I

INVITED DISCOURSES

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PULSARS

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1. Introduction

It seems hard to realise, today, that pulsars were totally unknown at the time of the last General Assembly. The discovery of pulsars dates from November 28th, 1967, when the first pulses were recorded from the source now known as CP 1919. Since then we have witnessed an astonishing phase of activity, amongst observers and theoreticians alike, which may be unique in the history of astronomy. Now, with at least 50 pulsars in the catalogues, we are in possession of a wealth of information about these remarkable sources. My aim tonight is to outline the observational evidence which leads us to the physical nature of pulsars. I shall happily leave to Professor Ginzburg the far more difficult task of weaving these strands into a logical pattern and devising a model to account for what is observed.

2. Pulsar Time-Keeping

It was the extreme regularity, and rapidity, of the observed pulses which, at the outset, differentiated pulsars from any other radio sources. So it is natural to commence with an account of the time-keeping properties of pulsars. First, to remind you of the typical pulsar behaviour, I show in Figure 1 a record which illustrates the nature of the emitted pulses. The rapid changes of pulse amplitude are common to most sources and the duration of each pulse is usually about 5% of the interval between pulses. Now that

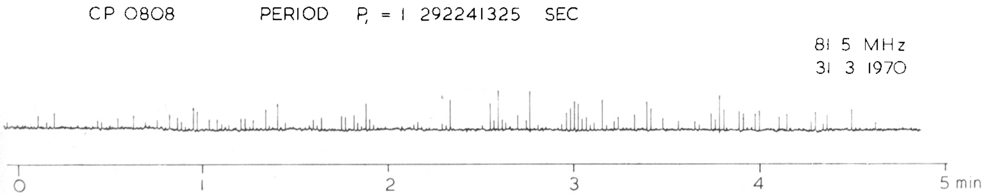

Fig. 1. A typical pulse-train from CP 0808 recorded by the Cambridge array at 81.5 MHz.

50 pulsars have been listed statistics are becoming meaningful and the histogram of periods illustrated in Figure 2 shows that nearly half of the total have periods in the range 0.5–1.0 sec. Observational selection cannot be serious, except for periods shorter than 0.1 sec and it is remarkable that the range of values is so small.

To establish the long-term stability of pulsar periods it is necessary, first, to make a large correction for Doppler variations caused by the Earth's orbital motion. This

De Jager (ed.), Highlights of Astronomy, 3–19.

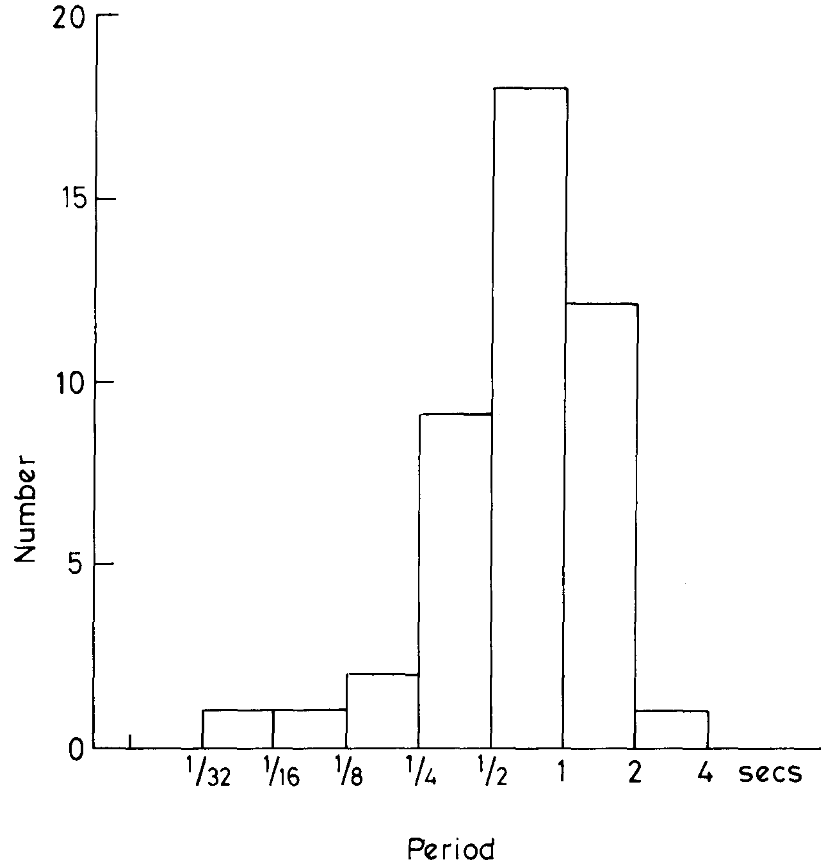

Fig. 2. Histogram of pulsar periods.

demands either an extremely accurate position, or extended observation over many months. In all instances where sufficiently accurate measurements have been possible, it has been found that the periods are systematically increasing – the pulsars are slowing down. It is convenient to consider the characteristic time $P/\dot{P}$ (where P is the period) which may be called the 'age' of a source. Ages vary from 2×10^3 yr to 10^9 yr. For the two most rapid pulsars NP 0532 and PSR 0833 there is an obvious relation between age and period in the sense that rapid pulsars are young, as may be seen in Figure 3, but for the more typical ages of 10^6–10^7 yr no such dependence is evident; presumably it is masked by the greater variation of other relevant parameters.

The greatest timing accuracy has been achieved on NP 0532, the Crab Nebula pulsar, which is conveniently endowed with an exceedingly sharp feature in the pulse. Recent radio work by the Arecibo team has enabled the period, at a given epoch, to be determined with a precision of 1 part in 10^{10} from one day's measurements. Slightly greater precision may be obtained at optical wavelengths. To achieve such results requires a knowledge of the Earth's position to within a few kilometres. For this source

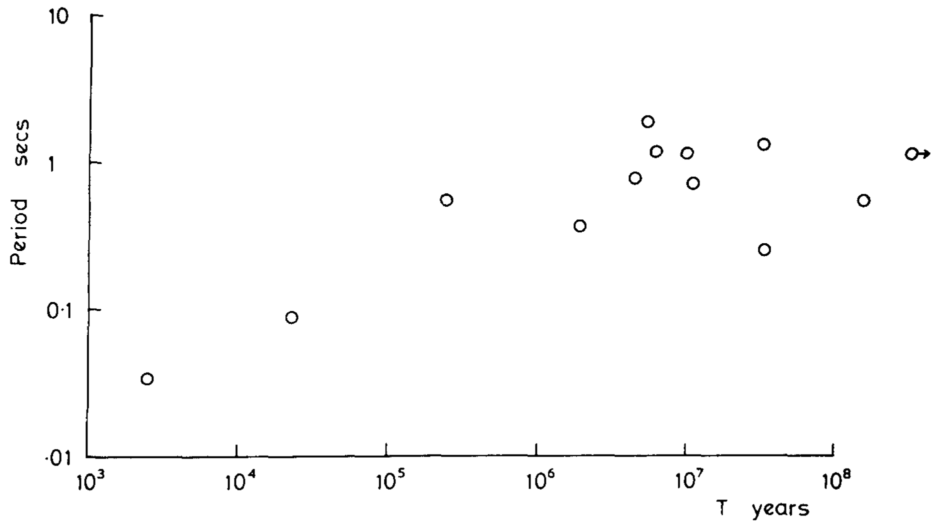

Fig. 3. Relation between 'age' ($P/\dot{P}$) and period.

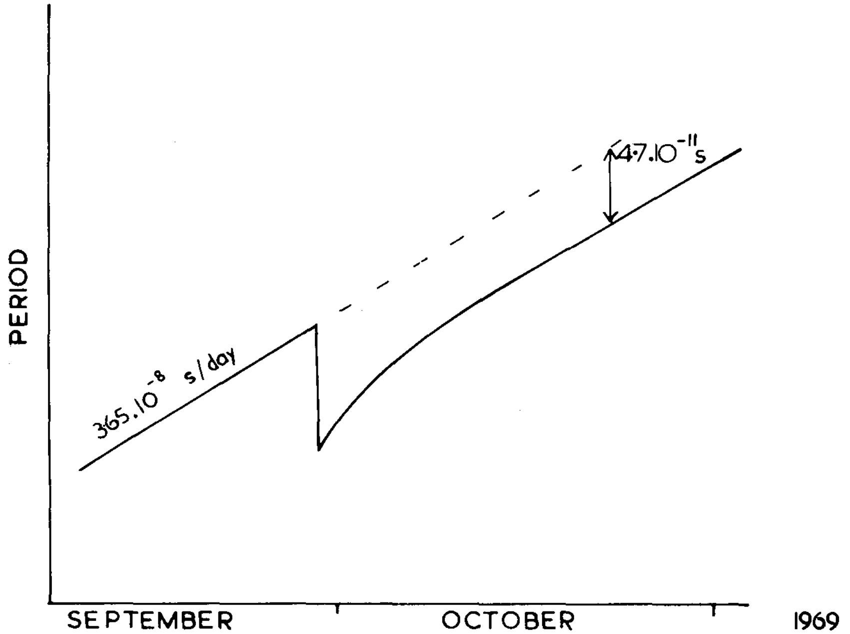

Fig. 4. Sudden change of period in NP 0532 – schematic.

alone it has been possible to obtain a value for the second time derivative $\ddot{P}$. This is important since the relation between P, $\dot{P}$ and $\ddot{P}$ sheds light on possible source models.

In no case have large periodic Doppler variations been found which would indicate that pulsars were members of binary systems. For NP 0532, however, a small, apparently periodic, modulation of amplitude 380 μsec and period 77 d was initially reported. Such an effect might arise if a body of planetary mass were in orbit about the pulsar source, but more extended timing data have not revealed the same effects and there is not yet complete agreement between optical and radio measurements.

The two most rapid pulsars, PSR 0833 and NP 0532, have both undergone sudden decreases of period. The manner in which these changes occurred is shown schematically in Figure 4. The decrease amounted to about two parts in 10^6 for PSR 0833 and took place around the end of February 1969. That for NP 0532 was smaller, being about 1 part in 10^8 and it occurred within one day of September 28, 1969. In

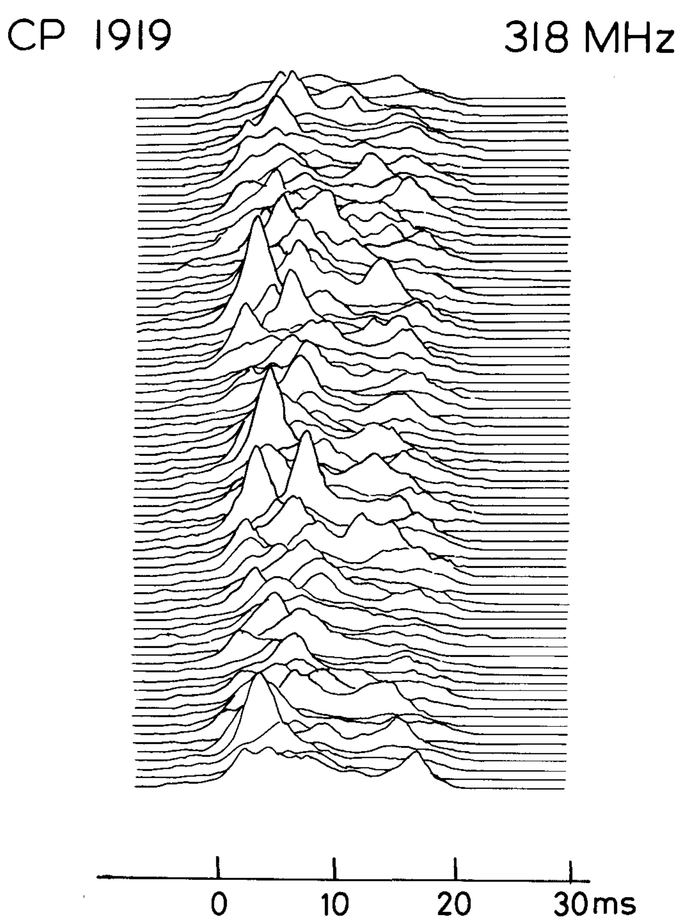

Fig. 5. Pulse to pulse variations recorded at Arecibo.

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neither case has the period reverted exactly to its original value. NP 0532 settled down within a few days to a new value, of the order 1 part in 10^9 shorter than the original period. For PSR 0833 the relaxation time appears to be several years. Observations of this type shed light on rotation models of pulsars and have been interpreted in terms of a quasi-rigid shell surrounding a liquid core.

3. The Radiated Pulses

Successive pulses from a given source usually exhibit rapid changes of intensity, shape and polarisation. Some idea of the complexity of this behaviour can be gained from Figure 5 which shows a montage of successive pulses from CP 1919 as observed at Arecibo. The average of many pulses, however, yields a stable envelope which endows each source with its characteristic signature. A selection of mean envelopes is shown in Figure 6. A tendency for double-peaked envelopes is common, particularly amongst the slower pulsars, but few generalisations can be made. The width of the envelope shows an obvious correlation with the pulsar period; on average the width is about 5% of the interval between pulses. If we regard pulsars as 'lighthouses' the rotating beam is therefore about 20° wide.

Occasionally pulsars are characterised by a weaker interpulse spaced almost, but

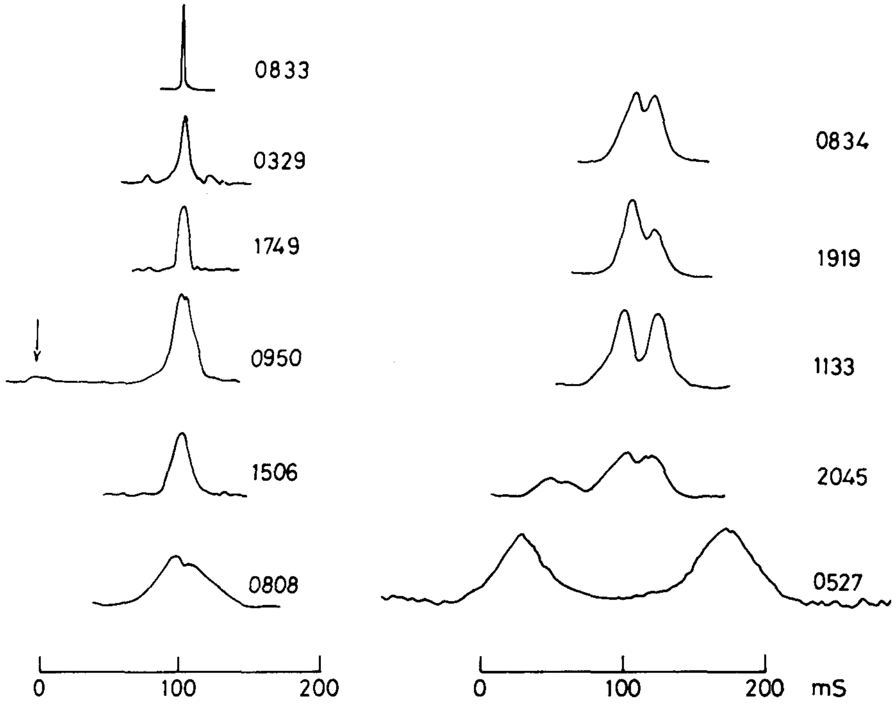

Fig. 6. Selection of mean pulse envelopes.

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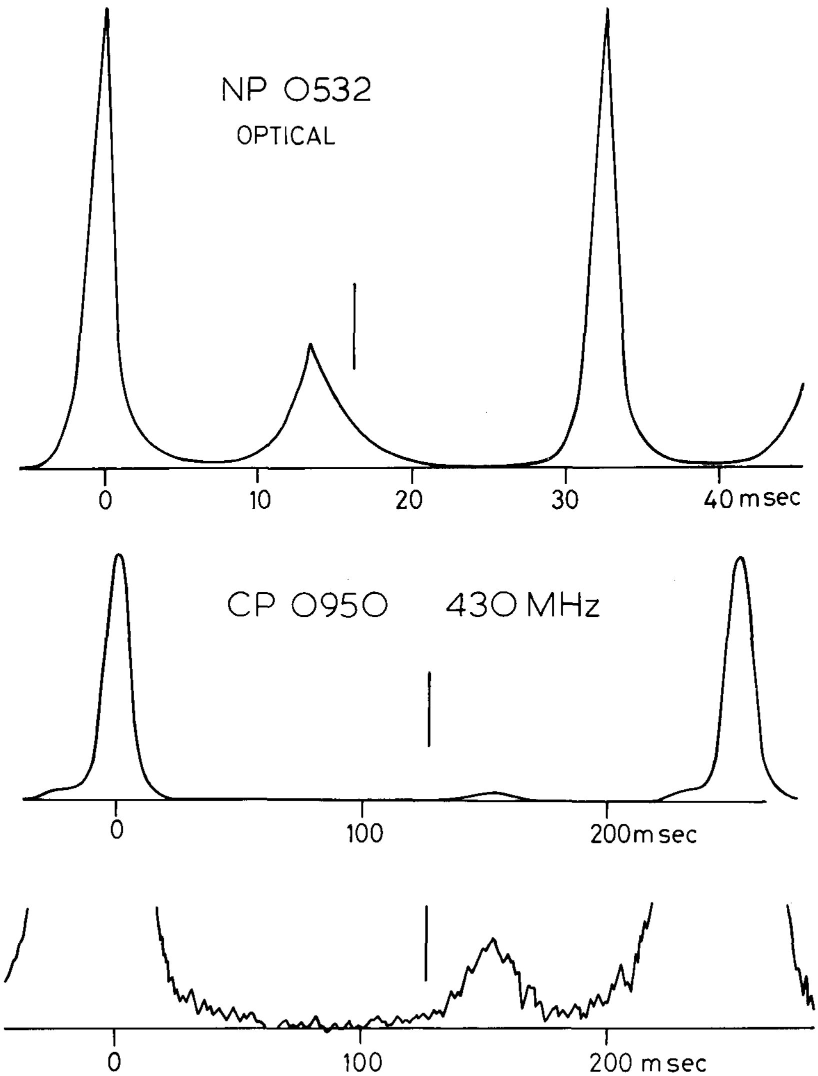

Fig. 7. Two examples of interpulses.

not exactly, midway between the main pulses. The best examples are NP 0532 and CP 0950 as illustrated in Figure 7. The phenomenon is comparatively rare and occurs in less than 10% of the known sources so that the pulsar 'lighthouse' typically gives only a single beam, rather than two separated by 180°. This fact is relevant in deciding the radiation mechanism of pulsars.

Pulse envelopes are not markedly wavelength-dependent as may be seen by comparing results at X-ray, optical and radio wavelengths for NP 0532 displayed in Figure 8. The radio pulse is somewhat more complex than the optical and X-ray pulse,

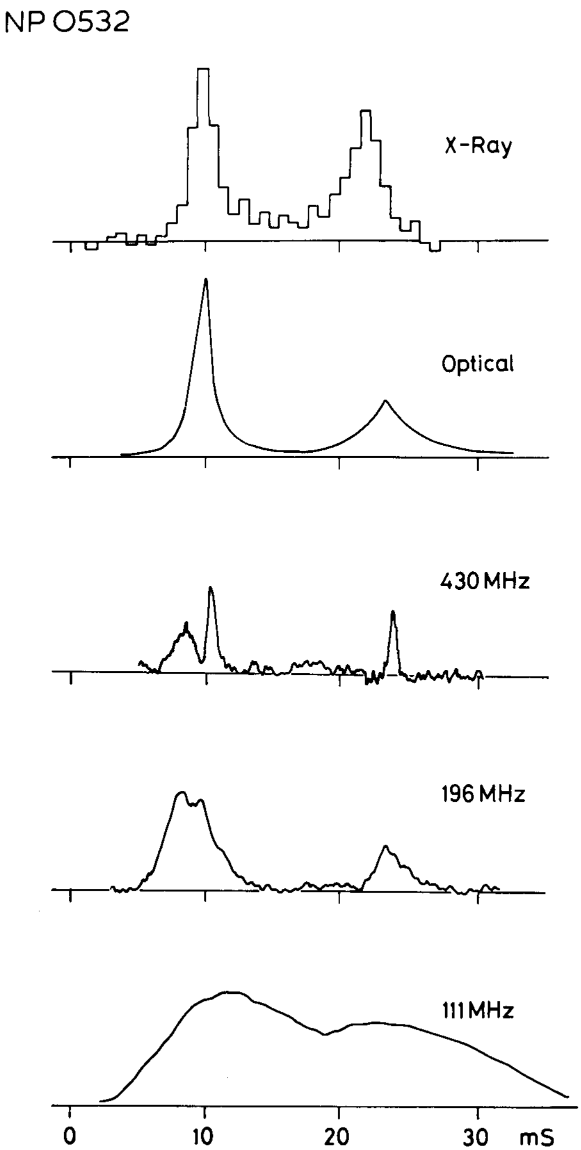

Fig. 8. Mean pulse envelope of NP 0532 at different wavelengths.

but the sharp feature following the 'precursor' coincides with the tip of the optical pulse to within a fraction of a millisecond. Several sources show an increase of pulse-width proportional to (wavelength)$^{0.25}$ at radio wavelengths, and occasionally a much faster broadening at the longest wavelengths. The latter is seen in Figure 8 and the effect can be explained by time-delays introduced by plasma irregularities in the interstellar medium.

The average of many pulses typically shows significant linear polarisation, sometimes approaching 100%. The percentage polarisation is often higher in the wings of the pulse and the polarisation angle sometimes rotates characteristically with position in the pulse. The behaviour of the linear polarisation vector in some cases is shown in Figure 9. Rotation of the vector within the pulse does appear to be a common

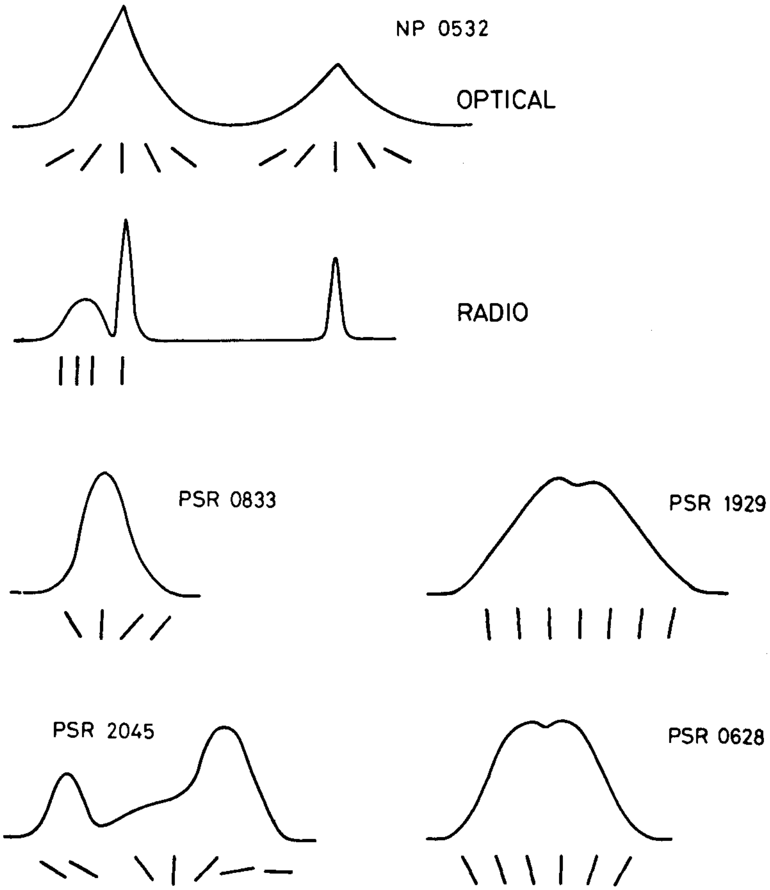

Fig. 9. Average pulse polarisation.

feature, although complex pulse envelopes are associated with less regular polarisation. These results are obviously of great significance concerning the radiation mechanism.

Averaging removes a wealth of fine detail which can be seen in single intense pulses. This 'sub-pulse' structure can occur on a time-scale down to 0.1 msec and usually shows strong linear or elliptical polarisation. Recognisable structure frequently occurs in successive pulses, but with a characteristic drift in time. This effect has been well-described as 'marching' sub-pulses and it has been detected in many sources. A schematic diagram illustrating typical behaviour is shown in Figure 10. The marching is generally in the sense of overtaking the main pulse and is sufficiently regular to allow the definition of three further periodic times. These are

P_2 – the separation of adjacent sub-pulse maxima in a single pulse. ($\approx$ 10–100 m sec)

P_3 – the time interval between the passage of successive 'marching' sub-pulses at a given point in the mean envelope. ($\approx$2–14 sec)

P_4 – the time required for a sub-pulse to march through the main pulsar period P. ($\sim$1–2 min)

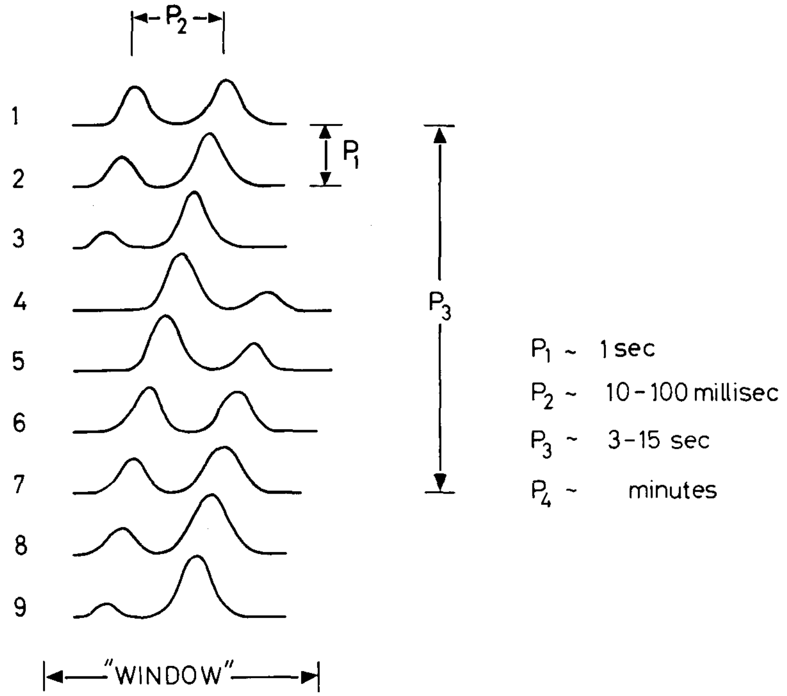

Fig. 10. Marching sub-pulses – schematic.

Time forbids a more detailed account of these interesting phenomena and the picture presented is an over-simplification, but the effects appear to indicate differential rotation between the pulsar 'lighthouse' and some modulating system.

The effects which have just been described lead to quasi-periodic variations of pulse intensity. In addition, irregular intensity changes on time-scales from seconds to months are typically found. There is much evidence based on simultaneous observations at different wavelengths, that variations on a time scale of minutes to hours can be ascribed to interstellar scintillation caused by the presence of irregularities of electron density within the galaxy. Indeed, the first studies of interstellar irregularities using the drifting diffraction pattern method have already been reported. But diffraction theory places severe limits upon what is possible and one is left with variations on the shortest, and longest, time scales which must be intrinsic to the sources themselves. The crab pulsar appears to be unique in occasionally emitting single intense pulses which exceed the average by a factor of 1000. If this behaviour is shared by other rapid pulsars it may aid their discovery in situations where pulse-smearing caused by irregular time-delays is a serious limitation.

4. Distribution in the Galaxy

When pulsar positions are plotted in galactic co-ordinates there is a significant clustering towards the plane, as shown in Figure 11, indicating that pulsars are to be

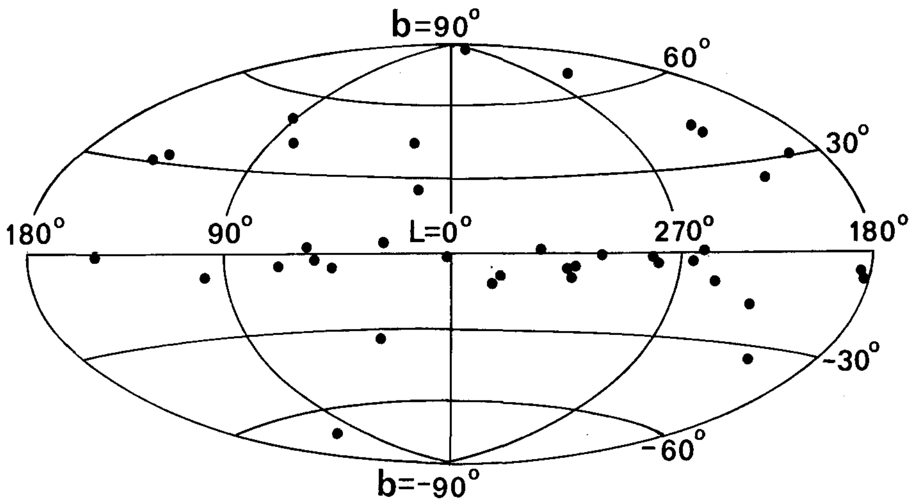

Fig. 11. Galactic distribution of pulsars.

associated with Population I. The maximum is slightly below the centre of the plane which may be due to our position being slightly above it. The histogram of the latitude dependence in Figure 12 shows that approximately 50% of all pulsars lie within $\pm 10°$ of the plane.

It is notable, however, that the distribution at higher latitudes can only be explained if there is a large spread of intrinsic intensity of the sources. A simple disk population of similar sources cannot be devised to fit the data at both high and low latitudes. This gives evidence that the concentration at low latitude is due to sources of much greater intrinsic luminosity than the high latitude sources. Since, on theoretical grounds, the most rapid pulsars are likely to be the most intense, it is interesting to investigate the

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period distribution in more detail to see if further light can be shed on this point. Numbers are unfortunately rather small, but dividing the total into two classes of high, and low, latitude as in Figure 13 does reveal a possible tendency for low-latitude sources to have shorter periods, indicating that they may be younger.

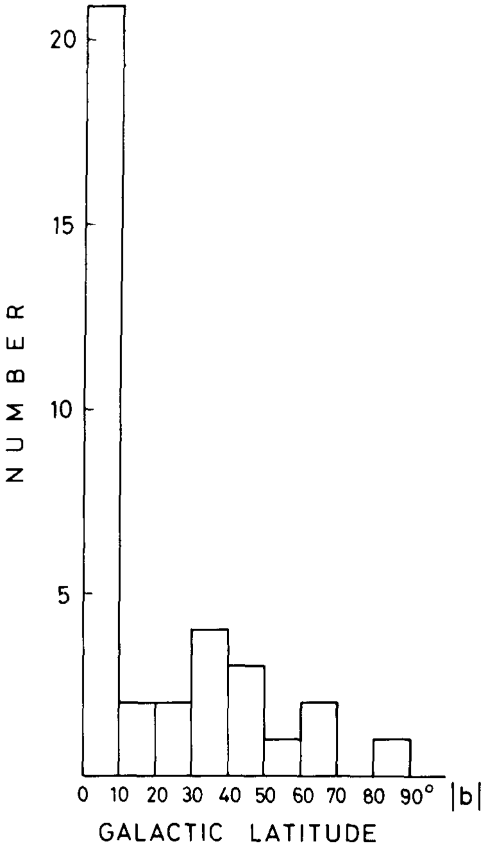

Fig. 12. Histogram showing galactic latitude dependence.

5. Pulsar Distances

From the galactic distribution, assuming that pulsars are, indeed, similar to Population I, it follows that the bulk of the sources are located within a few kiloparsecs. It is also possible to estimate distances from pulse dispersion. The received pulses have a dynamic spectrum, indicated in Figure 14, which fits very exactly that expected for dispersion in a plasma. Thus it is possible to measure the integrated electron content $\int n_e \, dl$ along the line of sight. This quantity is defined as the dispersion measure (DM). The observed values shown in Figure 15 indicate a wide spread but, typically, lie within 10–100 electron cm^{-3} parsec. Unfortunately the mean galactic electron density

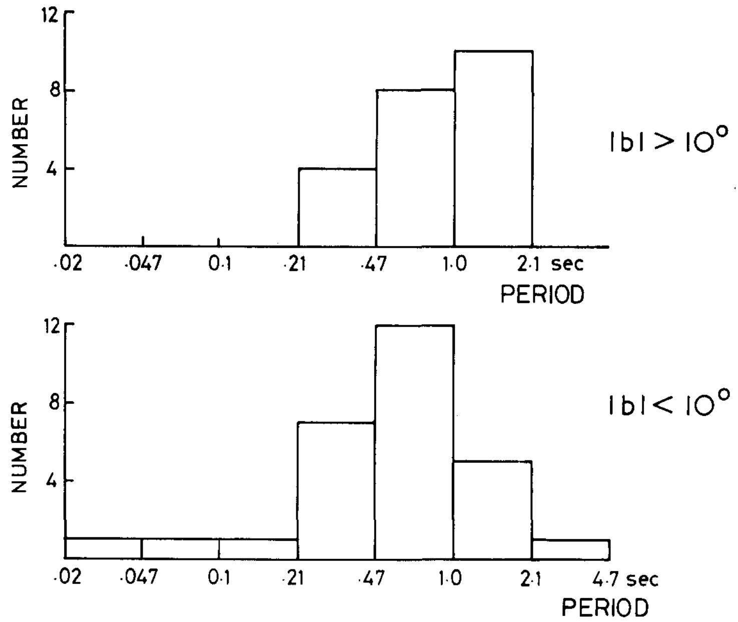

Fig. 13. Relation between period and galactic latitude.

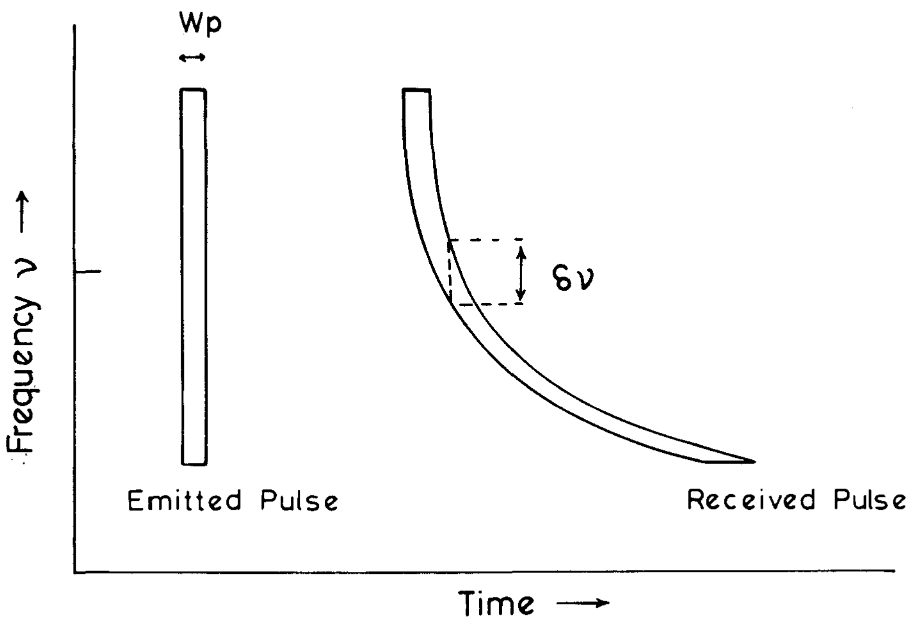

Fig. 14. Pulse dispersion – schematic.

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is somewhat uncertain, but adopting an average value of 0.03 electron cm^{-3} places typical distances in the range 30–3000 parsec. There is evidence that the largest values of DM may be caused by H II regions in the line of sight so that derived distances must be interpreted with caution.

A further method of distance measurement relies upon the detection of absorption by neutral hydrogen at 21 cm. Since the absorbing regions are associated with spiral arms we can, by observing the Doppler shift arising from differential rotation, detect

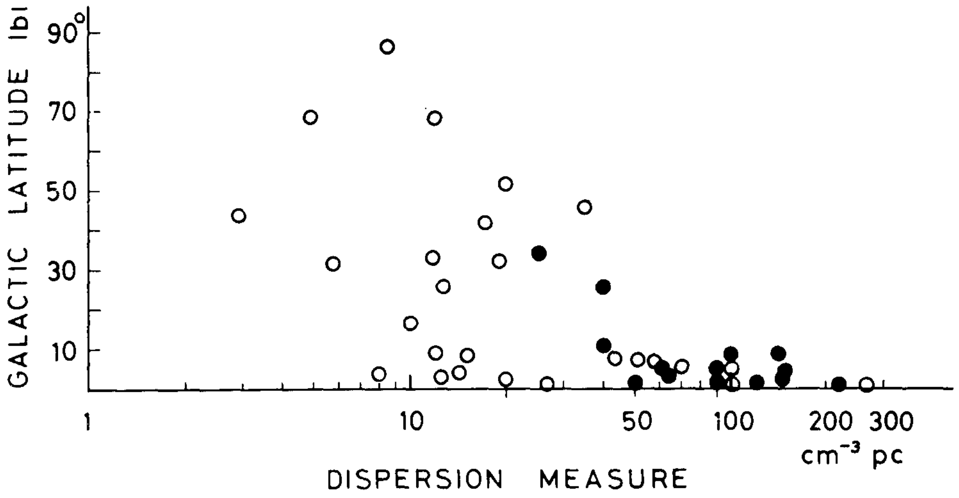

Fig. 15. Observed dispersion measures as a function of galactic latitude. Filled points represent sources believed to lie behind H II regions.

the spiral arms which cross the line of sight to a given source. This method can only be applied to strong sources in the galactic plane. In two cases absorption has been found in regions out to about one kiloparsec, corresponding to the local arm, but no absorption has been found in the Perseus arm at a distance of 4 kiloparsec.

6. Spectra

The extreme radio frequencies at which pulsars have been recorded vary from 40 MHz to nearly 10000 MHz. Spectra are not easy to obtain owing to intensity variations, but the general behaviour is shown in Figure 16. All sources show a steepening spectral index at high frequencies and low-frequency cut-offs are also common.

For the one case of NP 0532 the radio spectrum may be compared with optical, infra-red and X-ray data as in Figure 17. It is notable that the optical continuum is featureless. Integration shows that this source radiates far more energy in the X-ray band than at lower frequencies. It appears that quite different emission regimes are required to explain the radio and X-ray data.

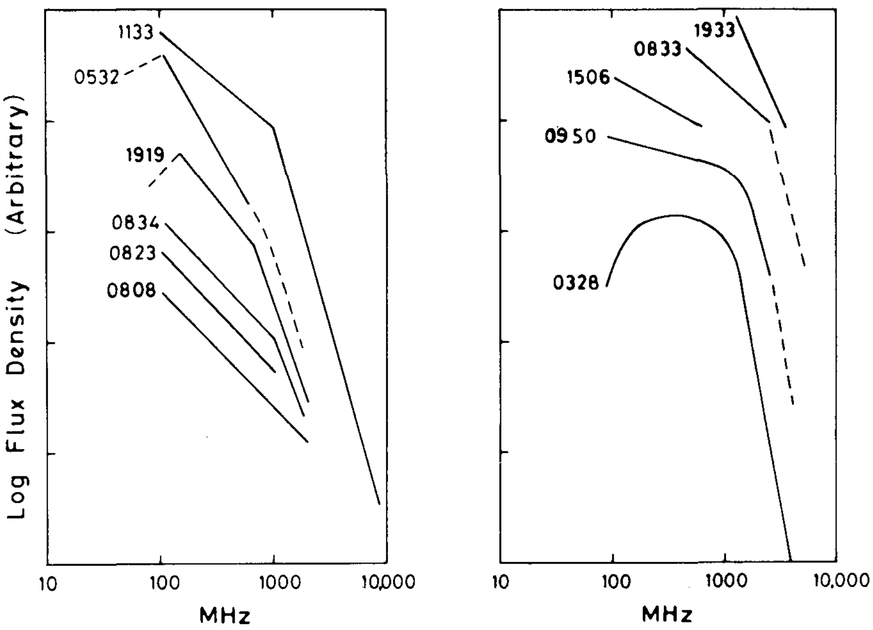

Fig. 16. Radio energy spectra.

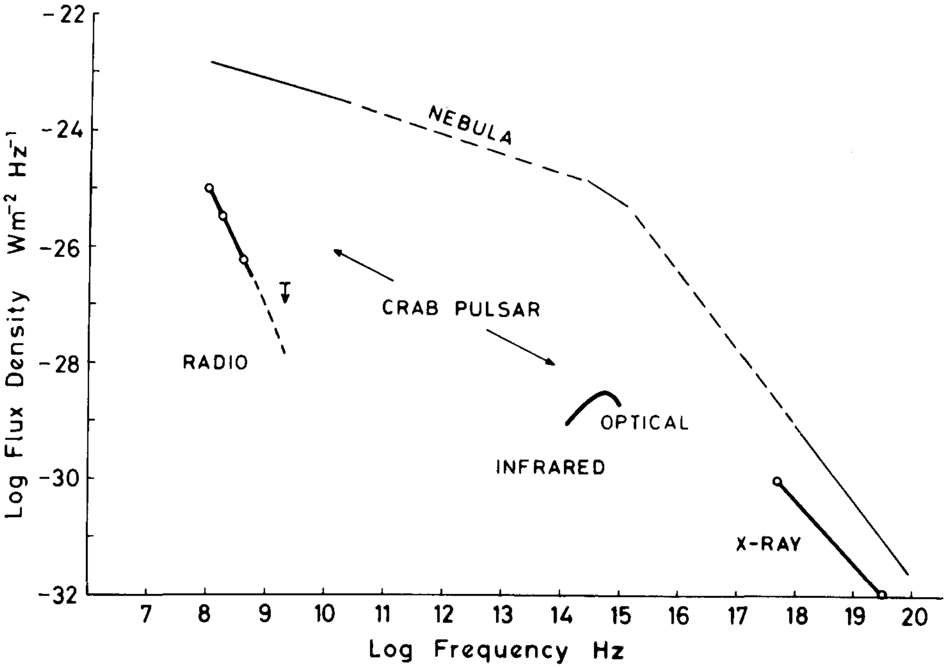

Fig. 17. Radio-X-ray spectrum of NP 0532.

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7. Physical Nature of Pulsars

Only two pulsars have been identified with previously known objects. These are the Crab Nebula pulsar NP 0532 (Figure 19) and PSR 0833 which lies in the radio source Vela X as shown in Figure 18. It is highly significant that both are supernova remnants and that they have the shortest periods, indicating that they are the youngest sources. Attempts to make optical identifications in other cases have failed, even for limiting magnitudes as great as $23^{m}.5$. Searches for pulsars in other known supernova remnants have also proved fruitless.

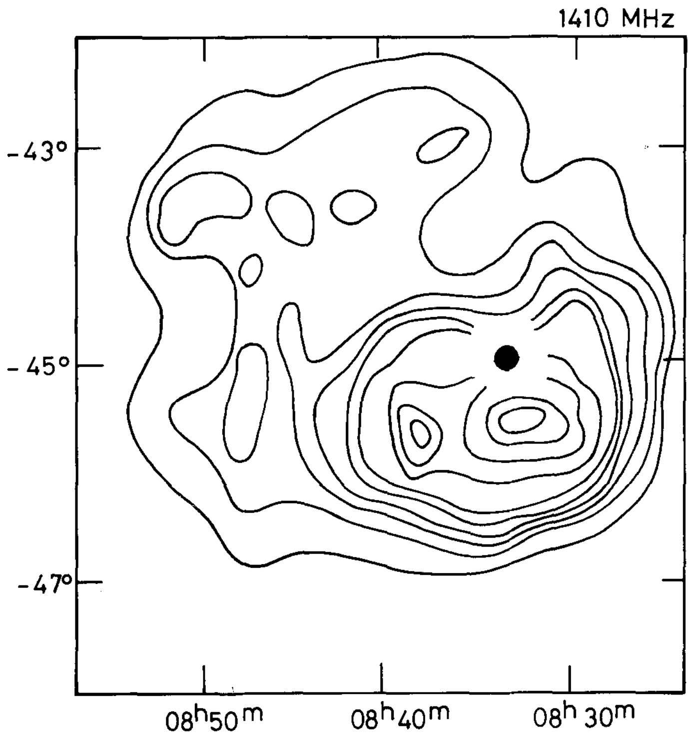

Fig. 18. PSR 0833 associated with the supernova remnant Vela X.

The space density of pulsars may be estimated from the dispersion measure of the nearest sources. Assuming a plasma density of 0.03 electron cm^{-3} leads to a space density of the order $5 \times 10^{-8}\ pc^{-3}$, a value comparable to that of O stars. If the radiation is a pencil beam, and not a fan beam, then some of the pulsars will not be seen and this estimate must be increased by a small factor (probably less than 10).

Pulsar energies may be derived in those cases where the distance is not too uncertain and it is convenient to consider the Crab pulsar (probably an extreme case) and CP 0329, a typical source of period 0.7 sec whose distance is known from 21 cm absorption studies. Integration over the radio spectrum leads to an (isotropic) radia-

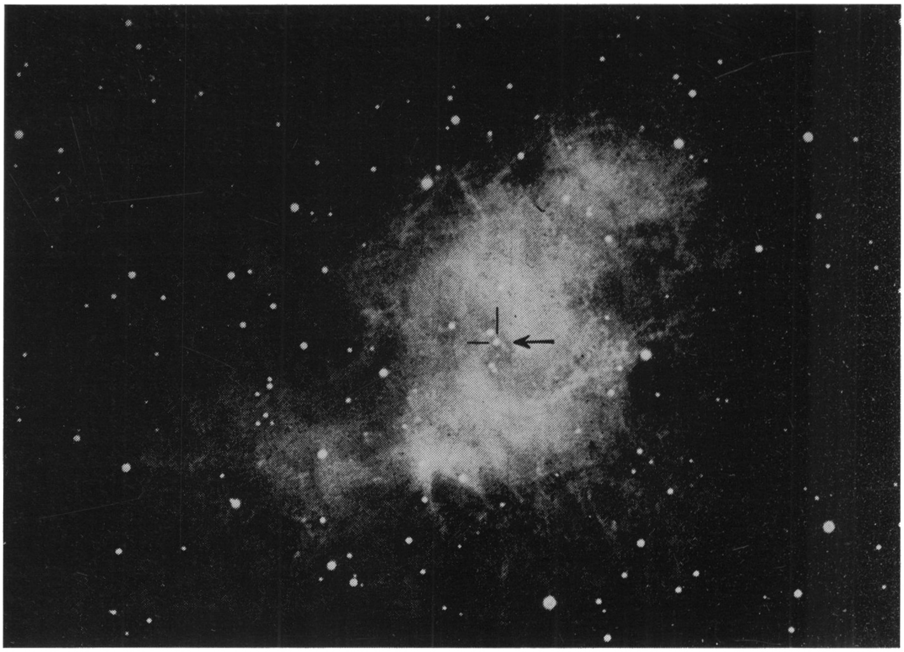

Fig. 19. Pulsar NP 0532 in the Crab nebula.

tion of $\approx 10^{30}$ erg sec^{-1} for CP 0329 and $\approx 6 \times 10^{30}$ erg sec^{-1} for NP 0532. In the latter case, as has been said already, the greatest energy is in X-rays and amounts to $\approx 10^{36}$ erg sec^{-1}. It is surprising that the radio emission in both cases is so similar, despite a 20:1 ratio of periods. Taking a typical pulsar age as 10^7 yr we obtain a total of $\approx 10^{45}$ erg to account for the radio pulsar alone. If all sources are similar to the Crab pulsar the dominant loss in electromagnetic radiation will be in X-rays when they are young and the above estimate may be increased by several orders of magnitude. To trespass, very briefly, on Professor Ginzburg's territory, it is worth pointing out that the typical pulsar, whose spin-down can be measured, can only just sustain the observed radio energy loss on the rotating neutron star model. Typical slow pulsars, therefore, are not expected to emit more powerfully in the X-ray band; this must be a property of young pulsars only.

Pulsars must be exceedingly small objects. From the period of 33 msec, in the case of NP 0532, we can derive that the massive time-keeping body has dimensions of a few thousand km or less since the surface velocity cannot exceed c. This is a conservative limit and the sharpness of detail in emitted pulses leads to dimensions, for the emitting region, which may be less than 100 km. The radiation density corresponds to a brightness temperature in excess of 10^{23} K, and consequently a coherent radiation mechanism is demanded. Having regard to the polarisation of the radiation it appears that a well-organized magnetic field must also be present.

We may therefore conclude that pulsars are bodies of planetary size or smaller, requiring approximately stellar energies, and endowed with the unique pulsed radiation properties that I have attempted to describe. These are undisputed facts. The way is therefore clear, or perhaps I should more accurately say open, for Professor Ginzburg to explain just what it is that lies behind this radiation.