Orbital modulation of emission of the binary pulsar J0737–3039B

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ABSTRACT
In the binary radio pulsar system J0737−3039, the slow pulsar B shows intense orbital modulations, with these being especially bright at two short orbital phases. We propose that these modulations are due to distortion of the pulsar B magnetosphere by the pulsar A wind which produces orbital phase-dependent changes in the direction along which the radio waves are emitted. In our model, pulsar B is intrinsically bright at all times but its radiation beam misses the Earth at most orbital phases. We employ a simple model of the distorted B magnetosphere using stretching transformations of Euler potentials of dipolar fields. To fit the observations we use parameters of pulsar B derived from the modelling of A eclipses. The model reproduces two bright regions at approximately the observed orbital phases, explains variations in the pulse shape between them and the regular timing residuals within each emission window. It also makes predictions for the timing properties and secular variations of pulsar B profiles.

Key words: magnetic fields – pulsars: J0737−3039B

1 INTRODUCTION
The double pulsar system PSR J0737−3039A/B contains a recycled 22.7-ms pulsar (A) in a 2.4-h orbit around a 2.77-s pulsar (B) (Burgay et al. 2003; Lyne et al. 2004). The emission of pulsar B is strongly dependent on the orbital phase. It is especially bright at two windows, each lasting for about 30°. One of the emission windows appears near the superior conjunction (when pulsar B is between pulsar A and the observer), and another approximately 70° before it. Pulse profiles have different shapes in the two windows. In addition, Ransom et al. (2004a) have detected a regular, orbital phase-dependent drift of emission arrival times by as much as 20 ms.

Previously, Jenet & Ransom (2004) suggested that the emission of B is initiated by γ-ray emission from A. This model seems to be inconsistent with the evolution of the A profile (Manchester et al. 2005). Zhang & Loeb (2004) suggested that B emission is triggered by particles from the pulsar A wind reaching deep into the magnetosphere. This model is incorrect because the authors neglected the magnetic bottling effect, which would reflect most pulsar A wind particles high above in the B magnetosphere (see Lyutikov & Thompson 2005, for a discussion of particle dynamics inside the B magnetosphere).

In this paper we explore an alternative possibility that the orbital brightening of B is due to distortions of the B magnetosphere by the pulsar A wind. We show that due to orbital phase-dependent distortions of the B magnetosphere, the polar magnetic field lines, along which emission is presumably generated, may be ‘pushed’ in the direction of an observer at particular orbital phases, while at other moments the radiating beam of B misses the observer.

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2 DISTORTION OF THE PULSAR B MAGNETOSPHERE
The magnetosphere of pulsar B is truncated, if compared to the magnetosphere of an isolated pulsar of the same spin, by the relativistic wind flowing outwards from pulsar A. The size of the magnetosphere is \( R_m \sim 4 \times 10^9 \) cm (Lyutikov 2004; Arons et al. 2004; Lyutikov & Thompson 2005), which is three times smaller than the light cylinder radius \( R_{LC} = \Omega c = 1.3 \times 10^{10} \) cm (\( \Omega \) is the angular frequency of the pulsar B rotation, \( c \) is the velocity of light). At intermediate distances, \( R_{NS} \leq r \leq (R_{LC}, R_m) \), neutron star magnetospheres are well approximated by a dipolar structure. This has been a longstanding assumption in pulsar theory (Goldreich & Julian 1969), and has recently been confirmed by the modelling of pulsar A eclipses (Lyutikov & Thompson 2005).

A small degree of distortion of the magnetosphere from its dipolar shape is expected at intermediate distances due to several types of electrical currents. First, distortions are due to confining Chapman–Ferraro currents (Chapman & Ferraro 1930) flowing in the magnetopause (a region of shocked pulsar A wind around the B magnetosphere). At the emission radius, \( R_{em} \sim 1–5 \times 10^9 \) cm (see below), any fractional distortions due to Chapman–Ferraro currents are expected to be small \( \sim (R_{em}/R_m)^3 \sim 0.001–0.02 \). In addition to confinement of the magnetosphere on the side facing pulsar A (the ‘dayside’), on the side opposite to pulsar A (the ‘nightside’) the magnetosphere of B extends to large distances, somewhat similar to the Earth magnetosphere under the influence of the solar wind. Secondly, similar to isolated pulsars, there are conduction Goldreich–Julian currents, arising on the open field lines due to the relativistic electromagnetic effects of rotation, and displacement currents, arising in oblique rotators due to temporal
variations of electromagnetic fields. At the emission radius these currents produce a distortion of the magnetic field of the order \(\sim (R_m/R_{LC})^2 \sim 10^{-3}\). Thirdly, there are internal currents flowing in the magnetosphere, such as ring currents, Birkland currents and other types of currents.

Clearly, the detailed structure of the pulsar B magnetosphere is even more complicated than that of the Earth, but at such large distances the light cylinder and magnetospheric radii distortions from its dipolar form are expected to be small. This should be the case in the emission generation region. In addition, because the magnetospheric radius \(R_m\) is several times smaller than the light cylinder we can make a simplifying assumption that at each given moment the structure of the inner magnetosphere is determined by the instantaneous direction of the magnetic moment of B and the direction of the line connecting two pulsars (which is, approximately, the direction of the pulsar A wind at the position of B). Under this approximation we expect that at each moment the structure of the inner magnetosphere may be estimated using methods developed for non-relativistic, quasi-stationary magnetospheres of solar planets interacting with the solar wind. This interaction is complicated, depending on a number of both macroscopic (e.g. wind pressure, direction of magnetic field, dipole inclination) and especially microscopic (e.g. reconnection and diffusion rates) parameters. In what follows we use our experience with the solar wind–Earth’s magnetosphere interaction (e.g. Tsyganenko 1990) as a guide in studying the pulsar B magnetosphere.

One of the principal issues here is how magnetopause currents respond to the dipole magnetic field of the central object. Two extreme possibilities are (i) complete screening of the dipole, so that no pulsar magnetic field lines penetrate into the wind; and (ii) efficient reconnection so that most of the pulsar magnetic field lines that reach the magnetospheric boundary penetrate into the wind. In the case of the Earth’s magnetosphere, although reconnection does play an important role, on average, the interpenetration of the magnetic field is at most a 10 per cent (e.g. Stern 1987). (Rates of reconnection are strongly dependent on the direction of the magnetic field of the solar wind. On the dayside reconnection occurs most efficiently near the cusps, where the polar magnetic field lines reach the magnetopause.) Numerical modelling of the interaction of the relativistic pulsar A wind with pulsar B shows qualitatively similar results Arons et al. (2004). Thus, as a first approximation, we may assume that magnetopause currents screen out pulsar B magnetic field.

An additional source of magnetic field distortion is the ring current generated by particles trapped inside the magnetosphere. The modelling of pulsar A eclipses (Lyutikov & Thompson 2005) implies that high density, relativistic plasma (most likely composed of pairs) is present on closed field lines of pulsar B. In addition to bouncing between magnetic poles due to the effect of magnetic bottling, trapped particles drift along the magnetic equator. Viewed from the north magnetic pole, the positrons (which are likely to be the most energetic electrons) are field line-aligned in the direction of the pulsar B magnetic moment and the direction of the pulsar A wind at the position of B). Under this assumption we expect that at each moment the structure of the inner magnetosphere is determined by the instantaneous direction of the magnetic moment of B and the direction of the line connecting two pulsars (which is, approximately, the direction of the magnetic field at the position of B). Under this approximation we expect that at each moment the structure of the inner magnetosphere may be estimated using methods developed for non-relativistic, quasi-stationary magnetospheres of solar planets interacting with the solar wind. This interaction is complicated, depending on a number of both macroscopic (e.g. wind pressure, direction of magnetic field, dipole inclination) and especially microscopic (e.g. reconnection and diffusion rates) parameters. In what follows we use our experience with the solar wind–Earth’s magnetosphere interaction (e.g. Tsyganenko 1990) as a guide in studying the pulsar B magnetosphere.

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We expect that the effects of the ring current are negligible at the emission radius. A typical drift velocity of charge carried is \(u_d \sim c^2 \gamma_0 / \omega_B \sim 3 \times 10^4 \text{ cm s}^{-1}\) (here \(\gamma_0 \sim 10\) is a typical Lorentz factor of trapped particles, \(\omega_B\) is the cyclotron frequency). For particle density \(n \sim \lambda_{m \text{GJ}}(\Omega R_m/c) \sim 0.1 \text{ cm}^{-3}\), and the total current is \(I \sim j R_m^2 / c \sim \lambda_{m \text{GJ}}(\Omega R_m/c)^2 \sim 0.03 R_m\). Deep inside the magnetosphere, the magnetic field of the ring current is nearly constant, but the dipole field increases, so that at \(R_m \sim 10^7 \text{ cm} B_{\text{ring}} / B_d \sim 10^{-5}\). Qualitatively, the magnetic field of the ring current would become comparable to the dipole field at \(R_m\) when the energy density of trapped plasma is of the order of the magnetic field energy density.

There are other types of currents that can modify field structures like Birkland and tail currents (e.g. Tsyganenko 1990). Their influence on the structure of magnetosphere at intermediate distances is expected to be small and we neglect them here. Thus, we assume that the only currents contributing to the distortion of the magnetosphere are magnetopause Chapman–Ferraro currents which the screen pulsar B field. This simplification allows us to use models developed for the Earth’s magnetosphere in order to estimate distortions of the pulsar B magnetic field.

3 MOELLLING THE DISTORTED MAGNETOSPHERE OF B

There is extensive literature on modelling of the Earth’s magnetic field (e.g. Tsyganenko 1990). A number of analytical methods have been developed. For our purposes, we do not need to calculate the full structure of the magnetosphere, but only to estimate variations in the position of the polar magnetic field lines, where the emission of B is presumably generated. For this purpose we employ the method of the distortion transformation of Euler potentials (Stern 1994; Voigt 1981). A major advantage of the stretching model of magnetosphere is that it reproduces fairly well the structure of a tilted dipole (Stern 1994).

The magnetic field can be described by two Euler potentials \(\alpha\) and \(\beta\) (sometimes called Clebsch potentials)

\[
B = \nabla \alpha \times \nabla \beta
\]

so that the magnetic field line is defined by an intersection of surfaces with constant \(\alpha\) and \(\beta\) values. The magnetosphere of B enshrouded by the magnetopause resembles a dipole field compressed on the dayside and stretched out on the nightside. The structure of the nightside magnetosphere can be approximated by stretching transformations of the Euler potentials \(\alpha\) and \(\beta\).

Let us choose a system of Cartesian coordinates in the tail of the B magnetosphere, centred on pulsar B so that the \(\zeta\) axis is along the line connecting pulsars A and B and axis \(\mu\) is in the \(\mu\) – \(\zeta\) plane, where \(\mu\) is the magnetic moment of B, see Fig. 1. Let the magnetic dipole be inclined at angle \(\theta_\mu\) to the \(\zeta\) axis. The undistorted dipole Euler potentials are

\[
\alpha_0 = R_{\text{GS}} \mu \left( -x' \sin \theta_\mu + z' \cos \theta_\mu \right)^2 + y'^2 \sqrt{x'^2 + y'^2 + z'^2} \]

\[
\beta_0 = R_{\text{GS}} \arctan \left( -x' \sin \theta_\mu + z' \cos \theta_\mu \right).
\]

The stretching transformations along the \(\zeta\) axis are defined by potential \(f'(\zeta)\), so that new Euler potentials are expressed in terms of dipolar ones: \(\{\alpha, \beta\} = \{\alpha_0, \beta_0 = f'(\zeta)\}\). A degree of stretching depends on \(f'(\zeta)\). In modelling the Earth magnetosphere function \(f'(\zeta)\) is chosen to fit satellite data. As we are interested in the distortions at one particular location (assuming that radio emission is generated in a narrow range of radii), we choose \(f'(\zeta) = C = \text{const} < 1\), similar to the model of Voigt (1981) of the Earth’s magnetosphere. Thus, \(C\) measures the distortion of the magnetosphere at the emission radius.
Substituting $z' \rightarrow Cz'$ in equation (2) we find stretched magnetic fields in coordinates $\{x', y', z'\}$

$$B = \frac{r_0^3 \mu}{r^5} \left\{ 3Cz' \cos \theta_\mu + (2C^2 x'^2 - y'^2 - z'^2) \sin \theta_\mu, \right.$$

$$3y'C(z' \cos \theta_\mu + Cx' \sin \theta_\mu, \right.$$\n
$$C \left\{ 3Cx' \cos \theta_\mu + (2z'^2 - C^2 x'^2 - y'^2) \cos \theta_\mu \right\} \right\},$$ (3)

where $r' = \sqrt{C^2 x'^2 + y'^2 + z'^2}$. Integrating along a magnetic field line in the $y' = 0$ plane we find the equation for magnetic surfaces to be

$$\frac{r}{r_0} = \frac{(C \cos \theta_\mu \sin \theta' - \cos \theta_\mu \cos \theta' \sin \theta')^2}{(C^2 \theta'^2 + C^2 \sin^2 \theta')^{3/2}}.$$

(4)

where $r = \sqrt{x'^2 + z'^2}$ and $\theta' = \arcsin x'/r'$. Integrating along the $z'$ axis and $\theta'$ is a parameter related to the maximum extension of a field line. From equation (4) we find that the polar field lines in the tail of stretched magnetosphere are defined by

$$\tan \theta_p = \frac{1}{C} \tan \theta_\mu.$$ (5)

This provides an estimate of the deviation of polar field lines from the direction of the magnetic dipole. Qualitatively, polar field lines are pushed toward the $z'$ axis. The method of the field line stretching is only approximate and has limited applications. Its main drawback is that it offsets force balance, so that there is a non-vanishing Lorentz force in the new configuration. In addition, because the stretching method has been devised for magnetotail, it is not clear how well it reproduces the structure of the inner magnetosphere (in the original model of Voigt 1981) the stretching method is applied to tailward distances larger than approximately half the stand-off distance).

### 4 ORBITAL MODULATION OF B

Let us introduce another Cartesian system of coordinates $x, y, z$ centred on pulsar B, so that its orbital plane lies in the $x - y$ plane (see Fig. 1). The spin axis of pulsar B is inclined at an angle $\theta_\Omega$ to the orbital normal and at angle $\phi_\Omega$ with respect to the $x - z$ plane. The magnetic moment of pulsar B has a magnitude $\mu$, is inclined at an angle $\chi$ with respect to $\Omega$ and executes a circular motion with phase $\phi_{oi} = \Omega t_0$, so that $\phi_{oi} = 0$ corresponds to the magnetic moment in the $\Omega - x$ plane. At a given orbital position, the unit vector along the direction of the pulsar A wind is approximately $I_w = \{ \cos \phi, \sin \phi, 0 \}$.

In the observer frame the components of the unit vector $\tilde{\mu}(t)$ along the instantaneous magnetic moment $\mu(t)$ are

$$\tilde{\mu}_x = \tilde{\mu}_x^0, \quad \tilde{\mu}_y = \cos \theta_\Omega \tilde{\mu}_y^0 + \sin \theta_\Omega \tilde{\mu}_z^0,$$

$$\tilde{\mu}_z = \cos \theta_\Omega \tilde{\mu}_z^0, \quad \tilde{\mu}_y = \sin \theta_\Omega \tilde{\mu}_y^0; \quad \tilde{\mu}_z = \cos \chi.$$

(6)

Using equation (5) we can find the direction of the magnetic polar field lines in the distorted magnetosphere

$$s_p = \frac{\tilde{\mu} - (1 - C) \cos \theta_\Omega I_w}{\sqrt{1 + (3 - 4C^2 + C^2) \cos^2 \theta_\mu}},$$ (8)

where $\cos \theta_\mu = |\tilde{\mu} \cdot I_w|$ is the absolute value of cosine of the angle between the direction of the wind and the direction of the magnetic moment.

To estimate the influence of the orbit-dependent magnetic field distortion on the observed radio emission, we assume that the emission is generated near the polar field line in a region with a half opening angle of $\sim 2^\circ$; in accordance with the width of the emission profile of pulsar B. Thus, if the magnetic polar field line deviates from the line of sight by more than $2^\circ$, we expect the emission of B to be weak. The trajectory that the magnetic polar field line makes on the sky depends on many parameters. To limit available phase space we use the results of the modelling of the pulsar A eclipse (Lyutikov & Thompson 2005), which implies that $\theta_\Omega \sim 60^\circ$ and $\chi \sim 75^\circ$. In total, we have to fit at least six parameters: $\phi_{iG}; \theta_\Omega; \chi; \Omega$, magnetospheric radius; impact parameter; and distortion coefficient $C$. Using the results of Lyutikov & Thompson (2005), the two principal parameters that remain to be determined are $\phi_{oi}$ and $C$.  

Figure 2. Cosine of the angle $\theta_{\text{ob}}$ between the line of sight and the direction of the polar field line in a distorted magnetosphere as a function of rotational phase $\phi_{\text{rot}} = \Omega t$ and orbital phase $-\pi/2 < \phi_{\text{orb}} < \pi/2$ measured from the superior conjunction. The parameters of the model are $\theta_2 = 60^\circ$, $\phi_2 = 67.5^\circ$, $\chi = 73.6^\circ$, $C = 0.7$. Emission is visible if $\theta_{\text{ob}} < 2^\circ$ corresponding to $\cos \theta_{\text{ob}} > 0.9994$. This happens at two orbital phases $\phi_{\text{orb}} = 0.03 - 0.43 (17^\circ - 24^\circ)$ and $\phi_{\text{orb}} = 1.09 - 1.45 (62^\circ - 83^\circ)$.

Figure 3. Configuration of the system, after Lyne et al. (2004). Light shaded segments indicate orbital phases where the B emission is strongest, the dark regions indicate the location of the emission in the best-fitting model.

For a given set of $\theta_2$, $\phi_2$, $\chi$ and $C$, the direction of the polar field line executes a non-circular curve on the sky. An observer will see emission when for some values of the pulsar B rotation phase $\phi_{\text{rot}}$ and the orbital phase $\phi_{\text{orb}}$, the polar field line points within $2^\circ$ of the line of sight.

By searching through parameter space we were trying to reproduce two emission windows located in the tail of B magnetosphere. After a number of trials, our best fitting parameters are $\phi_2 = -67.5^\circ$ and $C = 0.7$. To illustrate the fit, in Fig. 2 we plot a value of $\cos \theta_{\text{ob}} = s_p \cdot \hat{x}$ as a function of orbital phase $\phi_{\text{orb}}$ and rotational phase $\phi_{\text{rot}}$. Only points located above the line $\cos 2^\circ = 0.9994$ produce a pulse of radio emission. (We restrict ourselves to $-\pi/2 < \phi_{\text{orb}} < \pi/2$, corresponding to the tail pointing towards the observer.) Clearly, in the magnetospheric tail the polar field lines are pointing toward an observer at two orbital phases separated by approximately $70^\circ$, see Fig. 3. One of the phases, nearly coincident with the
the effect of field distortion, in Fig. 4 we plot a trajectory of the
the agreement with observations is impressive. In order to illustrate
of the model and the fact that we had to make a multiparameter fit,
second is located at
5 DISCUSSION AND PREDICTIONS

We have constructed a simple model of orbital variations of pulsar
emission. Small distortions of the inner magnetosphere of B by
pulsar A wind change direction of the polar field lines, pushing the
radiative beam of B towards the line of sight at two orbital phases.
The main implication of the model is that B is always intrinsically
bright. The model reproduces fairly well the absolute orbital loca-
tion of bright emission windows, their width ~20° and separation
~70°. It also naturally explains the different profiles at two emission
windows, because at different orbital phases the line of sight crosses
the emission region along different paths.

In this paper we considered only the nightside magnetosphere.
The stretching method does not produce a realistic structure of the
dayside (Stern 1994). Qualitatively, we expect that on the dayside
polar field lines will also be shifted from the direction of the magnetic
pole and will be pushed out of the line of sight, producing a dip in the
light curve of B close to the inferior conjunction. As the emission
beam is very narrow and the distortions can be considerable, it is
fairly easy for the beam of B to miss an observer. A more detailed
model of the magnetosphere is deferred to a subsequent paper.

Our suggestion that pulsar B is always intrinsically bright is con-
sistent with its spin-down and radio energetics. First, assuming that
an extension of the last open field line is determined by the size of
magnetosphere and that typical current density flowing on the open
field lines is of the order of the Goldreich–Julian current density,
the total potential over open field lines [a quantity that is usually
related to efficiency of pair production (e.g. Arons & Scharlemann
1979)] is independent of $R_{in}$: $\Phi_{\text{rot}} \sim \sqrt{L_{\text{SD}}/4\pi c}$, where $L_{\text{SD}} = 1.6 \times 10^{30}$ erg s$^{-1}$ is the spin-down luminosity of B Lyne et al. (2004). This ranks it as the 20th smallest (but not exceptional) out of
nearly 1500 pulsars with measured spin-down luminosities (see
www.atnf.csiro.au/research/pulsar/psrcat). Secondly, its peak lumin-
osity of ~3 mJy at 820 MHz (Ransom, private communication) is
usual for isolated pulsars with similar properties.

There is a number of predictions of the model. First, at different
orbital phases the centre pulse corresponds to somewhat different
rotational phases. Near $\phi_{\text{orb}} = 1/7$, the centre pulse is at $\phi_{\text{orb}} \sim
11.5$, decreasing to $\phi_{\text{orb}} \sim 8^\circ$ at $\phi_{\text{orb}} = 24^\circ$, remaining the same at
$\phi_{\text{orb}} = 62.5$ and increasing back to $\phi_{\text{orb}} \sim 11.5$ at $\phi_{\text{orb}} = 83.1$, see
Fig. 5. Thus, one expects a drift of the profile as a function of
an orbital phase. Particular values for the drift angle and rate
are strongly dependent on the precise parameters of the model, but
the type of evolution is generic: during a visible phase the profile
 drifts approximately by its width. If averaged over a bright emission
window, the drift of the emission phase may be interpreted as a large
timing noise of B.

A drift of the emission phase as a function of orbital position
may have already been observed. Ransom et al. (2004a) reported a

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4.png}
\caption{Trajectory of the polar field line on the sky for $\phi_{\text{orb}} = \pi/8 =
22.5$, $C = 0.7$. Black dashed line, undistorted dipole, green solid line is at
orbital phase $\phi_{\text{orb}} = -\pi/4$ (misses the observer), blue line is at orbital phase
$\phi_{\text{orb}} = 0$ and red line is at orbital phase $\phi_{\text{orb}} = \pi/4$. The location of observer
is denoted by the circle. Upper and lower sets of curves correspond to two
magnetic poles.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5.png}
\caption{Dependence of the rotation phase of emission on the orbital
position and evolution of the emission pattern due to changes of $\phi_{\text{orb}}$. B radio
emission is seen at Earth at two shaded areas. At different orbital phases
the emission peak occurs at different rotation phases. Typical variations in
the emission phase are of the order of the profile width. The corresponding
drift the of arrival times for pulsar B is $\sim 15$ ms. The black region is the
current best-fitting $\phi_{\text{orb}} = -67.5$, the region in red is for $\phi_{\text{orb}} = -68.5$.}
\end{figure}
systematic change in arrival times of B pulses by 10–20 ms. This is consistent with the prediction of the model, as a change in arrival phase by 2° of the rotation phase of B corresponds to ~15 ms.

In our model, the weak emission of B observed throughout the orbit has a different origin to the bright emission. For example, it can be generated in a much wider cone, akin to interpulse emission (bridges) observed in regular pulsars.

Our second prediction is related to a secular evolution of the pulsar B emission properties. The emission beam of B is fairly narrow, so that small changes in the orientation of the rotation axis of B may induce large apparent changes in the profile. One possibility for the change in the direction of the spin is a geodetic precession of B, which should happen on a relatively short time-scale ~70 yr (Lyne et al. 2004). The geodetic precession will affect mostly the angle $\phi_2$. From our modelling we find that changes of $\phi_2$ by as little as ~1° strongly affect the observed B profile (see Fig. 5).

Thus, we expect that the profile of B may change on a time-scale of less than a year. According to the model, the average profile width remains approximately constant. The changes of the orbital phases of emission are not accompanied by substantial changes in the emission phase. (Note that if the emission geometry is non-trivial, e.g. elliptic instead of circular, one does expect changes in the emission phase.) As at different epochs the line of sight passes through different emission regions one may expect variations in pulse intensity. Thus, using different slices taken at different epochs one can construct a detailed map of the emission region. This should prove a valuable method in constraining pulsar radio emission mechanisms.

A longer evolution of the profile cannot be predicted unambiguously because we do not know the direction of the drift. Two possibilities include increasing or decreasing $|\phi_2 + 90°|$, see Fig. 6. In one case, two emission regions get closer together merging into one, while in the other case they separate and a new one appears.

Figure 6. Secular changes in the position of the emission regions due to geodetic drift: (a) $\phi_2 = -68.5°$; (b) $\phi_2 = -65°$ (current best-fitting value is $\phi_2 = -67.5°$). In case (a) the orbital separation between the two bright phases increases, in case (b) it decreases, so that two phases merge in one. With the exception of $\phi_2$, the parameters are the same as in Fig. 2.
approximately at a mirror reflection of the first, at $\phi_{orb} \approx -90^\circ$. We would like to stress again that exact details of the secular evolution are hard to predict using this very simple model.

For the stretching coefficient $C = 0.7$, the relative deformation of the magnetosphere at the emission radius is $\sim 30$ per cent. This is a fairly large distortion, which favours large emission altitudes, $R_{em} \geq 10^8$ cm. Large emission altitudes in isolated pulsars have been previously suggested by Lyutikov (2004). A more precise modelling of the B magnetic field may reduce required distortion and thus allow somewhat smaller $R_{em}$ values. Still, near the stellar surface distortions are expected to be tiny, so that the model requires a high emission altitude.

The success of this simple model is somewhat surprising, given the fact that we had to fit many parameters with a required precision of $2^\circ$. Qualitatively, the reason for the success of this model, as well as that of Lyutikov & Thompson (2005), is that, to the first order, magnetic field is well approximated by dipolar structure. Given the simplicity of the model, some of the parameters may not be well determined: small variations in parameters may induce relatively large observed changes.

A number of effects may complicate the picture. First of all, a non-trivial geometry of the emission region, e.g. elliptical instead of circular, may increase the quality of the fit. The fact that the B profiles in the two emission windows are different implies that emission geometry is indeed non-circular. A double hump profile in one of the windows also points to a more complicated emission geometry. Secondly, a non-spherical A wind will produce distortions dependent on the orbital phase. Also, if the reconnection between the wind and magnetospheric field lines is important, the structure of the magnetosphere may depend on the direction of the magnetic field of the wind. We plan to address these issues in a subsequent paper. Clearly, detailed modelling of the B magnetosphere is required to further finesse the model.

When the paper had been mostly completed we learned the results of Burgay et al. (2005), who found secular changes in B profiles in general agreement with the predictions of the model.

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1 According to the model, we are not likely to lose pulsar B in the coming year, yet the model is not sufficiently detailed to guarantee it.

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