small star-quake on the neutron star. A decrease in radius of only 1 cm is sufficient to account for the speed-up observed in the Vela pulsar.