Chin. J. Astron. Astrophys. Vol. 6 (2006), **Suppl. 2**, 18–23
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Polarised Views of the Drifting Subpulse Phenomenon

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Abstract I review recent results concerning the shape of drifting subpulse patterns, and the relationship to model predictions. While a variety of theoretical models exist for drifting subpulses, observers typically think in terms of a spatio-temporal model of circulating beamlets. Assuming the model is correct, geometric parameters have been inferred and animated "maps" of the beam have been made. However, the model makes very specific predictions about the curvature of the drift bands that have remained largely untested. Work so far in this area indicates that drift bands tend not to follow the prediction, and in some cases discontinuities are seen that are suggestive of the superposition of out of phase drift patterns. Recent polarimetric observations also show that the drift patterns in the two orthogonal polarisation modes are offset in phase. In one case the pattern in one of the modes shows a discontinuity suggesting no less than three superposed, out-of-phase drift patterns! I advise caution in the interpretation of observational data in the context of overly simplistic models.

Key words: pulsars: general

1 THE CAROUSEL MODEL

Although the drifting subpulses phenomenon has now been approached from a number of different theoretical perspectives (e.g. Zheleznyakov 1971; Kazbegi et al. 1991; Wright 2003; Clemens & Rosen 2004; Young 2004; Gogoberidze et al. 2005; Fung et al. 2006), most observational studies have assumed the applicability of the so-called carousel model (Ruderman 1972). This model postulates that the modulations have a spatio-temporal origin: the subpulse structure is due to the passing of the line of sight over multiple "beamlets", while the temporal, pulse-to-pulse modulation is due to the slow circulation of the beamlet system (Figure 1(a)). In the usual physical model, the beamlets consist of radiation beamed tangentially to local magnetic field lines, within "tubes" of plasma, each flowing outward from a localised breakdown ("spark") of a potential gap over the magnetic pole (Ruderman 1972). The circulation of the sparks is attributed to $\boldsymbol{E} \times \boldsymbol{B}$ drift.

Edwards & Stappers (2002) showed that the carousel model makes very specific predictions regarding the shape of drift bands. Specifically, assuming that the beamlets are uniformly spaced in magnetic azimuth, the variation of subpulse phase with pulse longitude obeys a geometric relationship. This is because it is linearly tied via the number of beamlets (N) to the magnetic azimuth of the observer (ψ), which in turn obeys the following relation:

$$\tan\psi = \frac{\sin\phi\sin\zeta}{\cos\zeta\sin\alpha - \cos\phi\sin\zeta\cos\alpha}, \tag{1}$$

where ϕ is pulse longitude, ζ is the angle between the spin axis and the line of sight, and α is the angle between the magnetic and spin axes (see Figure 1(b)). The reader may recognise the similarity between this relation and the common "rotating vector model" for the position angle of linear polarisation, χ. The reason for this similarity is that all of the pertinent angles are related according to the spherical triangle of

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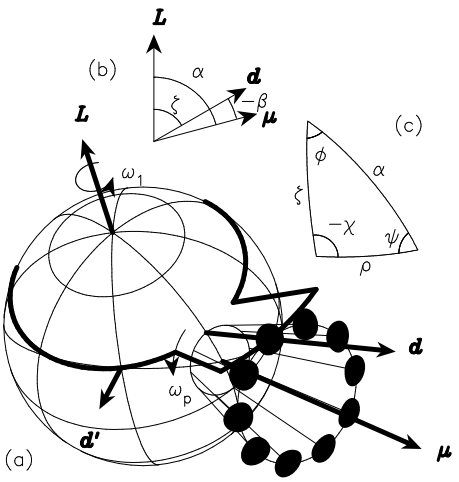

Fig. 1 Diagram of sub-pulse emission geometry, reproduced from Edwards & Stappers (2002). In part (a) the angular momentum, magnetic moment, and line-of-sight vectors are shown with symbols $\boldsymbol{L}$, $\boldsymbol{\mu}$, and $\boldsymbol{d}$ respectively. Part (b) shows the main vectors as they appear in the plane they share when the sight-line makes its closest approach to the magnetic pole. The angles ζ (between the sight-line and the spin axis), α (between the magnetic and spin axes) and $\beta \equiv \zeta - \alpha$ (between the sight-line and the magnetic axis at their closest approach) are shown. In part (a) a second line of sight ($\boldsymbol{d}'$) is drawn, along with the meridian it shares with with the magnetic pole. The spherical triangle formed by $\boldsymbol{L}$, $\boldsymbol{\mu}$ and $\boldsymbol{d}'$ is duplicated in part (c).

Figure 1(c). The subpulse phase, θ, is linearly related to magnetic azimuth, plus a generally small additional term describing the circulation of the carousel over the course of the pulse:

$$\theta(\phi) \;=\; -N\mathrm{sgn}\,\beta\tan^{-1}\left[\frac{\sin\phi\sin\zeta}{\cos\zeta\sin\alpha-\cos\phi\sin\zeta\cos\alpha}\right]+\phi\left(n+\frac{P_1}{\hat{P}_3}\right)+\theta'. \qquad (2)$$

Here θ' is an arbitrary constant, P_1 is the pulse period, $\hat{P}_3$ is the observed pulse-to-pulse periodicity of the drift bands (including a sign which specifies the direction of the drift slope), and n is an integer specifying the order of aliasing present.

It is important to note that by examining the dependence of modulation phase upon pulse longitude, this method tracks the drift band peaks according to local maxima along lines of constant longitude. This is in contrast to the more common technique of finding local maxima in individual pulses (i.e. lines of constant pulse number). The former method offers an important advantage: the amplitude-phase decomposition conveniently separates beamlet azimuthal spacing (i.e. circulation or subpulse phase) from colatitudinal amplitude windowing (i.e. subpulse amplitude and mean profile shape). In the latter method, subpulse peaks are "pushed" in pulse longitude, in the direction of increasing subpulse amplitude, and therefore do not cleanly track the azimuthal spacing of beamlets (see Edwards & Stappers 2002; Edwards & Stappers 2003).

2 WHY TEST THE CAROUSEL MODEL?

While the carousel model has been in use for over two decades in the interpretation of drifting subpulse patterns, until recently very little use had been made of the opportunity presented to test the model (however, see Wright 1981). Many examples exist of inferences being made on the basis of the correctness of the model, without any checks being made of the validity of this assumption. For brevity I will focus upon a critical look at one particularly interesting series of studies, namely the industry of "polar cap mapping" of systems of drifting subpulses (Deshpande & Rankin 1999; Deshpande & Rankin 2001; Asgekar & Deshpande 2001; Rankin et al. 2003; Asgekar & Deshpande 2005).

Deshpande & Rankin (1999) (hereafter DR99) detected, for the first time, a pair of "outrider" components surrounding the first harmonic of the drifting subpulse pattern in the fluctuation spectrum of PSR

B0943+10. While relatively marginal in terms of signal to noise ratio, and only detected in a small section of one of several observations, the detection was nevertheless exciting since it was potentially supporting evidence for the carousel model. This is because under that model, any overall overall pattern of intensity around the ring of beamlets would result in the convolution of all Fourier components with the Fourier transform of the azimuthal intensity dependence (Edwards & Stappers 2002). For an intensity pattern consisting of a strong steady component plus a weak variation $\propto \sin(\psi - \psi_0)$, this adds a small pair of components spaced $1/\hat{P}_3$ from the parent component. Although no such "outriders" appear around the DC component, DR99 pursued the possibility that this was the explanation for the extra components around the first harmonic.

Having assumed the applicability of the carousel model, DR99 set out to establish the values of all geometric parameters necessary to invert the transformation between the magnetic frame and the observer's frame, in order to "map" the observed intensity onto an animated display of the beam intensity distribution (or, equivalently, the polar cap excitation distribution). The first hurdle in this process is the unknown aliasing order, n. The traditional method of fluctuation spectrum analysis, the longitude-resolved fluctuation (LRFS), is insensitive to the sign or direction of drift, thereby doubling the number of aliasing possibilities in Equation 2. DR99 used a new technique called the harmonic-resolved fluctuation spectrum, later shown to be equivalent to the two-dimensional fourier transform of the longitude-time dependence of intensity(Edwards & Stappers 2002; Edwards et al. 2003). Having eliminated the aliasing possibilities previously admitted by the LRFS, DR99 apparently considered the aliasing question solved. However, even using the improved frequency measurements of Deshpande & Rankin (2001), an infinite range of possible values of n remain (Edwards & Stappers 2002).

To obtain the other geometric parameters, Deshpande & Rankin (2001) turned to polarimetric observations. Although the rotating vector model has been shown to hold in only a minority of pulsars (Everett & Weisberg 2001), and B0943+10 exhibits a featureless linear sweep of position angle giving no clear evidence for applicability of the model, it was taken by Deshpande & Rankin (2001) to apply. The values derived were reported to support the chosen aliasing solution, although as noted above other solutions are possible and only by combining the spectral results and with polarimetry can a unique solution be obtained (Edwards & Stappers 2002).

Having obtained nominal values for all relevant geometrical parameters, Deshpande & Rankin (2001) proceeded to form an animated map of the emission beam, a product which, if reliable, offers remarkable insights into conditions on the polar cap and/or in the magnetosphere. However, in my view this result is far from water tight. It relies on the reality of certain spectral features of marginal significance, the applicability of the rotating vector model for polarisation, and the applicability of the geometric predictions of the carousel model for drifting subpulses. Of the latter two conditions, the first has been proven to be generally false, and the second was until recently almost entirely untested. This was seen a sufficient motivation to rigorously test the geometrical predictions of the model.

As I will outline below, the carousel model in its basic form has now been shown to be generally inapplicable. It is therefore advisable to approach any inferences made from pulsar data on this basis, including polar cap maps, with caution.

3 TESTING THE CAROUSEL MODEL

For reasons outlined in the preceding sections, a study was conducted of the subpulse phase variation in several pulsars. The first pulsar to be examined was PSR B0320+39, at a frequency of 328 MHz (Edwards et al. 2003). Surprisingly, the subpulse phase was shown to exhibit a phase "jump" of roughly 180°, near the centre of the profile (Figure 2). Such a feature cannot be reconciled with the predictions of the carousel model in its simplest form. Several features of the drift bands are suggestive of an origin in superposed, out-of-phase patterns:

- the rapid 180° phase jump,
- the vanishing subpulse amplitude at this point,
- the continuity of the absolute value of the rate of change of subpulse amplitude at this point, and
- the continuity of, and indeed, absence of any feature whatsoever in the total intensity profile at this point.

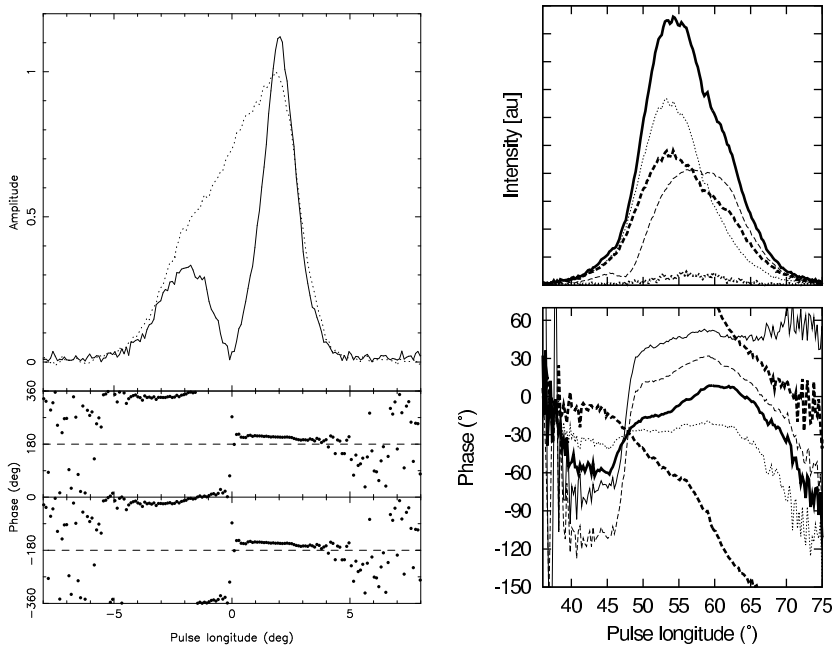

Fig. 2 Subpulse phase jumps. (Left) Pulse profile (dotted line), subpulse amplitude (solid line) and phase (points, plotted twice with linear slope subtracted) for PSR B0320+39 at 328 MHz. (Right) Pulse profile (thick solid line), subpulse amplitudes and phases for orthogonal polarisation modes (thin dotted and dashed lines, slope subtracted), for PSR B0809+74 at 328 MHz (see Edwards 2004 for full description).

Such features are familiar from other cases of superposed wave phenomena, for example in the presence of superposed orthogonal polarisation modes of shifting dominance.

Two possibilities were discussed by Edwards et al. (2003) for the origin of the putative "double images" of the drifting subpulse pattern, both invoking an underlying circulating carousel system. The first suggests that the two images originate from either side of the magnetic pole, with that from the far side reaching the observer by virtue of magnetospheric refraction. For an odd number of beamlets and an axisymmetric plasma distribution, the images will be in antiphase. The second follows the suggestion of Rankin (1993) that emission occurs at two discrete heights in the magnetosphere. The divergence of field lines results in nested cones of emission, while aberration and retardation shift their centres somewhat. However, the difference in emission height needed for sufficiently offset cones in this case is in excess of 10 000 km, which is strongly incompatible with other estimates of pulsar emission heights (e.g. Dyks et al. 2004).

The detection of the phase jump in PSR B0320+39 also led to the development of a completely new model for drifting subpulses. Clemens & Rosen (2004) suggested that drifting subpulses are a manifestation of non-radial oscillations of high wavenumber. In this model, the phase jump and amplitude nulling are neatly explained as corresponding to the passage of the line of sight over a nodal point in the oscillation. However, as a temporal oscillation, the subpulse phase should be a strictly linear function of pulse longitude, which is incompatible with minor but definite deviations from linearity detected by Edwards et al. (2003). Although amplitude windowing of the subpulses may produce apparently curved drift bands (Clemens & Rosen 2004), as noted in Section 1, the prime advantage of using subpulse phase to test models of drifting subpulses is that it is in fact unaffected by such windowing.

Further studies revealed more complex deviations for the simple model predictions. Edwards & Stappers (2003) found that at 1380 MHz, PSR B0320+39 showed subpulses that were much weaker, with a phase slope that contained strange deviations from linearity and only weak evidence for a phase jump. Furthermore, observations of PSR B0809+74 revealed unexplained deviations from the model curve at

328 MHz, which evolved to include a rapid phase jump of some $\sim 120^\circ$at 1380 MHz, accompanied by an attenuation of amplitude. Analogous to similar polarimetric behaviour attributed to non-orthogonal polarisation modes, the latter was interpreted as suggestive of the superposition of subpulse patterns that were not in pure antiphase, and potentially were not offset in phase by a constant amount across whole the pulse longitude range. Edwards & Stappers (2003) suggested that such circumstances could also explain the curious bidirectional subpulse drift seen in PSR B1918+19, in much the same way that polarisation position angle sweeps can undergo erratic jumps and sense changes in the presence of non-orthogonal radiation. Since then, further examples of phase steps (Weltevrede et al. 2006) and bidirectional drift (Champion et al. 2005; Weltevrede et al. 2006) have been found.

Observations made over thirty years ago have shown that the polarisation at a given pulse longitude is periodically modulated between two orthogonal states, for at least two pulsars (Manchester et al. 1975). Following a high resolution study of PSR B0809+74 by Ramachandran et al. (2002), it was suggested that this effect could be explained via the superposition of out-of-phase subpulse patterns in the two orthogonal modes (Edwards et al. 2003; Rankin & Ramachandran 2003). By decomposing the signal into its component orthogonal modes, Edwards (2004) showed that this was indeed the case in observations made at 328 MHz. Moreover, one of the modes showed a sharp phase jump accompanied by a reduction in subpulse amplitude (Figure 2), very similar to the feature seen in total intensity at 1380 MHz. The other mode showed no feature at all in this region, supporting the physical validity of the orthogonal mode decomposition. The implications of this result are startling: if the orthogonal modes are out of phase due to superposition then there are at least two images, but if the phase jump in one of the modes is also due to out-of-phase superposition, then there must be at least three distinct, out of phase "images" of the subpulse pattern, with polarisation effects somehow tied in to the multiple imaging process.

Single pulse polarimetry of PSR B0809+74 at 1380 MHz, and observations of two other pulsars at lower frequencies revealed significantly more complex behaviour. In these observations, the polarisation vector (composed of Stokes Q, U and V) was found to move along a periodic locus at the frequency of the subpulse modulation, however the first harmonic of this locus was elliptical, rather than linear as expected under the superposition of orthogonal polarisation modes.

4 SUMMARY AND CONCLUSIONS

Subpulse phase analysis presents a sensitive means for testing strong geometric predictions made by the standard carousel model for drifting subpulses. Testing this model is important because a variety of inferences have been made from observational results under the assumption that the model applies. In particular, procedure of "mapping" the polar cap of PSR B0943+10 relies heavily on this model, as well as assuming, despite the odds, that the geometric model for polarisation applies to this pulsar. A number of studies of subpulse phase have now been conducted, with results that strongly disagree with the standard model. Several features of the observed phase slopes are suggestive of the superposition of out of phase "images" of subpulse patterns. A polarimetric study of PSR B0809+74 indicates that out of phase, orthogonally polarised subpulse patterns are observed in superposition, and that these patterns themselves can consist of the superposition of two or more out of phase components. At other frequencies, complex, non-orthogonal periodic modulations of the polarisation were seen, with unknown origin.

In light of the strong deviations from the standard model observed in all cases so far, I suggest caution be exercised in the interpretation of observational results that assume its validity.

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