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ELONGATED BEAMS, INTERPULSES AND THE NEW MILLISECOND PULSAR

RAMESH NARAYAN AND V. RADHAKRISHNAN
Raman Research Institute, Bangalore 560 080, India.

ABSTRACT

The prominent interpulse of the new millisecond pulsar is consistent with very short period pulsars having fan-like beams, as suggested earlier by an independent study. It is shown that all the available data on interpulse statistics support this picture, and also indicate that pulsars with perpendicular rotation and magnetic axes are absent at long periods.

A NOTEWORTHY feature of the millisecond pulsar PSR 1937+214 is the strong interpulse. The discoverers of this pulsar[1] have drawn attention to the close similarity of its pulse/interpulse morphology with that of the Crab pulsar. We find this similarity of pulse structure in the two fastest known pulsars most remarkable, and discuss some likely implications in this note.

It is usually assumed that (a) pulsar radiation is emitted in circular beams from the two magnetic poles of a rotating neutron star, (b) the average beamwidth between the 10% intensity points is $\sim 15°$, (c) all orientations of the magnetic axis with respect to the rotation axis are equally likely. This makes the probability of observing an interpulse less than 1 in 20. The chance of the two fastest pulsars both having interpulses is then less than 1 in 400. Further, since both pulsars have *strong* interpulses, we may reasonably assume that both the main and interpulse arise from regions close to the magnetic pole, say within the 50% intensity contour of the beam. This corresponds to a beam diameter of $\lesssim 10°$ and reduces the probability to less than 1 in 1200. Clearly this is either an extraordinary coincidence, or the above picture needs to be revised.

One possible explanation suggested by the case of the Crab pulsar is that short period pulsars always have their magnetic axes nearly orthogonal to the rotation axis. All such pulsars which are detected would then automatically have strong interpulses. This hypothesis would be consistent with the correlation noted earlier[2], that interpulses occur predominantly in short period pulsars. This is shown by table 1 where all the 8 known interpulse pulsars are seen to have much shorter periods P than the median period of observed pulsars which is ~ 0.7 s. As noted by Manchester and Taylor[2], the total absence of interpulses for $P > 0.6$ s (table 2) then requires that the magnetic axis should gradually align with the rotation axis as the pulsar ages. However, we note that of the

TABLE 1

Pulsars with interpulses. τ is the characteristic age $P/2\dot{P}$, B is the derived magnetic field, $B=(10^{39} P\dot{P})^{\frac{1}{2}}$ gauss, and S_{MP} and S_{IP} are the radio fluxes in the main pulse and interpulse at ~400 MHz

Pulsar	P(ms)	$\log_{10} \tau$ (y)	$\log_{10}$ B(gauss)	$r=S_{IP}/S_{MP}$	IP-MP Separation
1937+214	1.58	>7.40	<9.10	0.5	180°
0531+21	33	3.09	12.58	0.36	145°
0833−45	89	4.05	12.53	~1*	90° (opt.) 180° (γ)
1055−52	197	5.73	12.03	0.85	155°
1929+10	227	6.49	11.71	0.02	174°
0950+08	253	7.24	11.39	0.018	155°
1944+17	441	8.46	11.02	<0.01⁺	not known
0823+26	531	6.69	11.98	0.005	180°

* At optical and γ-ray frequencies; there is no radio interpulse in this pulsar.
⁺ Actual value not known, but presumed to be very small since the interpulse was detected only recently[13].

30 known pulsars with an upper limit for their true age ($P/2\dot{P}$) of less than 5×10^5y, 28 have no interpulses. If all these pulsars had been born with perpendicular magnetic fields, their magnetic axes must have rotated by an angle of the order of the beamwidth in a much shorter time than 5×10^5y, which itself is an order of magnitude less than the average age of pulsars. The fact that numerous "old" pulsars are observed would then imply that such movement of the magnetic axis must slow down or stop before total alignment is reached.

On the other hand, there is some evidence based on the analysis of polarisation patterns[3], which suggests that short period pulsars in general have a mild tendency to be *aligned*, contrary to the above hypothesis. Further, in the case of PSR 0950+08 which has a short period of 0.253 s, there is strong evidence that the magnetic and rotation axes are nearly aligned[4]. In this context, an important new piece of evidence is that PSR 1937+214 is itself not a "young" pulsar in spite of its very short period. Recent measurements (Backer, private communication) have shown that $\dot{P} < 10^{-18}$ ss^{-1} for this pulsar. Its characteristic age $P/2\dot{P}$ is thus $\gtrsim 2.5\times10^7$y, which would be an upper limit to its true age if it had had a conventional history. On the other hand, if it is a recycled pulsar as has been argued by Radhakrishnan and Srinivasan[5], its true age should be $> 10^7$y[5,6]. Similar arguments have also been advanced by others[7], leading to an even higher age estimate. In either case, we should not be seeing an interpulse in PSR 1937+214, if the field alignment depends only on the time since birth. The same objection also applies to a few other pulsars in table 1 which are seen to have fairly large characteristic ages.

The high rate of interpulse occurrence in short period pulsars and the fall off with increasing period find a natural explanation, without requiring any special initial configuration of the magnetic field, in the recent work of Narayan and Vivekanand[8]. Interpreting the observed total change in position angle of the linear polarisation of a number of pulsars in terms of the magnetic pole model[9], they show that pulsar beams are not of circular cross-section as has usually been assumed so far. They find the beams to be elongated, and further, that the elongation varies as a function of period. Narayan and Vivekanand[8] estimate from the polarisation data that

$$R \sim 1.8\ P^{-0.65} \qquad (1)$$

where R is the ratio of the North-South to East-West beam diameters (directions being defined with respect to the rotation axis, as on Earth). They also find that the beam elongation is rather insensitive to the strength of the magnetic field, with perhaps a weak tendency for higher elongations to occur at lower fields.

If eqn. (1) is combined with an average EW beam diameter of $\sim 15°$ as deduced from pulse widths, it would predict a NS diameter of the order of 180° for $P \sim 0.05$ s. Of course, the equation must break down at small P, and there are uncertainties in the coefficient and exponent in eqn. (1). However, it is still clear that for very fast pulsars, such as the Crab and the new millisecond pulsar, one expects an interpulse, regardless of the field and viewing geometry. Another consequence is that the beaming fraction f, which is conventionally taken to be 0.2, should tend to 1 for such very short period pulsars.

TABLE 2

Interpulse statistics in selected ranges of pulsar period

	P<0.1s	0.1s<P<0.3s	0.3s<P<0.6s	0.6s<P
Total number of pulsars observed	4	39	101	187
Number of interpulse pulsars	2.5*	3	2	0
Average value of r	0.5	0.3	0.01	—
Expected number of IP pulsars for $\alpha_{max}=90°$	3.5	10	16	13
Expected number of IP pulsars for $\alpha_{max}=75°$	3.0	3.3	1.8	0.02

* We count the Vela PSR 0833–45 as ½ since it does not have an interpulse in the radio but only at optical and γ-ray frequencies.

Even at slightly longer values of P than say 0.05 s, one expects a high interpulse probability. Of the two other known pulsars with $P < 0.1$ s, PSR 0833-45 has interpulses as observed at gamma-ray and optical frequencies although only a single pulse is seen in the radio[2]. The inclusion of this pulsar could be questioned since our discussion is confined to radio pulses, whose relationship with higher frequency pulses and interpulses is not really understood. Even so, we have included this pulsar in table 2, with a weight of one-half, because the close agreement between the radio, optical and gamma-ray profiles of the Crab pulsar[2] suggests an intimate connection.

The binary pulsar PSR 1913+16 has a shorter period than Vela, but no interpulse. In this case, however, a possible explanation can be advanced. There are good reasons for believing that in close binary systems such as this one, the spin axes of the stars are likely to be perpendicular to the orbital plane. As it is known that the latter makes an angle of 47° with the plane of the sky[10], we expect the rotation axis of the pulsar to make an angle of ~45° with the line of sight. In this case, whatever be the orientation of the magnetic axis, any "interpulse" would correspond to the line of sight being offset by at least 45° from its magnetic pole. Since the binary pulsar is of greater than average luminosity[2], we may further argue that the line of sight passes near the magnetic pole responsible for the main pulse. The offset at the "interpulse" will then be approximately 90°. It is possible that we are missing the interpulse as a result of this maximally unfavourable geometry.

Going to longer periods, eqn. (1) says that the interpulse probability should drop rapidly with increasing P. This is in qualitative agreement with the overall results of table 2, though there are quantitative disagreements as we discuss below. We also find that the interpulse pulsars have fairly average magnetic fields, with a slight preponderence of low fields. This is again consistent with the marginal anticorrelation of beam elongation with field strength noted by Narayan and Vivekanand[8] on the basis of polarisation swings. The interpulse data appear therefore to confirm the picture of pulsar beams with period dependent elongation[8], with the interpulse in the new millisecond pulsar[1] forming the latest piece of supporting evidence.

We shall now look more closely at the period dependence of interpulse occurrence. Assuming at first that all orientations of the magnetic axis with respect to the rotation axis are equally likely, and that eqn. (1) represents the dependence of beam elongation on pulsar period, we can predict the number of interpulses to be expected in various period ranges. These are given in the fourth row of table 2, and there is clearly a large discrepancy with the observed numbers, particularly at long periods. This is not just a consequence of our assumption of beam elongation. Even assuming perfectly circular beams, we would still expect as many as 8 pulsars with $P > 0.6$ s to have interpulses. In fact, to explain the total absence of interpulses from 187 pulsars in this period range, we will need to "flatten" the NS size of the beams down to less than 2°, compared to the observed EW size of ~15°. We reject this as unlikely as it would imply a very small beaming fraction $f < 0.03$ for pulsars with periods > 0.6 s. The assumption of random orientation must be incorrect.

We find therefore, at least at long periods, that pulsars with perpendicular rotation and magnetic axes are not observed. In other words, if α is the angle between these axes, there appears to be a cut-off in α above some value which is significantly less than 90° As a purely geometrical question, we can ask what value of α_{max} is needed to explain the absence of interpulses in long period pulsars. Table 2 shows that for $\alpha_{max} = 75°$, very satisfactory agreement is obtained with the observed interpulse occurrence rates in all the period ranges.

We consider now the implications for the distribution with period of r, the ratio of interpulse to main pulse flux. We assume symmetry between the two magnetic poles, which leads to main and interpulses of equal strength in the following cases:

a) the magnetic axis is perpendicular to the rotation axis ($\alpha = 90°$) and/or
b) the line of sight to the observer is perpendicular to the rotation axis

As we move away from these symmetric situations, the ratio *r* falls below unity resulting ultimately in the total absence of detectable interpulses. It is not hard to visualise that the smaller NS beams of long period pulsars imply a more rapid fall to zero of the ratio *r*, as we depart from the symmetric configuration. Restricting α_{max} to a value less than 90° should then lead to a reduction of the average value of *r* with increasing period range. Just such an observed reduction is seen in tables 1 and 2 and adds further support for the validity of our assumption that $\alpha_{max} \sim 75°$.

The absence of long period pulsars with $\alpha \gtrsim 75°$ which we have just deduced from the observations could imply, for example, that neutron stars are not created with $\alpha \gtrsim 75°$. However, for the short period pulsars PSR 0531+21 and PSR 0823+26, the estimates of α of 86° and 82° respectively[4], seem to contradict this. Thus, either α decreases with increasing P, or these neutron stars must turn off at relatively short periods. It has been argued by Flowers and Ruderman[11] that α in fact *increases* with time, and hence P. It would appear therefore that pulsars with near-perpendicular fields must die young, well before their period reaches 1 s. We suggest that this is due to a cut-off in particle production or acceleration. We note that this could be reasonable in pulsar models such as that of Ruderman and Sutherland[12] which require one particular sense of field alignment with respect to the rotation axis.

In conclusion, the interpulse of the new millisecond pulsar provides supporting evidence that short period pulsars have highly elongated beams, and hence a higher probability for interpulses. A measurement and analysis of the polarisation swings in the main pulse and interpulse of the new pulsar will be of great value in testing our conclusions. We expect such measurements to indicate a large offset of the line of sight from the magnetic poles, as is already suggested by the observed high degree of average linear polarisation[1].

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Note added in Proof: We have recently received a preprint by M. Ashworth, A. G. Lyne and F. G. Smith (kindly sent by A.G. Lyne) describing polarisation observations on PSR 1937+214 which show a total sweep range of the position angle of less than 10° and 20° in the main pulse and interpulse respectively These values are consistent with our expectation that the line of sight in the pulsar is offset by large angles from the magnetic poles.

It has also been drawn to our attention that PSR 1822–09. which has a well-established interpulse (Cady and Ritchings, *Nature (London)*, **269**, 126, 1977; Fowler, Wright and Morris, *Astron. Astrophys.*, **93**, 54, 1981), is not included in our list. We regret this unfortunate oversight.