LOCATION OF THE CORE AND CONAL EMISSION REGIONS IN PSR 0329+54

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Abstract

We discuss the cross-correlation analysis of single pulses in the emission of PSR 0329+54 observed simultaneously at 102.5 and 1700 MHz. We have found that the observed correlations between the two frequencies are consistent with the model in which the subpulses in single pulses correspond to plasma excitations flowing from the neutron-star surface along dipolar magnetic field lines. The peaks of strongly correlated subpulses at the two frequencies correspond to the same field line at two different emission radii. We have found that the core (central) and the conal (outer) components of the pulse profile of PSR 0329+54 originate at the same distance from the neutron star.

Introduction

PSR 0329+54 is probably one of the best examples of a pulsar with both core (central) and conal (outer) components (Rankin 1983a). The subpulses in single pulses occur at different longitudes across the profile but most frequently under the profile components. Kardashev *et al.* (1986) observed single pulses of this pulsar simultaneously at 102.5 and 1700 MHz. They found significant correlations between the two frequencies at some longitude intervals. Strong subpulses at 102.5 MHz were highly correlated with strong subpulses at 1700 MHz. The times of arrival (TOA) of correlated subpulses at the two frequencies were associated according to a linear relationship (*cf.* figure 5 in Kardashev *et al.* 1986)

$$t(\nu_1) = At(\nu_2) + B, \qquad (1)$$

where $\nu_1 = 1700\,\text{MHz}$ and $\nu_2 = 102.5\,\text{MHz}$, $A \approx 0.77$, and $B \approx 30.5\,\text{ms}$. This relationship was exactly the same for both core (central) and conal (outer) components. We will discuss this important observational fact in the light of the standard magnetic-pole model of pulsar emission. We reproduce figure 5 of Kardashev *et al.* (1986) in our figure 1.

Figure 1 Correlations between the TOAs of strong subpulses at 102.5 and 1700 MHz of PSR 0329+54 (after Kardashev *et al.* 1986). The TOAs are corrected for dispersion time delays by profile alignment according to the known value of DM (to within an accuracy of about 0.1%). The two separate sets of data points correspond to the core (central) and conal (outer) components. The upper time axis for 102.5 MHz is scaled in such a way that $t_i(\nu_2) = 0$ corresponds to the center of the core component (profile midpoint). The dashed line describes a linear correlation between the two frequencies $t_i(\nu_1) = 0.77t_i(\nu_2) + 11.25\,\text{ms}$. This relationship is exactly the same for both the core and conal components.

A standard model

Let us consider a standard magnetic-pole model of pulsar emission. The relativistic particles emit radiation which is beamed tangent to the dipolar magnetic field lines. The emission is narrowband and the lower frequencies are emitted farther from the star than the higher ones. The subpulses correspond 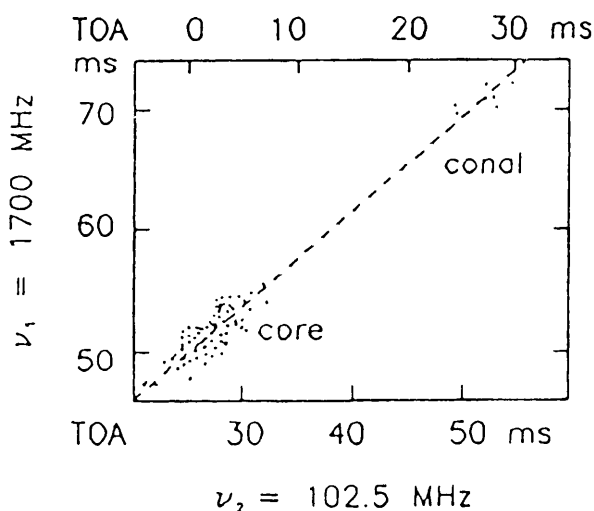to plasma excitations which flow from the stellar surface along the magnetic field lines. Therefore the peaks of strongly correlated subpulses observed at frequencies ν_1 and $\nu_2 < \nu_1$ correspond to the same field line at two different emission radii $r(\nu_1)$ and $r(\nu_2) > r(\nu_1)$. The subpulses observed at a single frequency at different pulse longitudes correspond to different field lines which will be labelled by the parameter $s_i = d_i/r_p$, where d_i is the distance from the magnetic axis to the base of the i-th field line at the polar cap surface, and r_p is the
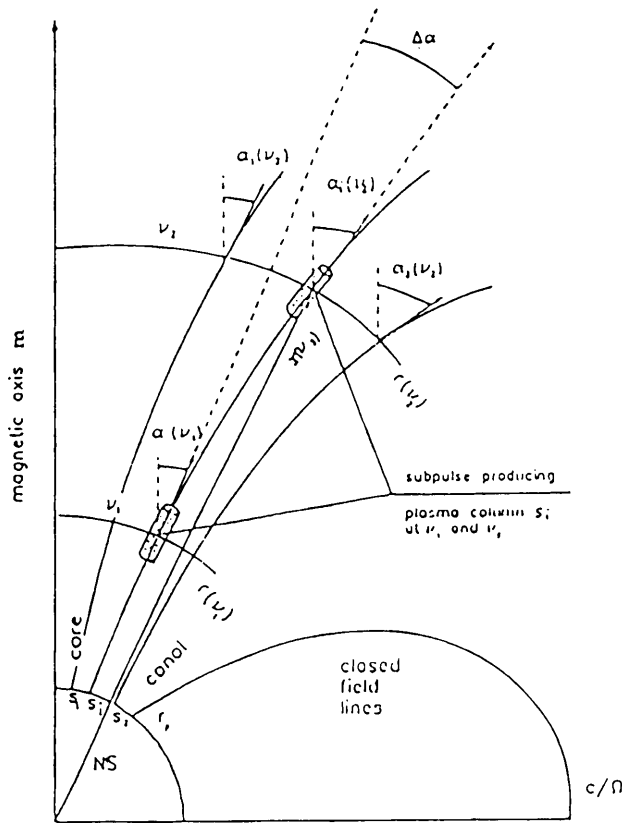
Figure 2 Geometry of the emission regions for PSR 0329+54. At a given frequency an observer sees different field lines as the pulsar rotates. This means that the pulse profile of this pulsar represents a central cut through the polar cap, with core emission originating near the magnetic axis and conal emission originating near the polar cap edge. Therefore, we assume that the angle between the rotation and the magnetic axes and the angle between the rotation axis and observer's direction are almost the same in PSR 0329+54.

Goldreich-Julian (1969) polar cap radius (figure 2).

In what follows we will assume that in PSR 0329+54 the pulse profile represents the central cut of the sight line through the polar cap, *i.e.* an observer passes very near the magnetic axis at the fiducial phase (profile center). This assumption is well justified by the presence of a strong core component in the pulse profile of this pulsar (see also Lyne and Manchester 1988).

The above model is illustrated in figure 2. Let us consider the i-th subpulse associated with the i-th field line originating at a distance $d_i = s_i r_p$ from the magnetic axis. The opening angle between the magnetic axis and the tangent to this line at different radii $r(\nu)$ is

$$\alpha_i(\nu) = \frac{3}{2} s_i \left(\frac{\Omega}{c}\right)^{1/2} r^{1/2}(\nu), \qquad (2)$$

where $\Omega = 2\pi/P$ is the pulsar angular frequency, P is the pulsar period, and c is the speed of light. Let $t_i(\nu_2)$ be a TOA at frequency ν_2 of the subpulse associated with i-th field line. In general, the corresponding TOA of the subpulse associated with the

same field line at frequency ν_1 can be expressed by the TOA at frequency ν_2

$$t_i(\nu_1) = t_i(\nu_2) - \Delta t_\alpha + \Delta t_r - \Delta t_{\mathrm{DM}}, \qquad (3)$$

where

$$\Delta t_\alpha = \frac{\Delta \alpha P}{2\pi \sin \theta} + t_0. \qquad (4)$$

t_0 is the arbitrary time corresponding to the fiducial phase in which $s = 0$ and $\alpha(\nu_2) = \alpha(\nu_1) = 0$, Δt_α is a time difference corresponding to different opening angles $\alpha_i(\nu_1)$ and $\alpha_i(\nu_2)$ as pulsar rotates, $\Delta \alpha = \alpha_i(\nu_2) - \alpha_i(\nu_1)$ (figure 2), and θ is the angle between the rotation and magnetic axes.

$$\Delta t_r = \left(\frac{1 + \sin \theta}{c}\right) [r(\nu_2) - r(\nu_1)] \qquad (5)$$

is the retardation-aberration time delay between the two emission radii, and

$$\Delta t_{\mathrm{DM}} = 4.15 \times 10^9 DM \left(\nu_2^{-2} - \nu_1^{-2}\right) \, \mu s$$

is the dispersion time delay between the two frequencies, where DM is the dispersion measure.

According to eq.(2), the angular difference in eq.(4) for a dipolar magnetic field has the form

$$\Delta \alpha_i = \frac{3}{2} s_i \left(\frac{2\pi}{cP}\right)^{1/2} \left[r^{1/2}(\nu_2) - r^{1/2}(\nu_1)\right], \qquad (6)$$

and, after correcting for interstellar dispersion by profile alignment, eq.(3) can be written in the form

$$\begin{aligned} t_i(\nu_1) = \; & t_i(\nu_2) - \\ & \frac{(9P/8\pi c)^{1/2} s_i}{\sin \theta} \left[r^{1/2}(\nu_2) - r^{1/2}(\nu_1)\right] + \\ & t_0 + \left(\frac{1 + \sin \theta}{c}\right) [r(\nu_2) - r(\nu_1)]. \end{aligned} \qquad (7)$$

If one scales the $t(\nu_2)$ time axis in such a way that $t_0 = 0$, which means that $t_i(\nu_2) = 0$ at the fiducial phase in which $\alpha(\nu_2) = 0$ then

$$t_i(\nu_2) = (9P/3\pi c)^{1/2} s_i r^{1/2}(\nu_2)/\sin \theta$$

and

$$\begin{aligned} t_i(\nu_1) = \; & t_i(\nu_2) \left[\frac{r(\nu_1)}{r(\nu_2)}\right]^{1/2} + \\ & \left(\frac{1 + \sin \theta}{c}\right) [r(\nu_2) - r(\nu_1)], \end{aligned} \qquad (8)$$

which explains the linear relationship between the TOAs at 102.5 and 1700 MHz presented in figure 1 (corrected for interstellar dispersion by profile alignment according to the known value of DM) and expressed in eq.(1). Moreover, as can be seen from

figure 1 the linear relationship between TOAs at 102.5 MHz and 1700 MHz in PSR 0329+54 is the same for core and conal subpulses. This means that the coefficients A and B in eq.(1) are the same for both the core and conal components. According to eq.(8) this, in turn, means that

$$\left.\frac{r(\nu_1)}{r(\nu_2)}\right|_{\text{core}} = \left.\frac{r(\nu_1)}{r(\nu_2)}\right|_{\text{cone}}$$

and

$$r(\nu_2)_{\text{core}} - r(\nu_1)_{\text{core}} = r(\nu_2)_{\text{cone}} - r(\nu_1)_{\text{cone}}.$$

The above conditions have a very important interpretation: core and conal emission originate at the same altitude $r(\nu)_{\text{core}} = r(\nu)_{\text{cone}}$ in PSR 0329+54. The core emission originates closer to the magnetic axis and the conal emission closer to the polar cap edge, *i.e.*, $s_{\text{core}} < s_{\text{cone}} \approx 1$, $[t_i(\nu) \propto \alpha_i(\nu) \propto s_i \, r^{1/2}(\nu)]$.

Conclusions

The important conclusion of this paper is that the emission associated with the central component (core) and outer components (conal) of the mean profile of PSR 0329+54 originates at the same distance from the neutron star. This is in strong contradiction to Rankin (1990) who argues that the core emission originates essentially at the neutron-star surface and occupies the entire polar cap. Within this interpretation conal components would originate further from the polar cap, in contradiction to results of this paper.