Abrupt changes in pulsar pulse profile through multiple magnetospheric state switching

R Yue\textsuperscript{1,2,3} and D B Melrose\textsuperscript{3}
\textsuperscript{1}Xinjiang Astronomical Observatory, Chinese Academy of Sciences, 150 Science 1-Street, Urumqi, Xinjiang, 830011, China
\textsuperscript{2}Key Laboratory of Radio Astronomy, Chinese Academy of Sciences, Urumqi, Xinjiang, 830011, China
\textsuperscript{3}SIfA, School of Physics, University of Sydney, Sydney, NSW 2006, Australia
E-mail: ryuen@xao.ac.cn, donald.melrose@sydney.edu.au

Abstract. A purely magnetospheric model is introduced for observed abrupt changes in pulsar radio profile. Motion of magnetospheric plasma is described by a drift frequency, $\omega_{\text{dr}}$, that depends on a parameter $0 \leq y \leq 1$, and a change in the magnetospheric state corresponds to a change in $y$. Emission is assumed to arise from $m$ spots distributed uniformly around the magnetic axis, so that spots drift by at the rate $m\omega_{\text{dr}}$. Observable features, such as subpulses, appear to rotate as $\omega_R = m\omega_{\text{dr}} - \omega_V$. The motion of the visible point, $\omega_V$, is ignored in a “standard” version of the viewing geometry that assumes a fixed line of sight (rather than a fixed line-of-sight direction), implying $\omega_V = 0$. With $\omega_V \neq 0$, the apparent motion of subpulses is not constant. An abrupt (or more gradual) change in $y$ implies a change in $\omega_R$, which affects the observed pulse structure and the average profile. We apply the model for profile shifts observed with PSR B0919+06.

1. Introduction
Discernible drifting subpulses was detected from more than 50\% of the radio pulsars sampled [1] implying difference in the rotation frequency of the subpulses, $\omega_R$, from that of the star, $\omega_*$. Abrupt changes in the drift pattern was observed from some pulsars [2], which implies that $\omega_R$ can change abruptly and then return to its initial value. Furthermore, instantaneous switches between different subpulse drift rates are also known to correlate with changes in the average pulse profile [3–6], implying that a change in $\omega_R$ may be responsible for a change in the pulse profile (we omit ‘average’ hereafter where no confusion is resulted). Changes are not necessarily abrupt as evident from the nulling PSR B0809+74 whose drift rate recovers to its normal value over tens of pulse periods after a null [7]. Another example is the “swooshing” in PSR B0919+06 [8,9], which shows quasi-periodic shifts in the pulse profile that also last for tens of periods [10].

An implication of $\omega_R \neq \omega_*$ is that the magnetospheric plasma does not corotate with the star, and the correlated changes in $\omega_R$ and the emission characteristics imply that the configuration of the magnetosphere changes when $\omega_R$ changes which affects the radio emission. The suggested interpretation of the abrupt changes of emission mode in PSR B1931+24 [11] involves switching between two limiting magnetospheric states, with one corresponding to the state of charge starvation in which screening of the vacuum electric field is inefficient due to insufficient plasma (and slowing down is due to magnetic dipole radiation as there is no wind), and the other to
the corotation or a “force-free” state [12, 13]. Switching of magnetospheric states then leads to changes to the global current, and the associated spin-down torque on the star, and this evidently also affects the pulse profile. The two limits are unrealistic for a real pulsar magnetosphere, and the switches must be between magnetospheric states intermediate between these limiting states. In this paper, we present and explore a model for \( \omega_R \) in a magnetosphere of multiple magnetospheric states as an alternative for interpreting the observed profile changes.

2. Apparent subpulse drift

We outline the three ingredients in our model for \( \omega_R \):

**Plasma flow (\( \omega_{dr} \)):** We identify a variable drift frequency, \( \omega_{dr} \), of the magnetospheric plasma in the source region for the radio emission as given by the electric drift, \( \mathbf{E} \times \mathbf{B}/B^2 \). In non-corotating magnetosphere, it has the form \( \omega_{dr} = y\omega_{\text{ind}} + (1 - y)\omega_{\text{cor}} \), with values intermediate between drift due, respectively, to the inductive (ind) electric field for a rotating dipole in vacuo and the electric fields corresponding to (oblique) corotation (cor) [14]. In addition to depending on the viewing angle, \( \zeta \), between the rotation axis of the pulsar and the line of sight, the obliquity angle, \( \alpha \), between the rotation and the magnetic axes, and the pulsar phase, \( \psi = \omega_t t \), the drift frequency also depends on \( y \) and a change in magnetospheric state corresponds to a change in \( y \).

**Emission structure (\( m \)):** A purely magnetospheric structure \( \propto \cos(m\phi_b) \) is assumed, where \( m \) is an integer and \( \phi_b \) is azimuthal angle around the magnetic pole. The structure may arise from an instability in the magnetosphere such as diocotron instability [15, 16]. Subpulses are then identified as emission spots (regions of emission) from a periodic wave-like disturbance with a specific spherical harmonic, given by \( l \) and \( m \), being favored implying \( m \) nodes (underdense) and antinodes (overdense) as a function of \( \phi_b \). The observer would then see individual emission spots drifting by at the rate \( m\omega_{dr} \).

**Motion of the visible point (\( \omega_V \)):** For radiation from near the stellar surface where field-line distortions may be ignored, pulsar visibility requires that visible radiation be emitted tangent to the magnetic field line at the source point and must be in the direction of the line of sight [17]. An implicit assumption in the “standard viewing geometry” is that the line of sight is a fixed line through the center of the star. In the exact geometry, the line of sight is treated as a fixed direction and not a fixed line, and this tangent line (in the line-of-sight direction) changes continuously as the pulsar rotates tracing out the trajectory of the visible point. The visible point moves along the trajectory with an angular frequency, denoted by \( \omega_V \), where it sub-rotates at some phases and super-rotates at other phases.

The implications of \( \omega_V \neq 0 \) on the trajectory through an open region is shown in figure 1 for the exact model as compared with the standard model in which the motion of the visible point is ignored. The two versions coincide only at one point (\( \psi = 0^\circ \)), and deviate as \( |\psi| \) increases. An equal time interval is indicated as separation of any two consecutive dots, and it is clear that the traversal time through the open region, assumed at \( 0.1r_L \), where \( r_L \) is the light-cylinder radius, is also different in the two versions. The difference is a result of a relative motion between the visible point and the pulsar rotation, both moving in the same direction, as opposed to the standard version in which such motion is absent due to the line of sight being assumed fixed. The result is that more dots are predicted in the exact version implying that the trajectory traverses the region over a longer duration, and enters and leaves the region at earlier and later \( \psi \), respectively, than that implied in the standard version.

Combining the above three ingredients to drifting subpulses in dipolar magnetic field structure, the observer sees emission spots flowing past at angular speed, \( \omega_R \), given by

\[
\omega_R(y;\psi) = m\omega_{dr}(\theta_V, \phi_V; y) - \omega_V(\zeta, \alpha; \psi),
\]

(1)

where the dependence on \( y \) and \( \psi \) are indicated, and \( \theta_V \) and \( \phi_V \) represent coordinates of the
trajectory of the visible point [17]. In the remainder of this paper, we (arbitrarily) fix \( m = 20 \) [18, 19].

3. Effects on pulse profiles

We consider observable changes in pulse profiles as implied by the model described in the previous section, and show how these can be related to \( y \). We assume a pulse profile composed of several different Gaussian components formed from radiation of their respective emission spots within the profile. Fig. 2 illustrates the effect of state switching on observed profiles initially placed at \( \psi = 0^\circ, \pm 25^\circ, \) and \( \pm 50^\circ \) (red) all with unit amplitude and width of two units for \( y = 0 \) and \( \omega_V = 0 \). When variation of \( \omega_V \) is included, \( \omega_R/\omega_* \) depends on phase \( \psi \) and the visible point crosses emission spots at a non-uniform rate. The effect is that the profiles appear to be displaced from their original locations, as shown in black, with the displacement increasing as \(|\psi|\) increases with symmetry about \( \psi = 0^\circ \). As \( m\omega_{dt} \) approaches \( \omega_V \), the visible point takes longer time to pass an emission spot giving the illusion of a broader profile. The broadening for profiles in black relative to that of the corresponding profiles in red at 10% amplitude in the order of increasing \(|\psi|\) are 27%, 32% and 54%, respectively, as shown in Fig. 2.

In our model, a change in the magnetospheric state corresponds to a change in \( y \) and manifests as a change in \( \omega_R \). Fig. 3 shows a pulse profile with its peak initially placed at \( \psi = -10^\circ \) (black) for \( y = 0 \). As \( y \) increases, \( \omega_R/\omega_* \) decreases implying that the visible point meets the emission spot at an earlier phase and traverses it in a longer elapsed time as measured by an observer. The profile peak then shifts to increasingly negative \( \psi \) at \(-11.0^\circ \) for \( y = 0.3 \) (dot-dashed), \(-12.2^\circ \) for \( y = 0.6 \) (gray) and \(-14.0^\circ \) for \( y = 0.9 \) (dashed), with broadened width of 1.1 \((y = 0.3)\), 1.2 \((y = 0.6)\) and 1.4 \((y = 0.9)\) times the original at 10% amplitude. Hence, the peak longitudinal phase and width of the observed profile changes as a result of a change in \( y \), with the variations being functions of \( y \).

Table 1. Values for the amplitude (\( A \), normalized at the peak of the profile), width (\( \sigma \)) and peak phase of the emission components for simulating the ‘stable’ profiles of PSR B0919+06 at 1425 MHz.

| Comp. | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|-------|-----|-----|-----|-----|-----|-----|-----|
| \( A \) | 0.12 | 0.09 | 0.09 | 0.28 | 0.46 | 0.16 | 0.19 |
| \( \sigma \) | 3.70 | 0.60 | 0.33 | 2.40 | 0.87 | 2.01 | 1.51 |
| \( -\psi^\circ \) | 17.5 | 15.4 | 14.6 | 14.4 | 13.2 | 12.8 | 11.1 |

The observations of PSR B0919+06 reveal shifting of the profile peak toward earlier phases where it remains for tens of pulsar periods before returning to its usual location [8]. During the event, known as swooshing, the profile peak shifts by \sim -5^\circ \) together with an increase in the profile width. Assuming \( \zeta = 58.1^\circ, \alpha = 53^\circ \) and a profile width of \( 20^\circ \) [8], we estimate seven emission spots (see Table 1) intersected by the trajectory of the visible point. The ‘stable’ profile at 1425 MHz is given in black in Fig. 4. As \( y \) varies, the emission spots shift, with the shift in \( \psi \) due to a change in \( \omega_R \) implying that the emission spots are intersected by the trajectory differently. The combined effect from each emission spots is that (i) the profile peak is shifted to increasingly negative phases and (ii) the profile width is broadened revealing some of the previously unseen emission components. The changes to the profiles during the event exhibit as gradually moving away from its stable position as \( y \) increases, reaching \( y = 0.42 \), then the pattern reverses as \( \omega_R \) returns to its usual value as \( y \) decreases and the profile appears to return
to its initial phase. This results in an overall shift in the profile peak of $\sim -4^\circ$ consistent with observations [8].

**Figure 1.** Differences in the trajectory through an open-field region (brown circle), in the magnetic frame, as predicted in the standard (gray) and the exact (black) models for $\zeta = 40^\circ$, $\alpha = 30^\circ$. The gray path is shifted by $-0.02$ along the $x_b$ axis for clarity.

**Figure 2.** Effects of $\omega_V \neq 0$ on profiles originally placed at $\psi = 0^\circ$, $\pm 25^\circ$ and $\pm 50^\circ$ for $y = 0$ and $\zeta = 10^\circ$, $\alpha = 20^\circ$ but assuming $\omega_V = 0$ (red). When $\omega_V$ is taken into account, the profiles are displaced to an earlier or later $\psi$ (black) with increased width at larger $\psi$.

**Figure 3.** Simulation showing gradual shifts in profile peak, to more negative $\psi$, and increase in the pulse width due to state switching from $y = 0$ (solid black) to 0.3 (dot-dashed), 0.6 (gray) and 0.9 (dashed) for $\zeta = 10^\circ$, $\alpha = 20^\circ$ incorporating $\omega_V \neq 0$.

**Figure 4.** Simulation for ‘stable’ profile of PSR B0919+06 (black) using the parameters in Table 1 and the ‘shifted’ profile (blue) at 1425 MHz. Profile shapes and locations of the pulse peak are changed as $\omega_R$ changes due to switching from $y = 0$ to 0.42.

4. Discussion and conclusions

We present a model for multiple magnetospheric states of a pulsar that exhibits time-variations in subpulse phase. We outline a quantitative definition for continuous set of “magnetospheric states” parameterized by $0 \leq y \leq 1$ where the inferred changes in magnetospheric states correspond to changes in $y$. We investigate the implications of the model for the interpretation of observed profile changes and show how the changes may be used to infer the change in $y$. Our model includes a traditionally neglected effect of the motion of the visible point and we show
that it has observable consequences in the emission region and the shape of pulse profiles. We attribute the profile shifts to a different phase to changes in magnetospheric state ($y$) through its effect on $\omega_R$ in a non-corotating pulsar magnetosphere. We show, using a Gaussian profile, that the peak phase of the profile and its width are unique functions of $y$ for given $\zeta, \alpha$ in our model. We consider PSR B0919+06 as a test case and argue that our model can reproduce the shift in the phase, the broadened profile and several related features. Other implications include:

- The observed subpulse drift rate results from the motion of the visible point at $\omega_V$ imposed on the ‘true’ flow rate of the emitting plasma. An equally-spaced distribution of subpulses that flow uniformly around the magnetic axis does not imply a constant subpulse drift rate. Even if the actual motion of subpulses around the magnetic pole is uniform, the observed drift rate across a pulse window is a function of $\psi$, and depends on $\zeta, \alpha$ and $y$.
- Pulsar profile shape and peak phase variations due to multiple state switching imply variations in the time of arrival (ToA) of pulses thus limiting the timing accuracy. Jitter noise may result from small random changes in $y$.
- In our model, switching in the magnetospheric state causes a change in the plasma flow ($\omega_R$) and hence the profile. A change in $y$ also causes a change in the ratio of the particle current to the displacement current and this evidently affects the global current and consequently $\nu$. This implies a causal link between radio emission and the torque on the star as revealed by the observed correlated changes in the $\nu$ and the pulse profile from some pulsars [20]. A quantitative treatment of such connections would require further exploration of the model to determine the current flow along open-field lines and how this current changes when $y$ changes, and it is beyond the scope of this paper.

Acknowledgements

RY acknowledges supports from NSFC Project no. 11573059; the Joint Funds of NSFC Grant No. U1531137; the Technology Foundation for Selected Overseas Chinese Scholar, Ministry of Personnel of China; and the Strategic Priority Research Program “The Emergence of Cosmological Structures” of the Chinese Academy of Sciences, Grant No. XDB09000000. DBM acknowledges support from the Australian Research Council through grant DP160102932.

References

[1] Weltevrede P, Edwards R T and Stappers B 2006 A&A 445 243
[2] Smits J M, Mitra D and Kuiper J 2005 A&A 440 683
[3] Wright G A E and Fowler L A 1981 Astron. Astrophys. 101 356
[4] Redman S L, Wright G A E and Rankin J M 2005 MNRAS 357 859
[5] Joshi B C 2012 Neutron Stars and Pulsars: Challenges and Opportunities after 80 years ed van Leeuwen J Proc. IAU Symposium 291 (CUP)
[6] Rankin J M, Wright G A E and Brown A M 2013 MNRAS 433 445
[7] van Leeuwen A G J, Stappers B W, Ramachandran R and Rankin J M 2003 A&A 399 223
[8] Rankin J M, Rodriguez C and Wright G A W 2006 MNRAS 370 673
[9] Wahl H M, Orfeo D J, Rankin J M and Weisberg J M 2016 MNRAS 461 3740
[10] Perera B B P, Stappers B W, Weltevrede P, Lyne A G and Bassa C G 2015 MNRAS 446 1380
[11] Kramer M, Lyne A G, O’Brien J T, Jordan C A and Lorimer D R 2006 Science 312 549
[12] Li J, Spitkovsky A and Tchekhovskoy A 2012 ApJL 746 L24
[13] Kalapotharakos C, Harding A K, Kazanas D and Contopoulos I 2012 ApJ 754 L1
[14] Melrose D B and Yuen R 2014 MNRAS 437 262
[15] Fung P K, Khechinashvili D and Kuiper J 2006 A&A 445 779
[16] Pétri J 2007 A&A 464 135
[17] Yuen R and Melrose D B 2014 PASA 31 e039
[18] Godoberidze G, Machabeli G Z, Melrose D B and Luo Q 2005 MNRAS 360 669
[19] Mitra D and Rankin J M 2008 MNRAS 385 606
[20] Lyne A G, Hobbs G, Kramer M, Stairs I H and Stappers B 2010 Science 329 408