Aust. J. Phys., 1987, **40**, 731–9

Two Types of Pulsar*

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Abstract

Some arguments for the subdivision of pulsars into two classes are considered: (i) short-period pulsars described by Smith's (1973) model and (ii) long-period pulsars for which the hollow-cone model is valid. The data for PSR 1937+21 ($P = 1 \cdot 56$ ms) are in good agreement with this conception, this pulsar being a typical representative of the first group of pulsars.

1. Introduction

Since the detection of pulsars in 1967 several models have been put forward to explain their observed properties. Attempts were made to describe characteristics of pulsar radio emission on the basis of only one particular model, but these attempts were unsuccessful, and in 1977 Manchester and Lyne proposed that different mechanisms generate radio emission in pulsars of C-type and S-type. The hollow-cone model was applied to C-type pulsars and the relativistic beaming scheme to S-type ones. Following this idea we suggested (Malov and Suleymanova 1982) that there are two types of pulsars: the first type is described by Smith's (1973) model (relativistic beaming near the light cylinder $r \sim r_{\rm LC} = cP/2\pi$, where P is the rotation period and c the speed of light). In the second one the hollow-cone (polar-cap) model operates, and radio emission is generated not far from the neutron star surface ($r \ll r_{\rm LC}$). Let us consider some arguments for this hypothesis.

2. Arguments for Dividing Pulsars into Two Types

(a) Relation between Equivalent Pulse Width W and Period P

On the basis of data for 299 pulsars (Manchester and Taylor 1980) we have fitted a relationship of the form

$$\log W = \alpha \log P + b$$

for pulsars with $P \gtrsim 1$ s and obtained $\alpha = 0 \cdot 57 \pm 0 \cdot 19$. This value is consistent with the polar-cap model, which for a dipolar magnetic field predicts $W \propto P^{\frac{1}{2}}$ (Gunn and Ostriker 1970).

* Paper presented at the Joint USSR–Australia Shklovskii Memorial Symposium on Supernova Remnants and Pulsars, held at Pushchino, USSR, 8–11 June 1986.

0004-9506/87/060731$02.00

For pulsars with $P \lesssim 0{\cdot}3$ s we have found that $\alpha \approx 1$. This accords with Smith's relativistic beaming model, as shown by Zheleznyakov (1971) who derived the relation

$$W \approx \frac{aP}{2\pi}(1-\beta^2)^{\frac{3}{2}}, \tag{1}$$

where a is a constant, $\beta = \Omega r/c = t/r_{\mathrm{LC}}$, Ω being the angular velocity. The individual values of α have substantial uncertainties, but nevertheless the general trend of α with P is consistent with our hypothesis (see Fig. 1).

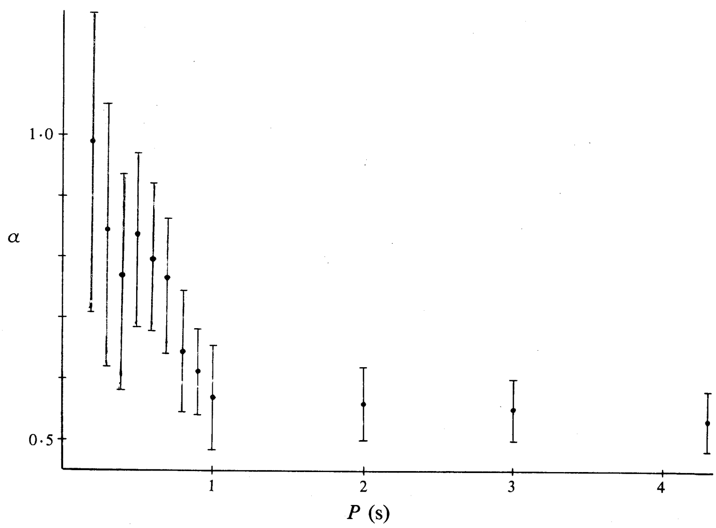

Fig. 1. Relationship between the gradient α of the curve log W against log P (see Section 2a) and the period P.

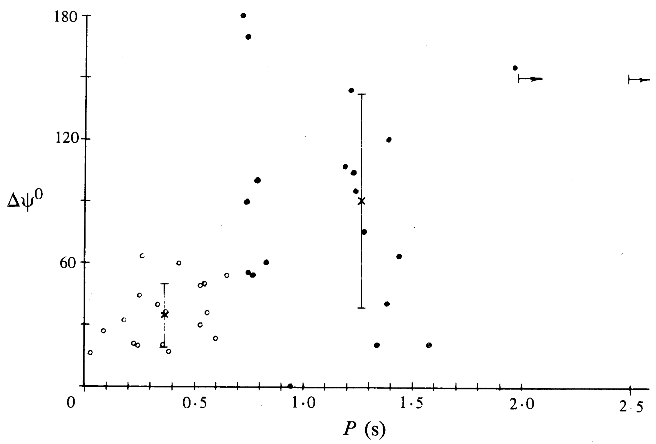

Fig. 2. Total change of position angle in integrated profiles for 38 pulsars ($P < 0{\cdot}7$ s, open circles; $P > 0{\cdot}7$ s, solid circles). Mean values and r.m.s. deviations are shown for these two groups.

(b) Variation of Linear Polarisation Position Angle through Integrated Pulse Profiles

Measurements at 410 MHz for 38 pulsars (Manchester 1971; Lyne *et al.* 1971; Hamilton *et al.* 1977; Backer and Rankin 1980) show that the average magnitude $\overline{|\Delta\psi|}$ of the change of polarisation position angle through the pulse is larger for pulsars with long periods than for those with short periods. The long-period pulsars show also a larger scatter in $|\Delta\psi|$ (see Fig. 2):

$$\overline{|\Delta\psi|} = 35°\pm 15°, \qquad P < 0\cdot 7\ \mathrm{s} \quad (N = 18),$$

$$\overline{|\Delta\psi|} = 90°\pm 50°, \qquad P > 0\cdot 7\ \mathrm{s} \quad (N = 20).$$

The result for long-period pulsars has a straightforward explanation in terms of the polar-cap model. Here the radio emission emerges from a magnetic pole and is concentrated in a narrow beam centred on the magnetic axis. The changing orientation of the linear polarisation reflects the changing orientation of the magnetic field lines as these are swept past our line of sight by the pulsar's rotation (see for example Radhakrishnan and Cooke 1969).

Short-period pulsars may have considerably less changes of position angle due to elongated beams, because the relativistic beaming model predicts that pulsar beams should be very extended in latitude (Smith 1977).

Table 1. Pulsars with interpulses

PSR	P (s)	Δ (parts of P)	$\delta = I_{\mathrm{IP}}/I_{\max}$
0531+21	0·0331	0·60	0·69
0823+26	0·5307	0·50	0·005
0950+08	0·2531	0·43	0·012
1055−52	0·1971	0·57	0·54
1822−09	0·7690	0·46	0·050
1848+04	0·2847	0·43	0·25
1929+10	0·2265	0·49	0·019
1937+21	0·0016	0·48	0·49
1944+17	0·4406	0·51	0·010

(c) Interpulses

One consequence of elongated beams is that short-period pulsars would be expected to have interpulses more often and the intensities of these interpulses would be higher than those from pulsars with long periods (if the interpulse is formed by the second pole). This conclusion is in agreement with observable data (see Table 1) (Taylor and Stinebring 1986).

(d) Difference of r.m.s. Arrival Time Residuals

For our two groups of pulsars r.m.s. residuals of arrival times (Helfand *et al.* 1980; Malov and Shabanova 1982) are given by (Fig. 3):

$$\bar{\sigma}_1(P < 0\cdot 7\ \mathrm{s}) = 8\cdot 5\ \mathrm{ms} \qquad (N = 18),$$

$$\bar{\sigma}_2(P \geqslant 0\cdot 7\ \mathrm{s}) = 1\cdot 2\ \mathrm{ms} \qquad (N = 14).$$

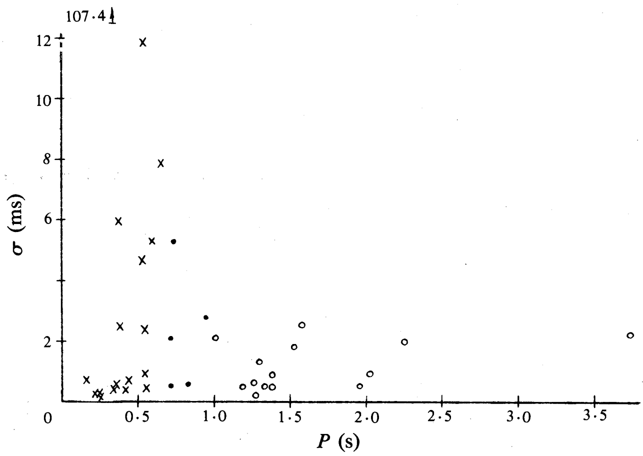

Fig. 3. Dependence of r.m.s. arrival time residuals on period: crosses, $P < 0{\cdot}7$ s; solid circles, $0{\cdot}7 \leqslant P \leqslant 1{\cdot}0$ s; and open circles, $P > 1{\cdot}0$ s.

Integrated profiles of long-period pulsars must be more stable than those of pulsars with short periods if the forms of the profiles are determined by the structure of magnetic field lines in an emission cone. Distortions of these lines and corresponding longitudinal phase variations of pulses increase when the ratio ϵ of the plasma energy to the energy of magnetic field increases:

$$\epsilon = \frac{8\pi\gamma_b n_b m_e c^2}{H^2} = \frac{8\pi\gamma_b m_e c}{PeH}, \tag{2}$$

where γ_b is the Lorentz factor of relativistic electrons in a beam, n_b their density and H the magnetic field. We have used the relationship $n_b = H/Pce$. If $\gamma_b = 10^7$ (Ruderman and Sutherland 1975), we then have

$$\epsilon = \frac{14}{PH_s}\left(\frac{r}{R_\star}\right)^3. \tag{3}$$

Hence near the surface of a neutron star we have $\epsilon \ll 1$, and phase variations must be low. For pulsars with short periods ϵ may be ~ 1 ($r \gg R_\star$), and phase variations must be higher.

(e) Nulling

Pulsars with long periods show 'nulling' more often (Ritchings 1976), and the probability of a null increases sharply at $P > 1$ s.

In the Smith model, variations of intensity may be caused by fluctuations of the number of emitting particles and their distance from the light cylinder. There are always particles in this region, and total absence of radiation is very rare. In pulsars with long periods fluctuations of the number of particles may occur but, in addition, the general mechanism generating radiation may be switched off. This mechanism is probably related to the production of electron–positron pairs, and when a period increases its efficiency decreases (Arons 1977). Therefore, pulsars with long periods would be expected to show more frequency nulling, and this is what is observed.

It is evident that the expected properties of the relativistic beaming mechanism are more frequently observed for shorter period pulsars. The period of PSR 1937+21 is $1 \cdot 56$ ms and this pulsar may be used to test our hypothesis.

3. PSR 1937+21: Pulsar Described by Smith's Model

First of all let us emphasise that the equatorial speed of rotation of this pulsar is $0 \cdot 13c$ (for $R_\star = 10$ km), and the light cylinder radius is $7R_\star$. Consequently we must take account of relativistic effects when considering processes in the pulsar magnetosphere. How does this pulsar conform to our scheme? The width of its profile is $W = 100\ \mu$s. Using data for six pulsars with $P < 0 \cdot 15$ s we obtained a value for α of $1 \cdot 012 \pm 0 \cdot 027$. This value is in good agreement with predictions of the Smith model ($W \propto P$). Further, as follows from our scheme, PSR 1937+21 would be expected to have an interpulse; such an interpulse is in fact observed. Finally, polarisation data (Ashworth *et al.* 1983) show small changes of position angle in the main pulse ($\Delta\gamma < 20°$). This fact is also in good agreement with our hypothesis.

Hence, data for PSR 1937+21 do not contradict the hypothesis of two types of pulsars, and this pulsar conforms with Smith's model. We may expect small r.m.s. arrival time residuals because (see equation 3) $\epsilon \ll 1$ everywhere in the magnetosphere of this pulsar (as a consequence of the very small r_{LC} value).

4. Spectra of Pulsars

Another pecularity of PSR 1937+21 is the lack of a low frequency cutoff in its spectrum (up to the frequency 26 MHz) (Sieber and Seiradakis 1984). It is known that an analogous spectrum is observed in PSR 0531+21 (Izvekova *et al.* 1981; Rickett and Seiradakis 1982). If such a cutoff is caused by absorption in the pulsar magnetosphere (Malov 1979), then it must be more prominent in pulsars where the plasma density is higher and levels of generation of emission at different frequencies are more distant. In short periodic pulsars all radiation must be generated near the light cylinder. In this case a low frequency cutoff would be expected to be faint or absent. Therefore, we expect that spectra of PSR 1913+16 ($P = 59$ ms) and PSR 1953+29 ($P = 6$ ms) and all pulsars with $P < 0 \cdot 1$ s would not show a low frequency cutoff. The confirmation of this prediction would provide support for the hypothesis of two types of pulsars.

5. Evidence for Elongation of the Radio Emission Beam in Pulsars

Narayan and Vivekanand (1983) concluded that cross sections of pulsar radio beams are not circular, because if they were we would expect the change of position angle $\Delta\psi$ to lie anywhere between 0° and 180° and the average value $\overline{|\Delta\psi|}$ to be independent of pulse period. However, this prediction contradicts observation. In suggesting elliptical beams of radio emission in pulsars Narayan and Vivekanand determined the ratios of axes R of these ellipsis for pulsars with different periods:

R	P (s)
$4 \cdot 9 \pm 0 \cdot 7$	$< 0 \cdot 388$
$2 \cdot 5 \pm 0 \cdot 5$	$0 \cdot 388 < P < 1 \cdot 2$
$1 \cdot 3 \pm 0 \cdot 3$	$> 1 \cdot 2$

These results are in agreement with our hypothesis. Thus pulsars with long periods must have nearly circular beams, and beams of short-period pulsars must be elongated in the meridional direction. Observations confirm this pattern.

Values of the total change of position angles through an average profile $\Delta\psi$ obtained by Narayan and Vivekanand are different for pulsars with different periods:

$\overline{\Delta\psi}$	P (s)
$45^\circ{\cdot}8$	$<0{\cdot}388$
$78^\circ{\cdot}5$	$0{\cdot}388 < P < 1{\cdot}2$
$105^\circ{\cdot}1$	$>1{\cdot}2$

Using these data we have calculated values of $\overline{\Delta\psi}$ for periods $P > 0{\cdot}7$ and $<0{\cdot}7$ s (cf. Malov and Suleymanova 1982):

$\overline{\Delta\psi}$	P (s)
$46^\circ{\cdot}7$	$< 0{\cdot}7$ $(N = 17)$
$115^\circ{\cdot}4$	$> 0{\cdot}7$ $(N = 13)$

It is worth noticing that Malov and Suleymanova used a more uniform sample, because pulsars were considered with monotonic behaviour of position angles only. Nevertheless, the effect of increasing values of $\Delta\psi$ and $\sigma_{\Delta\psi}$ with lengthening of period is evident in both samples.

6. Division of Pulsars on the Basis of Other Parameters

(a) Ejecting and Accreting Pulsars

On the basis of the minimum near $P \sim 0{\cdot}9$ s in the histogram of $N(P)$ (50 pulsars) Schwarzman (1970) put forward the hypothesis of two types of pulsars: (a) pulsars ejecting particles (objects with short periods) and (b) pulsars accreting gas from the interstellar medium (objects with $P \gtrsim 1$ s). The luminosity of an accreting pulsar depends on the density of the surrounding medium, and we must observe a decrease in pulsar luminosity with the removal of pulsars from the galactic plane. However, observations do not show a correlation (Malov and Suleymanova 1982); mean luminosities of 27 near pulsars ($|z| < 160$ pc) and 63 distant ones ($|z| > 160$ pc) are identical ($\langle \log L_R \rangle \approx 27$). Hence, observed differences of pulsars are not caused by the rate of accretion from the interstellar medium into neutron stars.

(b) Differences of Radio Emission Losses and Types of Pulsars

Malov and Malofeev (1981) noted that there are different efficiencies in the transformation of rotation energy into radio emission in pulsars with short or long periods, on the basis of accurate values of radio luminosities of 40 pulsars. Malov and Suleymanova used this fact as an additional argument in favour of the division of pulsars into two types.

Vladimirskii (1983) divided pulsars into two types on the basis of the parameter $\eta = L_R/\dot{E} \propto P^3 L_R/\dot{P}$, where $\dot{E} = I\Omega\dot{\Omega}$ is the rate of loss of rotation energy by a neutron star. The basis of this division was the minimum at $\eta \approx 5\times10^{-6}$ in the histogram of $N(\eta)$ (for 199 pulsars). However, data for 293 pulsars with known values of $\dot{P}$ (Manchester and Taylor 1981) do not confirm this minimum. A new histogram (see Fig. 4) has one maximum only, just near $\eta = 5\times10^{-6}$. We have analysed

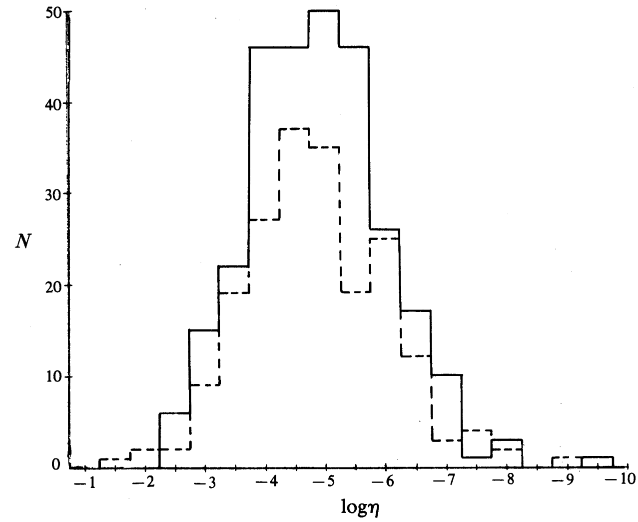

Fig. 4. Histogram of $N(\eta)$ where the solid line shows the present results and the dashed line Vladimirskii's (1983) results.

all correlations considered by Vladimirskii and conclude that the primary parameter of pulsar classification is the period. This is quite clear because $\eta \propto P^3$.

(c) Differences in Structure of Pulsar Magnetospheres

The largest known value of pulsar period (4·3 s) is nearly 3000 times the smallest (1·6 ms) and such a difference characterises the size of pulsar magnetospheres, regions where generation of radio emission occurs. If the pulsar magnetic field is dipole then its relative changes are 10 orders of magnitude in observed pulsars. It is clear that the properties of these objects must be quite different. In particular, the location of regions of plasma instabilities and the consequent generation of coherent radio emission may move away from distances $r \ll r_{\mathrm{LC}}$ (pulsars with $P \gtrsim 1$ s) to the light cylinder (pulsars with small magnetospheres, i.e. short periods).

In the 'current losses' model (Beskin *et al.* 1983, 1984) the observed characteristics of pulsars are determined by the parameter

$$Q = 2P^{1\cdot 1}\dot{P}^{-0\cdot 4}\,. \tag{4}$$

It follows that, although this model differs from known schemes on physical grounds and the predictions, nevertheless all properties of pulsars must depend on the value of the period P, because we have from (4) that Q is approximately proportional to P.

7. Differences in Slowing-down Mechanisms

Peng *et al.* (1982) and Huang *et al.* (1982) have considered two mechanisms of slowing neutron star rotation as a result of losses of angular momentum caused by (i) cyclotron radiation and (ii) magneto-dipole radiation of superfluid neutron vortices. The first mechanism is related to pair emission $(\nu, \bar{\nu})$, the second to dipole radiation of neutron magnetic momentum resulting from the interaction between neutrons and the electromagnetic field by circular motion of neutrons. Both these mechanisms work effectively if $P > P_m$ ($0 \cdot 5 < P_m < 1 \cdot 25$ s) and cause an increase of periods with rates $\dot{P} \propto P^2$. Peng *et al.* (1982) have given the diagram of log $\dot{P}$ versus log P (for 255 pulsars), showing differences in the slowing down of pulsars. If $P < 1$ s, magneto-dipole radiation of neutron stars as a whole plays the main role, and $\dot{P} \propto P^{-1}$. For pulsars with $P > 1$ s, slowing down is caused by the mechanisms of Peng *et al.* (1982) and Huang *et al.* (1982), and $\dot{P} \propto P^2$.

These results allow a division of pulsars into two types on the basis of different mechanisms of slowing down (Huang *et al.* 1983); however, in this case the main parameter of this division is again the pulsar period.

Mnatsakanyan (1979) has suggested that there are two types of pulsars with different initial periods $P_1 \sim 0 \cdot 5$ s and $P_2 \sim 1 \cdot 25$ s). This conclusion is based on the existence of two maximums in the observed histogram of $N(P)$.

Hence, the period P determines a magnetosphere structure and a mechanism of pulsar radiation, as well as processes inside a neutron star determining the rate of its evolution.

8. Conclusions

The results obtained show that new data confirm the hypothesis of two types of pulsar and the main parameter of this division is the pulsar period P. The young pulsar PSR 0531+21 and the very old PSR 1937+21 have many similar properties. They show small changes of the position angle through integrated profiles, and both have interpulses and straight (in logarithmic scales) spectra. Therefore we may conclude that the basic observable characteristics of any pulsar are determined by its period P and do not depend on its history and evolution.

Let us note that the scheme considered describes the observed data only roughly. Probably there are pulsars where two mechanisms of slowing down and two mechanisms of generating radio emission work. In fact, during the evolution of a pulsar with a short period, the size of its magnetosphere increases, additional mechanisms of slowing down are switched on, and these changes must lead to changes in the observed spectra and profiles. Moreover, not all pulsars may possess a dipole magnetic field, and if they do the field may evolve. During an evolution 'relief' of a neutron star, the surface within the polar cap may change also. All these effects of course make the pattern considered more complicated. However, the hypothesis of two types of pulsar helps in our mind to understand the main properties of pulsars and shows new directions for investigations of these objects.

Acknowledgments

I would like to thank the two referees for helpful comments and suggestions for improving this paper.

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Manuscript received 19 March, accepted 19 October 1987