

Chapter 6

Radio and γ -ray light curve fits for individual pulsars

In Chapter 5 the insights gained in Chapter 4 were employed to show how it is possible to obtain best-fit solution contours to observed radio and γ -ray light curves (LCs) by eye using geometric models of pulsar emission. This was done by generating atlases of increasingly higher resolution in (α, ζ) -space and manually identifying which possible solutions best fit the data (see Section 5.1). These solution contours were then used to estimate the value of the geometrical factor f_Ω for a given pulsar, by averaging the calculated values of $f_\Omega(\alpha, \zeta)$ within the regions identified by the solution contours in (α, ζ) -space (Section 5.2).

Using this approach, we will obtain values for the same parameters for the six pulsars chosen for this study, as well as estimates of the errors on these values. How various constraints lead to the eventual best-fit contours will also be discussed. In the next Chapter, the parameters obtained for these six pulsars will be compared to those obtained by Weltevrede et al. (2010), who constrained α and $\beta = \zeta - \alpha$ by using the rotating vector model of Radhakrishnan & Cooke (1969), along with estimates of the beam half opening angle ρ .

6.1 A bird’s eye view of the LC fits

Figure 6.1 indicates best-fit model LCs for each of the six pulsars, for both the OG and TPC models. Values for α and ζ are inferred for each pulsar, with typical errors of $\sim 5^\circ$ (see Table 6.1), after constraining the possible solution space by eye using conservative contours that delimit regions within which the LCs provide reasonable fits to the data. The latter contours have been estimated by comparing predicted LCs for different (α, ζ) combinations, at a 1° resolution, with the data. The values tabulated in Table 6.1 are the average values of α , ζ , and β implied by the solution contours, while the errors are chosen conservatively so as to include the full (non-rectangular) contour (see Section 5.1 for details). For both the TPC and OG model relatively oblique geometries seem to be preferred, i.e., α and ζ closer to 90° than 0° . The fact that the α and ζ results yielded by the OG and TPC models are relatively similar (within $\sim 10^\circ$ of each other) indicates that these “outer magnetospheric models” deliver robust results. The last column of Table 6.1 lists the inferred f_Ω values with errors. All the f_Ω values obtained in this study are ~ 1 , as expected, indicating that the luminosities of the observed LCs may be representative of the total luminosities of the

corresponding pulsars. For all the pulsars, except PSR J0742–2822, the value of f_Ω for the OG best-fit profile is lower than that for the TPC best-fit profile, and the magnitude of this difference is ~ 0.1 in all of the cases except PSR J0659+1414 where the predicted f_Ω values differ by ~ 0.5 . This difference between the TPC and OG predicted f_Ω values is mainly due to the absence of emission originating from below the null-charge surface in the OG case. How the omission of this emission effects the predicted f_Ω values is beyond the scope of the current study.

Note that once a solution is found at a particular α and ζ , it is worthwhile to study the LCs around the position $\alpha' = \zeta$ and $\zeta' = \alpha$ (i.e., when the angles are interchanged). Such a “complementary solution” provides a good fit in some cases (see the alternative solutions listed in Table 6.1; denoted as “AltTPC” or “AltOG”). Each pulsar’s best-fit LCs are discussed in more detail below.

6.2 Results for the individual pulsars

In this section, the characterising rotational parameters of the six pulsars in this study (their period P and period derivative $\dot{P}$), as well as the various quantities derived from these parameters, will be needed for the discussion of the results obtained in this study. In the interest of clarity, these values are again summarised in Table 6.2.

6.2.1 PSR J0631+1036

Background

Zepka et al. (1996) reported the discovery of PSR J0631+1036 in the ultra high frequency (UHF) radio band in a search conducted at the Arecibo Observatory targeting *Einstein* IPC X-ray sources, with $P = 288$ ms and $\dot{P} = 8.29 \times 10^{-14}$ s.s $^{-1}$ (see Table 6.2 for more detail). The reported dispersion measure (DM) of 125.36 ± 0.01 cm $^{-3}$ pc (Weltevrede et al., 2010) corresponds to a distance of 3.6 ± 1.3 kpc according to the Cordes & Lazio (2002) model, and is very high for a pulsar in the Galactic anti-centre. This high DM is possibly caused by the foreground star-forming region 3 Mon at a distance of 0.75 kpc (Shevchenko & Yakubov, 1988). In addition, this pulsar could be interacting with (or be embedded in) the dark cloud LDN 1605, so that the distance estimated using the Cordes & Lazio (2002) model is possibly too large. Zepka et al. (1996) adopt a distance of 1 kpc consistent with the observed X-ray absorption.

The presence of sinusoidal X-ray pulsations was claimed by Torii et al. (2001) using *ASCA* data, following the discovery of a faint *ROSAT* PSPC X-ray source at the pulsar position reported by Zepka et al. (1996). However, Kennea et al. (2002) were not able to confirm X-ray pulsations from this source using *XMM-Newton* observational data, which probably implies that the X-ray point source is not associated with PSR J0631+1036. The derived upper limit on the X-ray luminosity of the point source (for the assumed distance of 1 kpc) of 1.1×10^{30} ergs $^{-1}$ (0.5–2.0 keV) is low compared to the Becker & Truemper (1997) relationship between the X-ray luminosity and $\dot{E}$ for pulsars. This may point to a larger pulsar distance.

Zepka et al. (1996) claimed a marginal detection of pulsed γ -rays by EGRET, but their LC does not resemble that observed with *Fermi* LAT, and their estimated energy flux is an order of magnitude higher than that obtained from the *Fermi* LAT data (Weltevrede et al., 2010).

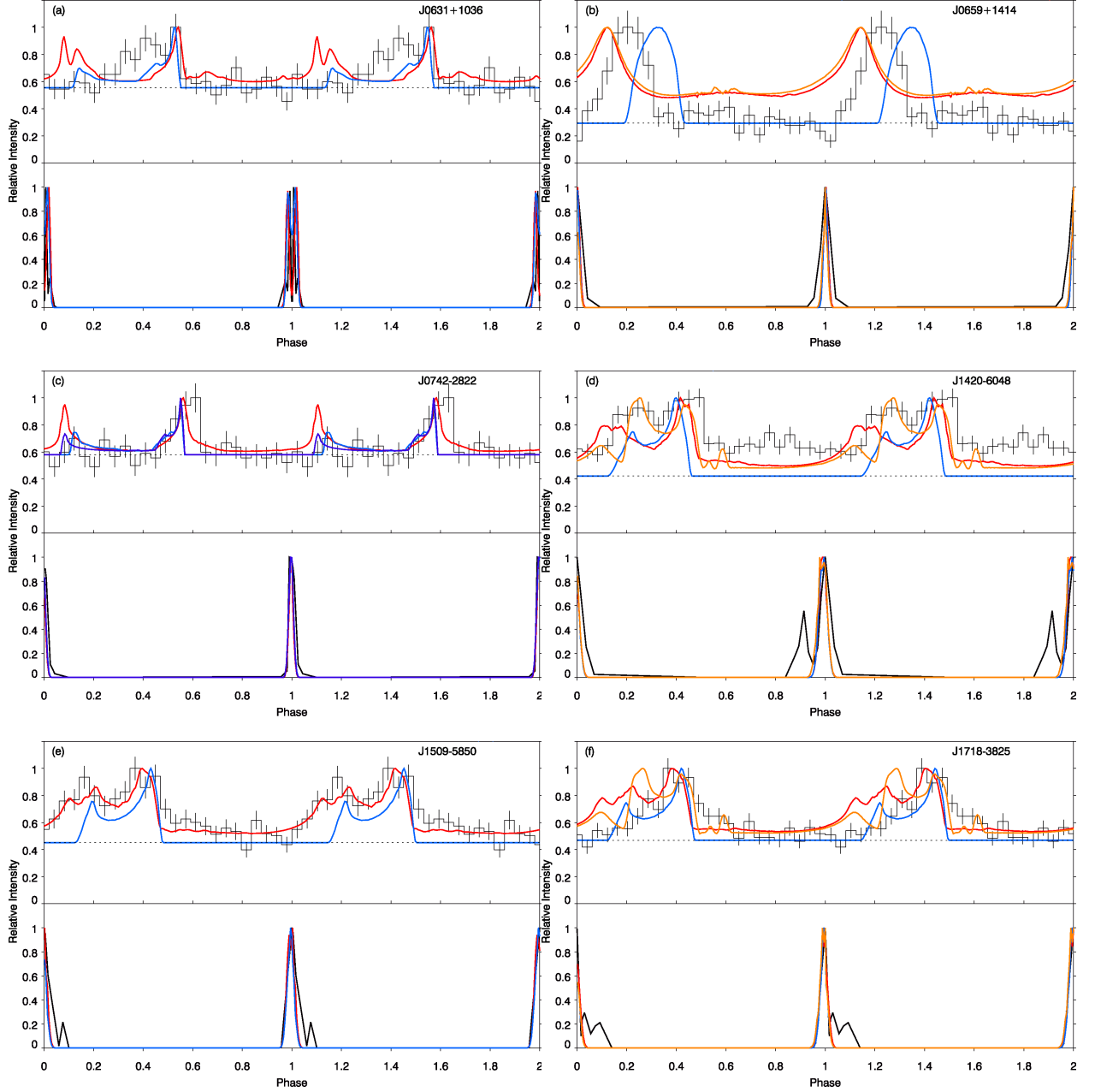


Figure 6.1: Model LC fits to the γ -ray and radio data (upper and lower panels, respectively) for each of the pulsars. Blue lines are OG fits (alternative OG fits are purple), and red lines are TPC fits (alternative TPC fits are orange). See Table 6.1 for the values of (α, β) corresponding to each fit. The histograms are *Fermi* LAT data, while the black lines in the radio panes are 1.4 GHz radio data from Weltevrede et al. (2010). *Note: two rotations are shown for clarity, and the radio LCs are not shifted as in the atlases in Chapter 5 (preserving the actual radio-to- γ phase lag).*

Table 6.1: Values for α , ζ , β , and f_Ω derived for the six pulsars for both the OG and TPC models.

Pulsar	Model	α ($^\circ$)	ζ ($^\circ$)	β ($^\circ$)	f_Ω
PSR J0631+1036	OG	74 ± 5	67 ± 4	-6 ± 2	0.93 ± 0.06
	TPC	71 ± 6	66 ± 7	-5 ± 3	1.04 ± 0.04
PSR J0659+1414	OG	59 ± 3	48 ± 3	-12 ± 5	1.16 ± 0.53
	TPC	50 ± 4	39 ± 4	-13 ± 6	1.64 ± 0.04
		38 ± 1	50 ± 4	11 ± 4	1.63 ± 0.05
PSR J0742–2822	OG	86 ± 3	71 ± 5	-16 ± 6	0.99 ± 0.10
		71 ± 6	86 ± 4	16 ± 6	0.81 ± 0.09
	TPC	64 ± 8	80 ± 4	15 ± 6	0.88 ± 0.41
PSR J1420–6048	OG	67 ± 5	45 ± 7	-22 ± 9	0.77 ± 0.13
	TPC	64 ± 6	43 ± 8	-21 ± 9	0.90 ± 0.10
		42 ± 5	63 ± 5	21 ± 9	0.77 ± 0.06
PSR J1509–5850	OG	66 ± 4	50 ± 7	-18 ± 8	0.77 ± 0.11
	TPC	61 ± 5	44 ± 7	-18 ± 8	0.89 ± 0.10
PSR J1718–3825	OG	67 ± 6	48 ± 6	-19 ± 8	0.76 ± 0.12
	TPC	61 ± 5	43 ± 6	-19 ± 8	0.86 ± 0.07
		42 ± 6	62 ± 5	19 ± 7	0.83 ± 0.10

Table 6.2: Rotational and derived parameters for the six pulsars. Taken from Weltevrede et al. (2010).

Pulsar (J2000)	Pulsar (B1950)	P (s)	$\dot{P}$ (10^{-14} s.s $^{-1}$)	τ_c (10^3 yr)	B_0 (10^{12} G)	$\dot{E}$ (10^{35} erg.s $^{-1}$)
PSR J0631+1036		0.288	8.29	43.6	5.55	1.73
PSR J0659+1414	B0656+14	0.385	5.50	111	4.66	0.38
PSR J0742–2822	B0740–28	0.167	1.69	157	1.69	1.43
PSR J1420–6048		0.068	8.29	13.0	2.41	104
PSR J1509–5850		0.089	0.92	154	9.14	5.15
PSR J1718–3825		0.075	1.33	89.5	1.01	12.5

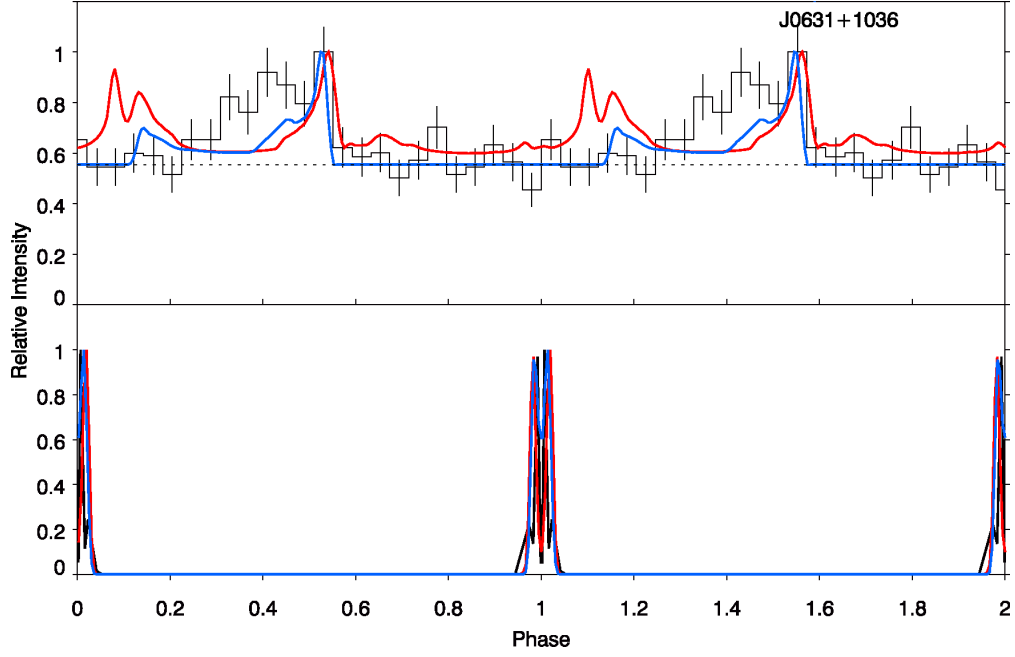


Figure 6.2: OG (*blue*) and TPC (*red*) best-fit model pulse profiles for PSR J0631+1036.

The radio and γ -ray LCs

The radio profile of PSR J0631+1036 is dominated by two high peaks, and is composed of four components with a very deep minimum at the pulse phase of the symmetry point, shown in Figure 6.2. The complex structure of this profile, specifically the presence of the outer components which are strongest at low frequencies, makes it hard to fit using the simplistic radio model used in this study, despite the high degree of mirror symmetry. The profile is thus regarded as a closely spaced two-peak profile with a width of approximately 0.1 in normalised phase, thereby including the outer components in the width determination.

The γ -ray profile of PSR J0631+1036 displays a single, broad peak, with a full width at half-maximum (FWHM) of 0.25 in rotational phase (Weltevrede et al., 2010), lagging the radio profile by 0.44. Note that the highest intensity is located at 0.55 in phase, and not at the middle of the broad structure between 0.2 and 0.6 in phase.

The best-fit LC solutions

Figure 6.2 shows the best-fit solutions for PSR J0631+1036. The best-fit profiles predicted by both the TPC and OG models have their strongest peak around 0.55 in normalised phase. Although this matches the location of the strongest peak in the data, the two models were not able to simultaneously reproduce the broad peak found in the data and the radio-to- γ phase lag. The structure of the observed radio profile provides the first constraint on the possible solution space. The two closely spaced peaks in the radio profile mean that the best-fit solutions must be located in the two narrow bands at $\beta \simeq \pm 5$ (Figure 6.4). The width of the two-peak radio profile is accurately reproduced, but it is difficult to reproduce both the correct phase difference between the two radio peaks (Δ_r) and the relative intensity of the minimum between the two peaks simultaneously. The relatively long period of this pulsar’s rotation is reflected in the solution space, in that the predicted

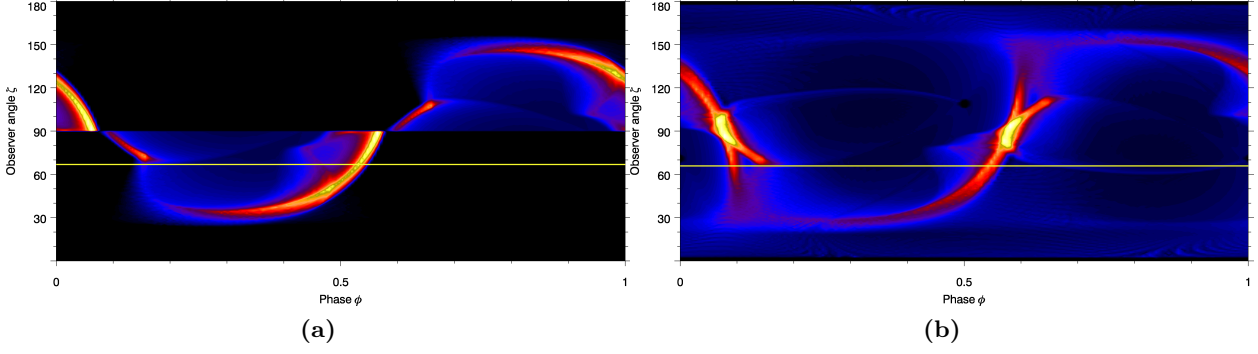


Figure 6.3: Cut phaseplots for the best-fit solutions of PSR J0631+1036. (a): OG, $(\alpha, \zeta) = (74^\circ, 67^\circ)$, and (b): TPC, $(\alpha, \zeta) = (71^\circ, 66^\circ)$.

radio emission is only visible in a narrow region along the diagonal, where $|\beta| < 13^\circ$, since the radio beam is relatively smaller in this case. The range of possible β values is further constrained by the requirement to reproduce Δ_r . LCs on or near the diagonal $\alpha = \beta$ are effectively excluded as solutions, as Δ_r is too large there (see Figure 6.4, where the light grey area corresponding to single-peak solutions is excluded).

The TPC model predicts a secondary feature around 0.1 in phase with a relative intensity comparable to that of the main peak. When comparing this feature to a similar one predicted by the OG model (at similar (α, ζ) values), it can be seen that only one of the two “peaks” that make up the structure of this feature (the one at 0.15 in phase) is present in both predicted profiles. Looking at the phaseplots corresponding to these best-fit OG and TPC profiles (Figure 6.3 (a) and (b)), it can be seen that the first of the two peaks in this structure for the predicted TPC profile is attributable to emission originating below the null-charge surface, while the second peak in this structure can be ascribed to emission originating above the null-charge surface (See Sections 4.3.2 and 3.2).

The second constraint on the possible solution space is provided by the radio-to- γ phase lag required to fit the data. Profiles farther from the origin than about $(\alpha, \zeta) = (66^\circ, 66^\circ)$ in the OG case, and $(\alpha, \zeta) = (62^\circ, 62^\circ)$ in the TPC case (Figure 6.4), have main peaks sufficiently late in phase to reproduce the observed radio-to- γ phase lag. Boundaries (iv) and (vi) in Figure 6.4 indicate this. Further, it can be seen that the main peaks in these profiles move later in phase as one moves away from the origin along the constant- β diagonals, with these main peaks becoming too late in phase across the boundaries (i) and (v).

The last constraint on the possible solution space is provided by the secondary feature appearing roughly between 0.05 and 0.2 in phase discussed earlier. In the TPC case this constraint serves to completely eliminate all profiles at positive β . In the OG case, however, it can be seen that below boundary (ii), and above boundary (iii), the relative intensity of this secondary feature is high enough to classify the profiles beyond these boundaries as two-peaked, thus eliminating the predicted profiles as possible solutions.

It should be pointed out that, while the best-fit contours for both γ -ray models are bounded by the same constraint boundaries when considering radio peak multiplicity, separation, and reproduction of radio-to- γ phase lag, the OG contours appear slightly farther from the origin along the constant- β diagonals. This is due to the gap not being on the last open field line in the OG model, but between $r_{\text{ovc}} = 0.90$ and $r_{\text{ovc}} = 0.95$ (see Section 3.2). Furthermore, the TPC model predicts

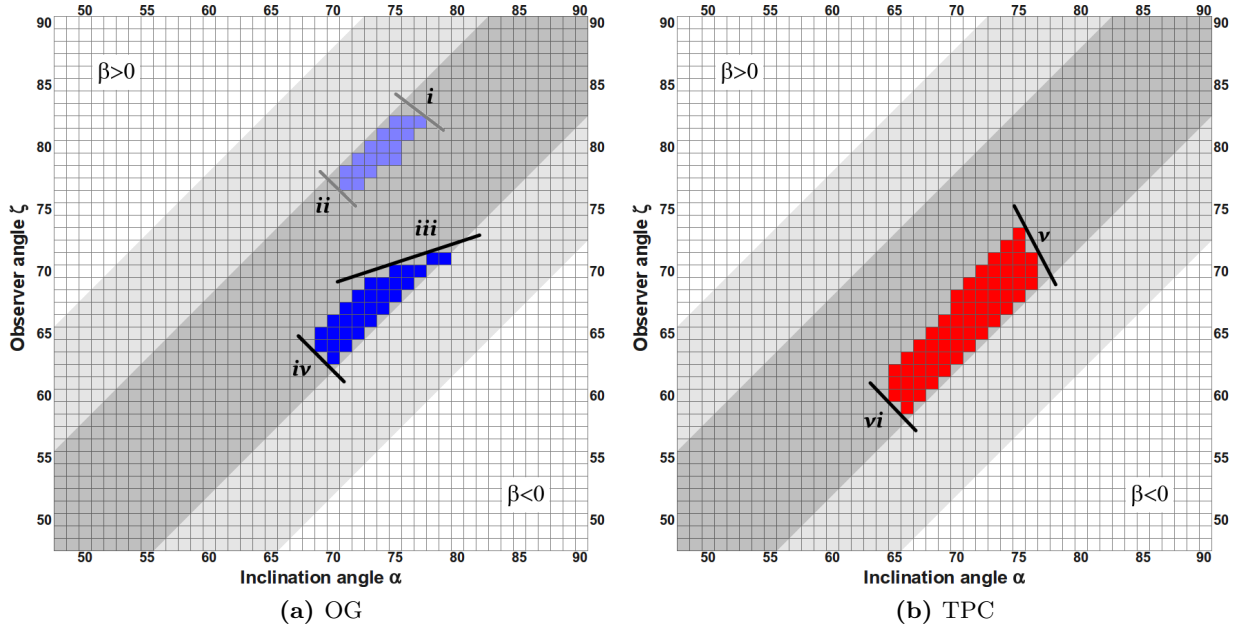


Figure 6.4: The solution contours for PSR J0631+1036 in phase space for the OG and TPC models. Radio LCs are produced in the grey band (along the diagonal) with the light grey and dark grey bands denoting single-peak and two-peak radio profiles respectively. The lines (*i-vi*) indicate boundaries to the contours due to the γ -ray profile. The faded contour in (*a*) indicates a possible solution contour rejected in favour of the non-faded contour.

higher off-peak emission than the OG model due to the emission originating below the null-charge surface, but it does not sufficiently overpredict the observed background emission to disqualify the predicted profiles as possible solutions. The predicted (α, ζ) are consistent, with errors, between the two γ -ray models.

Figure 6.4 shows the resulting solution contours in (α, ζ) -space. Region **I** in Figure 6.4 (*a*) is rejected in favour of region **II**. As illustrated in Section 5.1, values for α and ζ can be inferred by considering the extent of the remaining contours, yielding $(\alpha, \zeta) = (74^\circ \pm 5^\circ, 67^\circ \pm 4^\circ)$ in the OG case, and $(\alpha, \zeta) = (71^\circ \pm 6^\circ, 66^\circ \pm 7^\circ)$ in the TPC case. These correspond to derived values for β of $(-6^\circ \pm 2^\circ)$ and $(-5^\circ \pm 3^\circ)$ respectively.

Corresponding f_Ω values can be derived from these contours as described in Section 5.2. Figures 6.5(*a*) and (*b*) show the range of $f_\Omega(\alpha, \zeta)$ values allowed by the obtained solution contours. These correspond to values for f_Ω of (0.93 ± 0.06) in the OG case, and 1.04 ± 0.04 in the TPC case (see Table 6.1).

6.2.2 PSR J0659+1414 (B0656+14)

Background

Manchester et al. (1978) reported the discovery of PSR J0659+1414 (also known as PSR B0656+14) at radio frequencies (408 MHz) in the second Molonglo pulsar survey. For PSR J0659+1414 $P = 385$ ms and $\dot{P} = 5.50 \times 10^{-14}$ s.s $^{-1}$. Brisken et al. (2003) obtained a distance to the pulsar of 288^{+33}_{-27} pc via parallax measurements using very long baseline interferometry. PSR J0659+1414 is associated with the Monogem ring supernova remnant (SNR 203.0+12.0, Thorsett et al., 2003), which has a 25° diameter and is easily detectable as a bright, diffuse ring in soft X-rays. It also

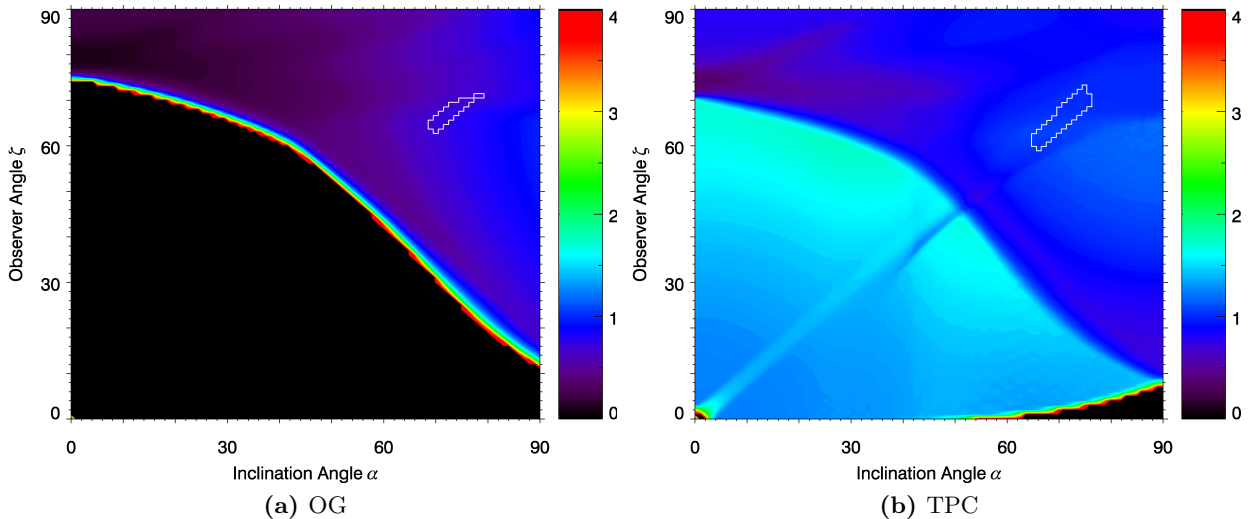


Figure 6.5: The f_{Ω} contours for PSR J0631+1036 with the (α, ζ) solution contours superimposed. The values reported for f_{Ω} are inferred from the range of values included inside the individual superimposed contours.

has a possible pulsar wind nebula (PWN) at optical (Shibanov et al., 2006) and X-ray (Marshall & Schulz, 2002) wavelengths.

In X-rays, PSR J0659+1414 is one of three very similar, isolated pulsars nicknamed the “Three Musketeers” by Becker & Truemper (1997). The other two are PSR B1055–52 and Geminga (PSR J0633+1746). PSR J0659+1414 is one of the brightest isolated NSs in the X-ray sky (Córdova et al., 1989). De Luca et al. (2005) concluded that the observed X-ray emission is consistent with a cooling middle-aged NS. The profile observed by *XMM-Newton* in soft X-rays is roughly sinusoidal, and is consistent with thermal emission from an NS with a non-uniform temperature distribution, with hotter polar caps. At higher energies, the non-thermal component of the X-ray emission dominates and the profile becomes a single peak. De Luca et al. (2005) also concluded that both the sinusoidal soft X-ray profile, which suggests that only one pole is visible from the Earth, and the low amount of modulation at soft X-ray wavelengths, point toward an aligned rotator. The modelling of the soft X-ray emission is, however, complicated by an apparent anti-correlation between the hot and cool black-body components of the thermal part of the emission, which can’t be easily understood without invoking significant multipole components of the magnetic field, or magnetospheric reprocessing of thermal photons (De Luca et al., 2005).

Caraveo et al. (1994) reported the detection of a possible optical counterpart to PSR J0659+1414, using ESO images. The association of this optical source with PSR J0659+1414 was confirmed by Kern et al. (2003), who observed non-thermal optical pulsations at the period of the radio pulsar. The optical LC has a two-peak structure similar to the γ -ray profiles observed in other pulsars such as the Vela pulsar. The first optical peak following the radio peak is aligned with the single γ -ray peak located at 0.21 in phase (Weltevredet et al., 2010), while the second peak’s position corresponds to that of the peak in the X-ray profile observed above 1.5 keV by *XMM-Newton*.

Ramanamurthy et al. (1996) reported a marginal detection of pulsed γ -rays from this pulsar by EGRET. The LC later observed by *Fermi* LAT is similar to the one seen by EGRET, but has a much lower background due to the superior angular resolution of *Fermi*. The γ -ray efficiency of PSR J0659+1414 is very low, at 0.0084 ± 0.0008 , assuming $f_{\Omega} = 1$ and that the pulsar is at the

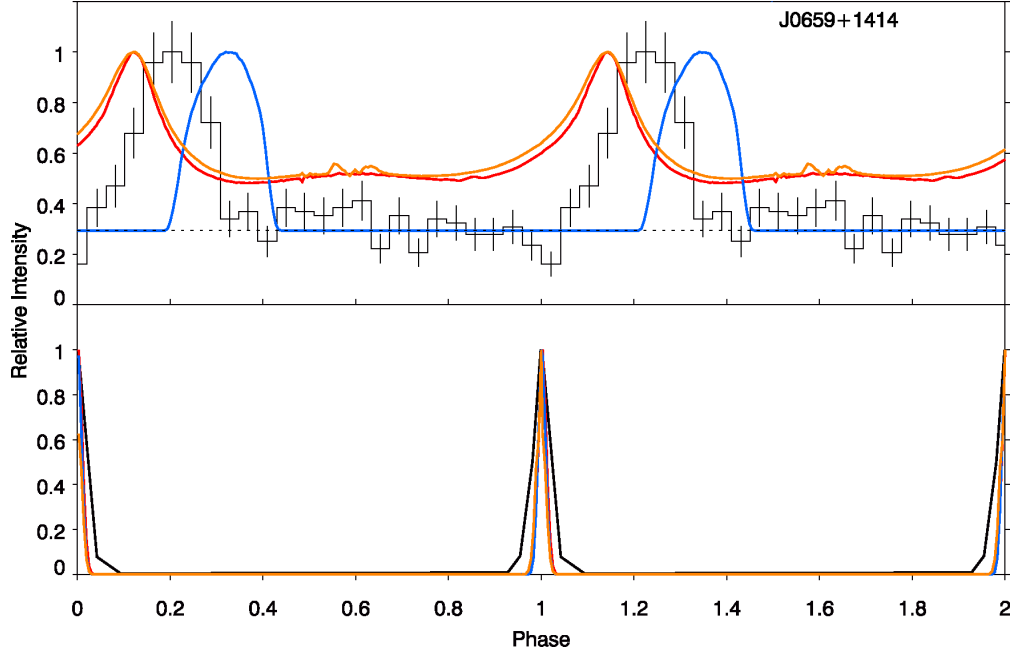


Figure 6.6: OG (*blue*) and TPC (*red* and *orange*) best-fit model pulse profiles for PSR J0659+1414.

distance reported by Brisken et al. (2003) (Weltevrede et al., 2010). This low efficiency can not be due to an underestimated luminosity, as the distance to the pulsar is well known.

The radio and γ -ray LCs

The radio profile of PSR J0659+1414 at 1.4 GHz is roughly triangular, with a width of approximately 0.1 in phase.

The γ -ray profile of PSR J0659+1414 has a single peak with $\text{FWHM} = 0.2$, lagging the radio peak by 0.21 (Weltevrede et al., 2010). This is the smallest radio-to- γ phase lag of all the pulsars in this study, and proves very difficult to reproduce.

The best-fit LC solutions

Figure 6.6 shows the best-fit profiles predicted by the OG and TPC models. In both cases, single-peak profiles are predicted, but in the TPC case the background (off-pulse) emission intensity is significantly overpredicted. Both the predicted OG and TPC profiles fail to reproduce the required radio-to- γ phase lag. The width of the radio profile is also not well reproduced, but this is due to the long period of this pulsar compared to, e.g., PSR J1420–6048. Recall from Section 4.4 that the width of the predicted peaks of single-peak radio profiles decreases as P increases.

The first constraint on the possible solution space is provided by the requirement of radio visibility and peak multiplicity, and confines the possible solution space to lie in two narrow diagonal bands along lines of constant β . These are diagonals with $-15^\circ \leq \beta \leq -7^\circ$ and $7^\circ \leq \beta \leq 15^\circ$, indicated by the light grey bands in Figure 6.8. The single-peak radio profile of this pulsar results in contours that cover a larger range in β ($\sim 8^\circ$ compared to $\sim 4^\circ$) than those of PSR J0631+1036, which had an observed two-peak radio profile.

The position of the peak in the γ -ray profile of this pulsar is hard to fit with either the OG or TPC model, as it is too early in phase to be produced by cutting the phaseplot tangent to the

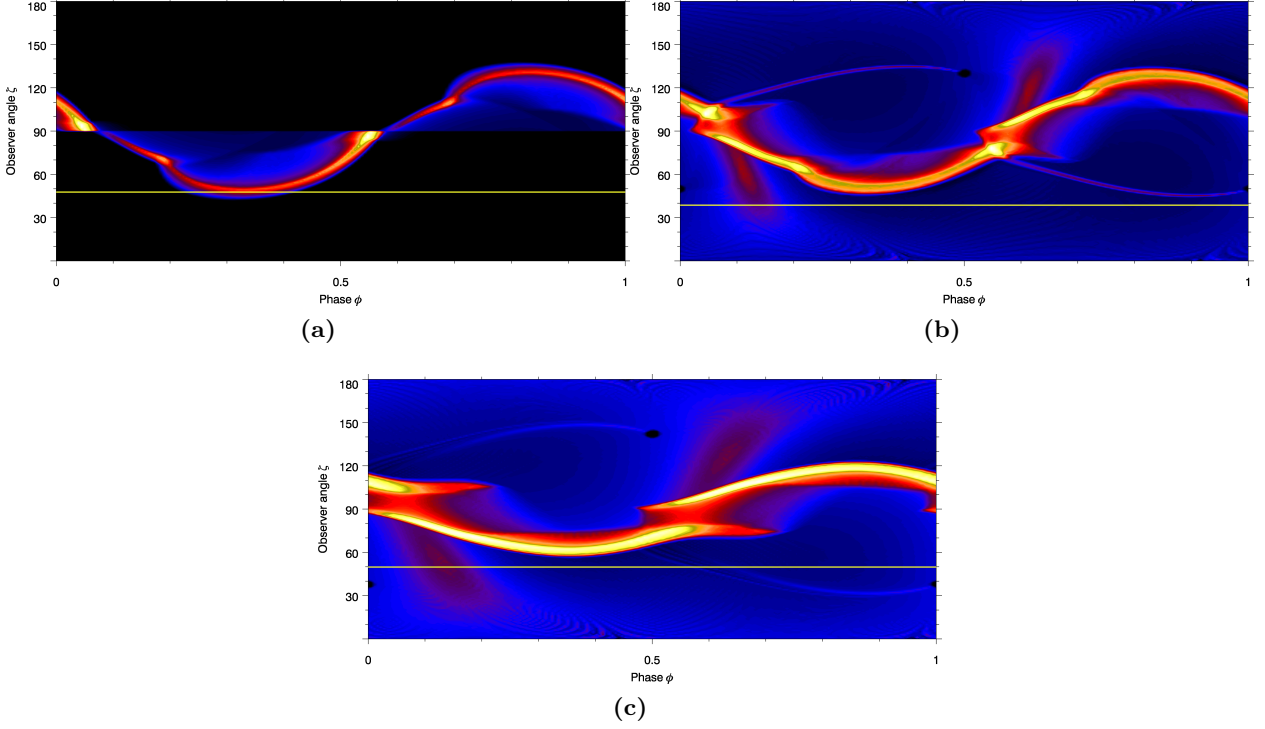


Figure 6.7: Cut phaseplots for the best-fit solutions of PSR J0659+1414. (a): OG, $(\alpha, \zeta) = (59^\circ, 48^\circ)$, (b): TPC, $(\alpha, \zeta) = (50^\circ, 39^\circ)$, and (c): AltTPC, $(\alpha, \zeta) = (38^\circ, 50^\circ)$.

caustic, where most single-peak profiles are encountered (see Section 4.1). For the OG case, the single-peak profiles produced by means of these cuts are the closest fit to the data, although the main peak appears around 0.35 or later, whereas the data show a peak at 0.21. The TPC model, however, does not produce single-peak profiles for such tangential cuts, but has a secondary peak around 0.1 for the profiles in the narrow gap between regions **II** and **III** in Figure 6.8 (b). The origin of this peak can easily be understood when looking at Figure 6.7. Profiles in the gap between boundaries (ix) and (x) have a two-peak structure, and can be understood as being composed of two components: one associated with the “bump”, and one associated with the tangentially cut caustic. The smaller of the two peaks, the one associated with the “bump” around $(\phi, \zeta) = (0.15, 60^\circ)$, is produced by emission originating from below the null-charge surface, and as such is not present in the OG case, as is evident when comparing (a) with (b) and (c) in Figure 6.7. To understand how these two components interact, it is useful to move away from the origin along the $\beta \simeq -11^\circ$ diagonal (Figure 6.8 (b)), and consider how the profiles change. Starting inside region **III** in Figure 6.8 (b), single-peak profiles produced by cutting only through the “bump”, as in Figure 6.7 (b) and (c), can be seen. At boundary (x) the cut intersects both the bump and, tangentially, the caustic, producing two-peak profiles. The component attributable to the caustic, however, very quickly becomes significantly more intense than the component due to the bump, again resulting in roughly single-peak profiles as the boundary (ix) is crossed, similar to those produced at comparable (α, ζ) using the OG model, but with the secondary component due to the bump still present. While the relative intensity of this component remains constant at around 0.4–0.5, its continued presence in the LCs farther from the origin along the $\beta < 0^\circ$ diagonal serves to broaden these γ -ray profiles sufficiently to disqualify region **II** from the possible solution space.

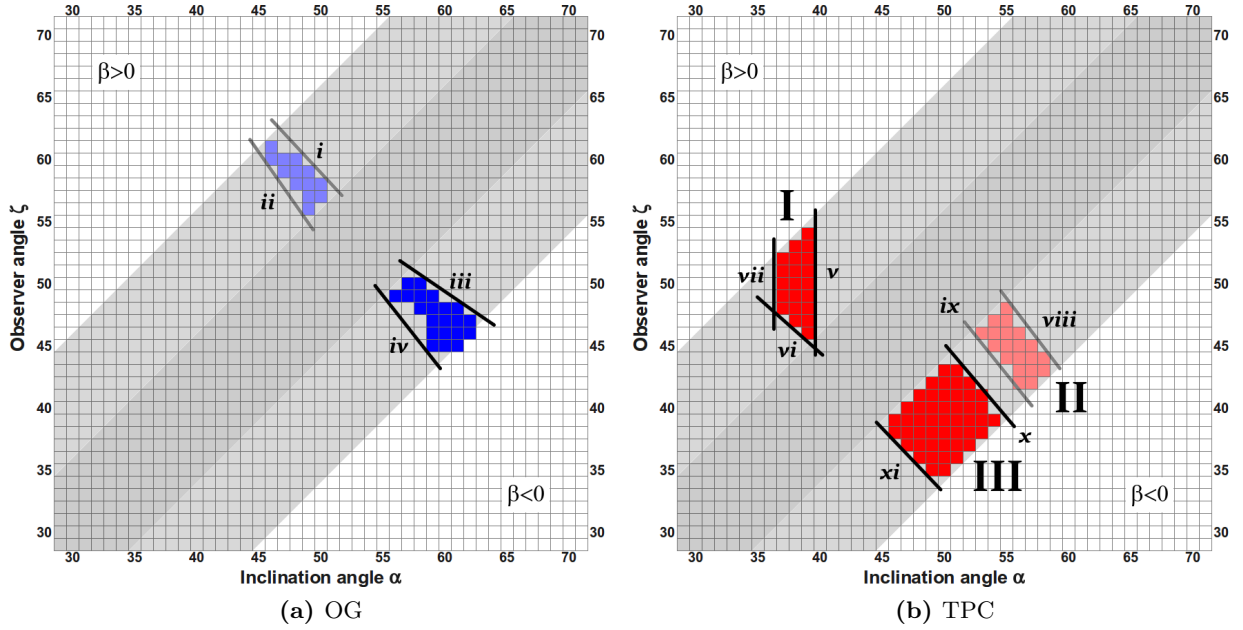


Figure 6.8: The solution contours for PSR J0659+1414.

It is interesting to note that boundary (x) is roughly co-located with the γ -ray visibility boundary for the OG model. Also, while the OG model predicts no off-pulse emission, the TPC model overpredicts the relative intensity of the background for profiles closer to the origin in (α, ζ) -space along the $\beta \simeq -11^\circ$ diagonal than approximately $(\alpha, \zeta) = (37^\circ, 48^\circ)$, which constitutes boundary (xi). Boundaries (vi) and (vii) arise similarly (region **I** in Figure 6.8 (b)).

The last TPC boundary to account for is boundary (v), bounding the region at positive β in Figure 6.8 (b). The γ -ray profiles become two-peak beyond this boundary, despite still cutting the caustic almost tangentially. The secondary peak in the profiles beyond this boundary at first appears close to the main peak in phase, but rapidly moves toward later phases as α is increased. This peak, while not comparable in intensity, is much sharper than the main peak for most of these profiles, except for those profiles where it has moved to very late phases. This secondary peak is produced by cutting through the “footprint” of the so-called notch produced by bunching magnetic field lines visible in Figure 6.7 (a) and (b) as thin lines extending from the polar caps, which correspond to the dark circles (see Section 3.2).

The OG contours (Figure 6.8 (a)) have lower boundaries at (ii) and (iv) going down the constant- β diagonals where the γ -ray profiles become too narrow (as the cuts start missing the visible γ -ray radiation), while the upper boundaries (i) and (iii) (as well as boundary ($viii$) in the TPC case, region **II**) show the point at which the profiles start exhibiting a two-peak structure due to diminished bridge emission. Note that the shape of the γ -ray profile would be a very good fit to the data if the requirement to reproduce the radio-to- γ phase lag was relaxed.

6.2.3 PSR J0742–2822 (B0740–28)

Background

Bonsignori-Facondi et al. (1973) reported the discovery of PSR J0742–2822, with $P = 167$ ms and

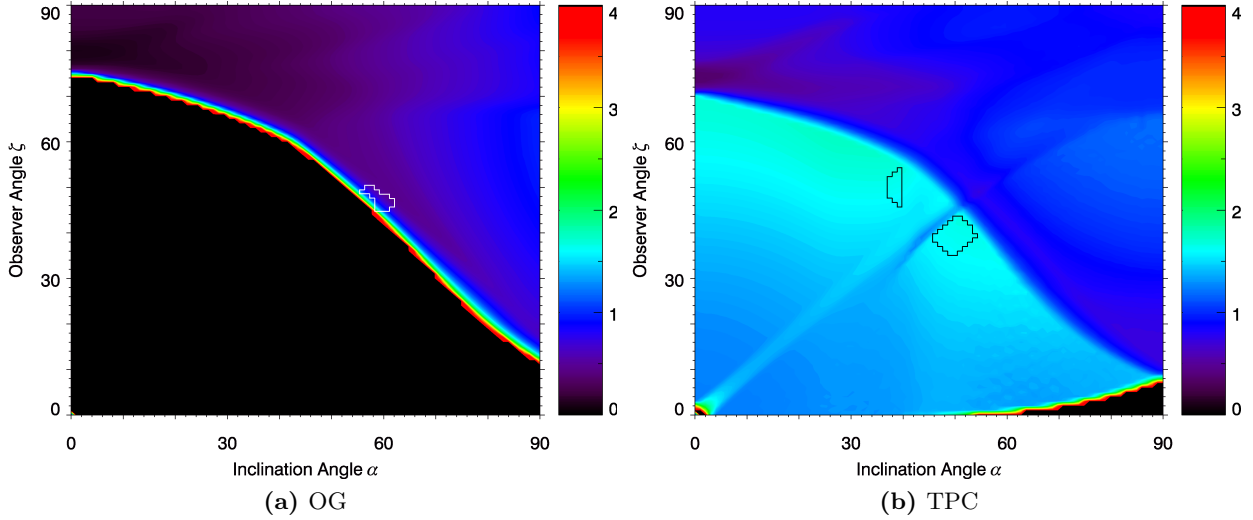


Figure 6.9: The f_{Ω} contours for PSR J0659+1414 with the (α, ζ) solution contours superimposed.

$\dot{P} = 1.69 \times 10^{-14} \text{ s.s}^{-1}$, at radio frequencies as a result of the Bologna 408 MHz pulsar search. The distance of 1.9 kpc derived by Bonsignori-Facondi et al. (1973) from the reported DM of $80 \pm 15 \text{ cm}^{-3} \text{ pc}$, using the Taylor & Cordes (1993) model, was argued by Koribalski et al. (1995) to be an underestimation after deriving a kinematic distance of between $2.0 \pm 0.6 \text{ kpc}$ and $6.9 \pm 0.8 \text{ kpc}$ from measurements of HI absorption spectra. Koribalski et al. (1995) argued that this difference was due to an overestimation of the electron density of the foreground Gum Nebula in this direction. The Cordes & Lazio (2002) model has a steep gradient in the electron density in this direction, and was constructed so that its distance predicted from the DM is consistent with the kinematic distance derived by Koribalski et al. (1995).

Weltevrede et al. (2010) reported a *Fermi* LAT γ -ray detection of PSR J0742–2822 above 0.1 GeV. Considering the above mentioned distance measurements, Weltevrede et al. (2010) adopted a distance of 2 kpc with the note that it could possibly be as distant as 7 kpc. They also note, however, that if the pulsar was at the distance upper limit of 7 kpc, as determined by Koribalski et al. (1995), the γ -ray efficiency would be $\sim 70\%$, and that such a large efficiency may indicate that PSR J0742–2822 is nearer than this distance upper limit.

The radio and γ -ray LCs

The radio profile of PSR J0742–2822 has a single peak with a small tail at its trailing end, extending at most to 0.1 in phase.

The γ -ray profile of PSR J0742–2822 is single-peak with $\text{FWHM} = 0.10$, with the main γ -ray peak lagging the radio peak by 0.61 in phase. The large radio-to- γ phase lag of PSR J0742–2822 is hard to reproduce with either the OG or TPC models.

The best-fit LC solutions

Figure 6.10 shows the best-fit profiles predicted for the OG and TPC cases. Both the width and peak multiplicity of the radio profile are easily reproduced. The fine structure of the radio peak resembles to some extent the profiles predicted by the radio model on the boundaries between single-

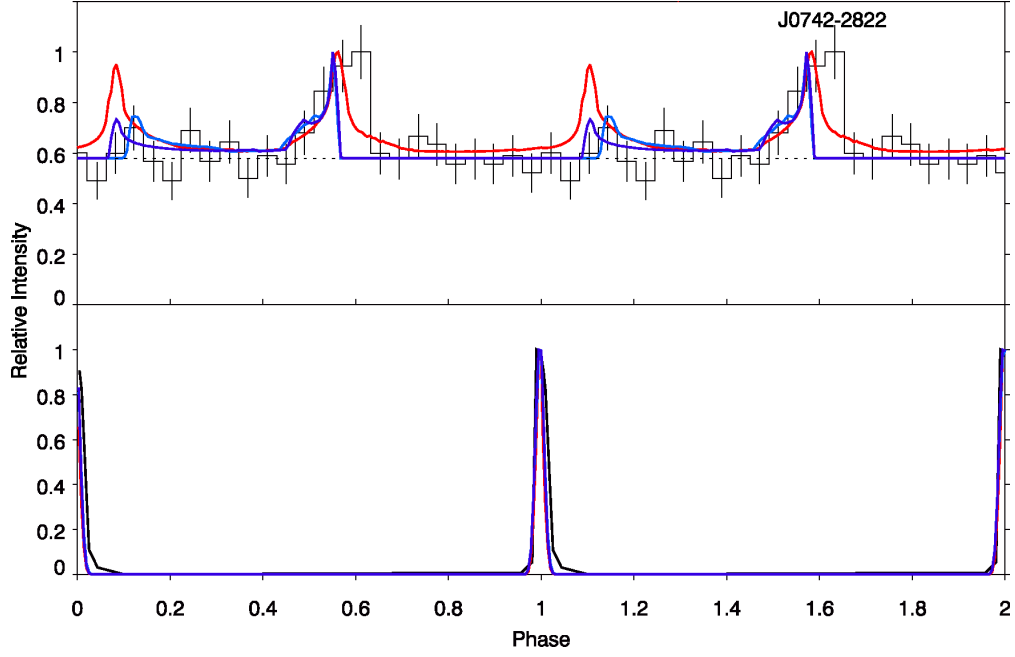


Figure 6.10: OG (*blue and purple*) and TPC (*red*) best-fit model pulse profiles for PSR J0742–2822.

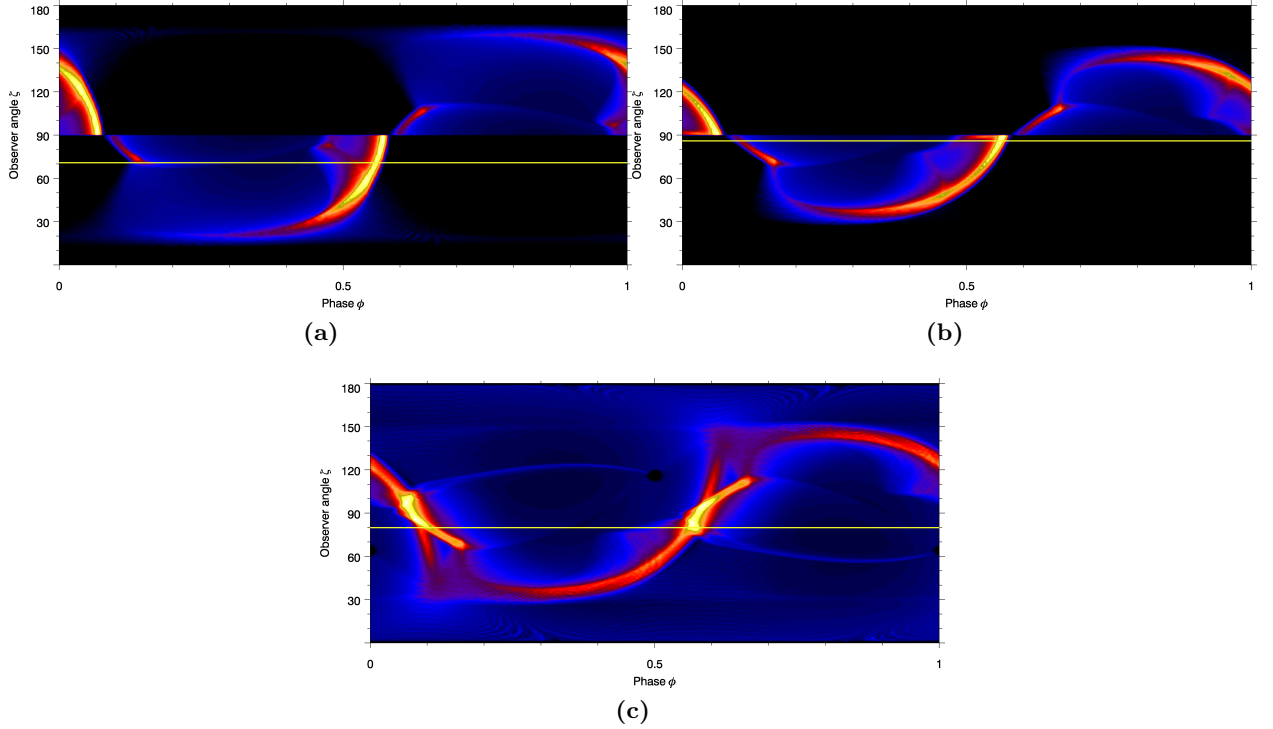


Figure 6.11: Cut phaseplots for the best-fit solutions of PSR J0742–2822. (a): OG, $(\alpha, \zeta) = (86^\circ, 71^\circ)$, (b): AltOG, $(\alpha, \zeta) = (71^\circ, 86^\circ)$, and (c): TPC, $(\alpha, \zeta) = (64^\circ, 80^\circ)$.

and two-peak profiles (the boundaries between the light and dark grey bands in Figure 6.12), but the solution space is not confined based on this similarity. The reason for this is that the characteristics of the predicted profiles in this transition region (i.e., having a complex structure at the peak) may be strongly influenced by the choice of mesh bin size in the geometric emission code. For modelling purposes, it is assumed that the radio profile is a single-peak one, and from this it is possible to

apply a first constraint on the possible solution space.

In Figure 6.12, the grey bands indicate where radio emission is visible, with single-peak and two-peak profiles being predicted in the light and dark grey bands respectively. The solution contours must lie within one, or both, of the light grey bands.

For both the OG and TPC cases (Figure 6.10), the radio-to- γ phase lag is reproduced, although the peak in the predicted γ -ray profiles corresponds more closely to the location of the centre of the observed γ -ray peak than to the location in phase where the strongest emission is observed. The profiles predicted by the OG model have sharper peaks, and drop off more sharply after the peak is reached than the profile predicted by the TPC model. The OG profiles also display some structure leading up to the main peak which is almost totally absent in the TPC profile. The TPC profile does, however, predict a significant secondary peak around 0.1 in phase. While the predicted OG profiles show a small feature around 0.1 in phase, it never becomes significantly intense to be comparable with the main peak.

The very large radio-to- γ phase lag of PSR J0742–2822 necessitates relatively high values for α and ζ for both the OG and TPC cases since a very high caustic cut is the only cut which can feasibly reproduce this large lag. Comparing phaseplots (a) and (b) in Figure 6.11 (OG phaseplots corresponding to $\alpha = 86^\circ$ and $\alpha = 71^\circ$ respectively), it can be seen that the range of ζ at which the radio-to- γ phase lag is reproduced, is larger for larger α (see Section 4.1). The radio-to- γ phase lag thus provides a second constraint on the solution contours, along with the radio peak multiplicity and visibility. Boundaries (ii) and (iii) in Figure 6.12 indicate where the predicted radio-to- γ phase lag becomes sufficiently large for the profile to be accepted as a possible solution.

For the TPC case, a secondary effect contributes to the establishment of a corresponding boundary (boundary (v) in Figure 6.12), in that the predicted secondary peak at early phases becomes too intense and broad. This secondary peak’s intensity becoming comparable with that of the main peak also serves as basis for boundary (iv) (in Figure 6.12 (b)).

The final constraint on the extent of the solution contours is provided by the fact that only radio emission from one magnetic pole should be visible. At the high values of α and ζ where these fits are found, one starts seeing radio emission from both poles of the pulsar (separated by ~ 0.5 in phase). Boundary (i) in Figure 6.12 shows where a second radio peak begins to appear in the predicted profiles.

6.2.4 PSR J1420–6048

Background

D’Amico et al. (2001) reported the discovery of PSR J1420–6048 as a result of the Parkes multi-beam pulsar survey, with $P = 68$ ms and $\dot{P} = 8.29 \times 10^{-14}$ s.s $^{-1}$. It was discovered as a possible counterpart at radio frequencies (1.4 GHz) to the EGRET γ -ray source 3EG J1420–6038, following the suggestion by Roberts et al. (1999) that a young, energetic pulsar is most likely responsible for this γ -ray source, as well as the observed PWN (the Rabbit PWN). PSR J1420–6048 is located within $\sim 0.3^\circ$ of the centre of the EGRET γ -ray source (Roberts et al., 2001), and PSR J1420–6048’s association with it is made even more plausible by its large spin-down power and distance (Weltevrede et al., 2010). However, the pulsating X-ray source PSR J1418–6058 in the Rabbit PWN, detected in γ -rays at a period of 111 ms by the *Fermi* LAT, is located only 0.24°

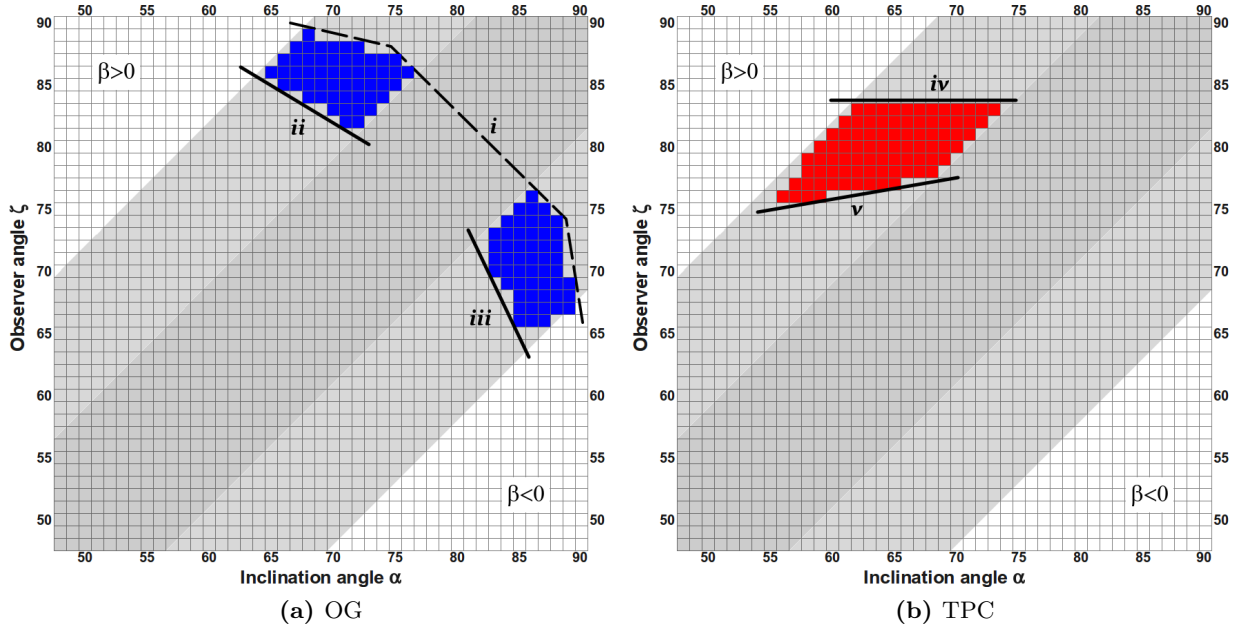


Figure 6.12: The solution contours for PSR J0742–2822.

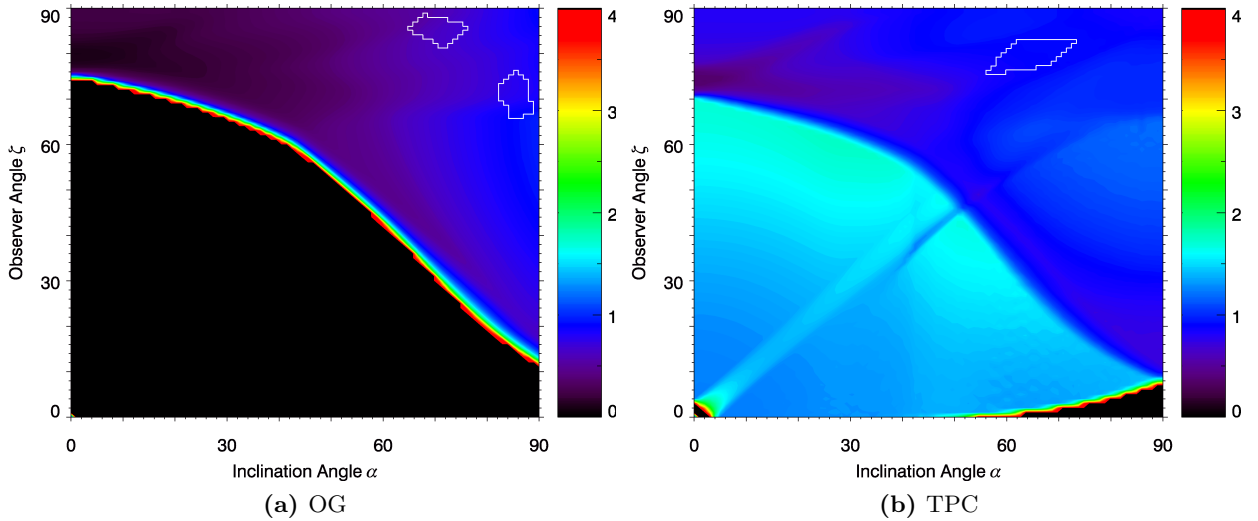


Figure 6.13: The f_{Ω} contours for PSR J0742–2822 with the (α, ζ) solution contours superimposed.

away from PSR J1420–6048, and 0.54° away from 3EG J1420–6038, making the association of PSR J1420–6048 with the EGRET source less clear cut. A weak detection of X-ray pulsations from the source PSR J1418–6058 was also reported by Ng et al. (2005), with a period of 108 ms, making this association even less clear.

Weltevrede et al. (2010) reported a *Fermi* LAT detection of pulsed γ -rays from PSR J1420–6048 at the same period as that of the radio pulsar. The reported background radiation level is an underestimation of the actual level by an unknown margin due to the small angular separation between PSR J1420–6048 and PSR J1418–6058. The background level reported by Weltevrede et al. (2010) does not take into account the flux of PSR J1418–6058, but rather estimates the background following a simple measurement of the flux in the $1^\circ - 2^\circ$ ring around the pulsar.

Roberts et al. (2001) also reported a marginal detection of X-ray pulsations at the radio pulsar’s

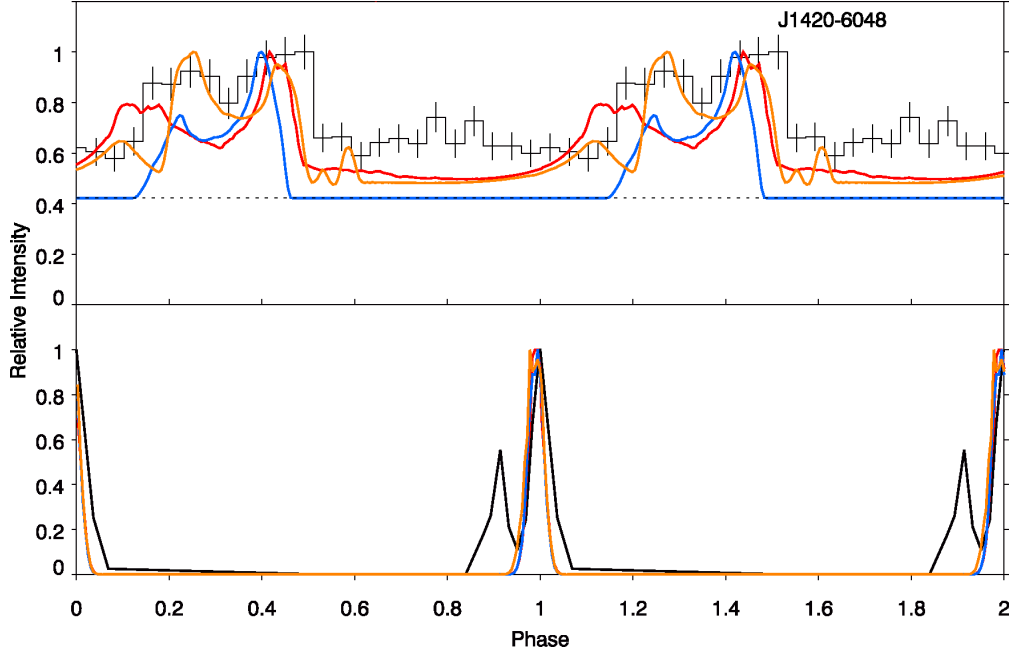


Figure 6.14: OG (blue) and TPC (red and orange) best-fit model pulse profiles for PSR J1420–6048.

period by *ASCA* from within the X-ray nebula AX J1420.1–6049.

The radio and γ -ray LCs

The radio profile of PSR J1420–6048 has a two-peak structure, with the later component being stronger. This pulse profile shape is commonly observed for young pulsars with characteristic ages of < 75 kyr (Johnston & Weisberg, 2006).

The γ -ray profile of PSR J1420–6048 has a broad, single-peak structure within current count statistics, but may develop into a two-peak profile as more data are added (Weltevrede et al., 2010). Viewed as such, the two possible peaks lag the radio profile by 0.26 and 0.44 in phase respectively, which would correspond to $\Delta_\gamma = 0.18$.

The best-fit LC solutions

The best-fit profiles predicted by the OG and TPC models are shown in Figure 6.14. The predicted radio profile agrees well with the second observed radio peak in terms of the width of the main peak, but does not have the required two-peak structure. Due to the asymmetry of the two-peak radio profile, the leading peak was ignored in the fitting process, as the conal radio model used in this study cannot produce profiles with a significantly weaker peak leading the main peak.

The extent to which the radio-to- γ phase lag is reproduced is hard to evaluate due to the broad, flat structure of the γ -ray peak. It is further hampered by the possibility that the γ -ray profile may intrinsically be a two-peak profile, instead of a single-peak one. For the OG case, the predicted profile has a primary peak around 0.4 in phase, with a smaller secondary peak around 0.25 in phase. Between these two peaks considerable bridge emission is seen. The predicted radio-to- γ phase lag of this OG best-fit profile corresponds well with that of the possible ‘second observed peak’, while the secondary OG peak’s position corresponds well with that of the possible ‘first peak’, even though the relative intensity is considerably underpredicted in this area.

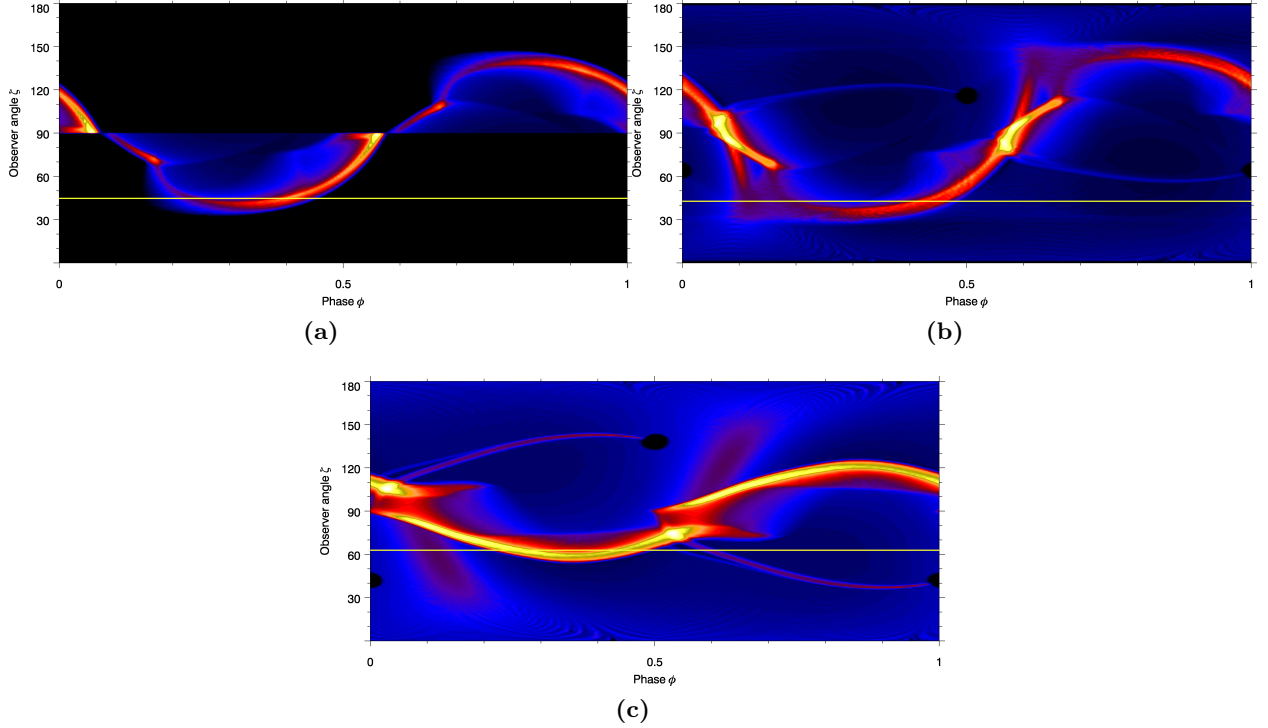


Figure 6.15: Cut phaseplots for the best-fit solutions of PSR J1420–6048. (a): OG, $(\alpha, \zeta) = (67^\circ, 45^\circ)$, (b): TPC, $(\alpha, \zeta) = (64^\circ, 43^\circ)$, and (c): AltTPC, $(\alpha, \zeta) = (42^\circ, 63^\circ)$.

While the first constraint on the possible solution space is provided by the radio visibility, which confines the possible solution space to $-30^\circ < \beta < -12^\circ$ and $12^\circ < \beta < 30^\circ$, the second constraint for both the OG and TPC cases is provided by the width of the observed γ -ray peak. Boundaries (ii), (iv), (vii), and (ix) in Figure 6.16 indicate where the peaks of the predicted γ -ray profiles become too narrow. These profiles are produced in the small region of (α, ζ) values where the cut through the phaseplot barely touches the edge of the caustic, as would be the case for the approximate range of $\zeta = 35^\circ$ to $\zeta = 40^\circ$ in Figure 6.15.

Boundary (i) in Figure 6.16 (a) indicates where the bridge emission between the main peak and the secondary peak sufficiently underpredicts the intensity of the observed emission to disqualify profiles farther away from the origin as solutions. This can be understood to be where the cut is made too far above the flat part of the caustic. Boundary (v) arises similarly.

The bridge emission becoming too low is not the only factor to take into account at high ζ beyond the caustic tangent region. At higher α , the intensity of the “swept-back” part of the caustic (around 0.1–0.2 in phase, usually responsible for the first peak in Vela-like pulse profiles) becomes very low. At even higher ζ ($\sim 80^\circ$), emission attributable to the small limb located between approximately 0.1 and 0.2 in phase can be seen (see Figure 6.15), but this still significantly underpredicts the “first peak” in the γ -ray profile. These two effects combine to produce boundary (iii), while boundaries (vi) and (viii) are due solely to the predicted bridge emission being much lower than the observed profile.

The TPC profile around $(\alpha, \zeta) = (64^\circ, 43^\circ)$ is much broader than that predicted in the OG case, although it still has a similar structure. The secondary peak in the TPC case is composed of two parts, one produced by the same phaseplot feature as in the OG case (the caustic; at about

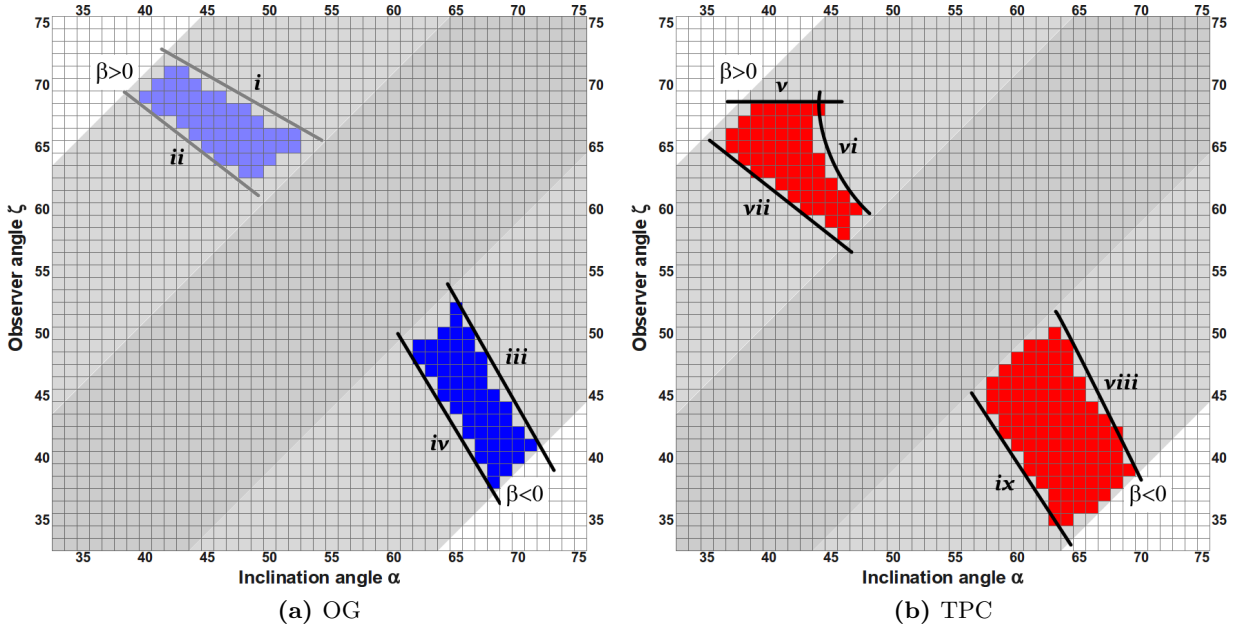


Figure 6.16: The solution contours for PSR J1420–6048.

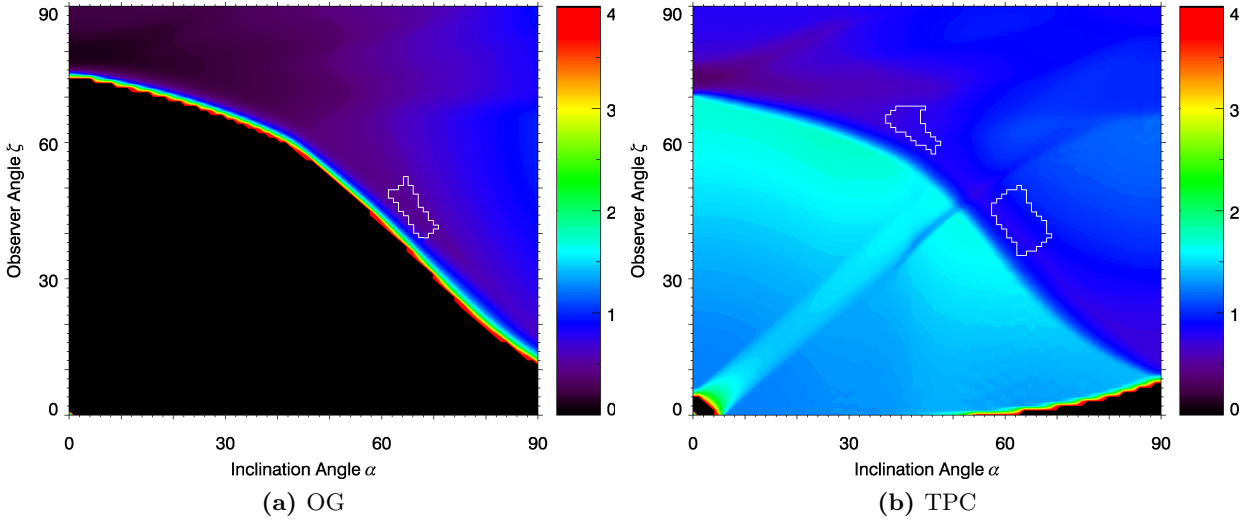


Figure 6.17: The f_{Ω} contours for PSR J1420–6048 with the (α, ζ) solution contours superimposed.

$\phi \approx 0.4$), and the other (the leading part) by the aforementioned “bump” feature (around 0.1 in phase) not present in the OG case. The TPC profile around $(\alpha, \zeta) = (42^\circ, 63^\circ)$, however, has a very different structure, and is produced by cutting the phaseplot as shown in Figure 6.15 (c). It has three small off-peak features. The earliest of is easily identified with the “bump” while the second and third ones are identified with the footprint of the notch in the magnetic field on the phaseplot ($\phi \sim 0.55$). Interestingly, for too low α values the constraint provided by the predicted bridge emission is no longer effective, and is superseded by the constraint provided by the width of the observed γ -ray profile, as the predicted profiles become too broad.

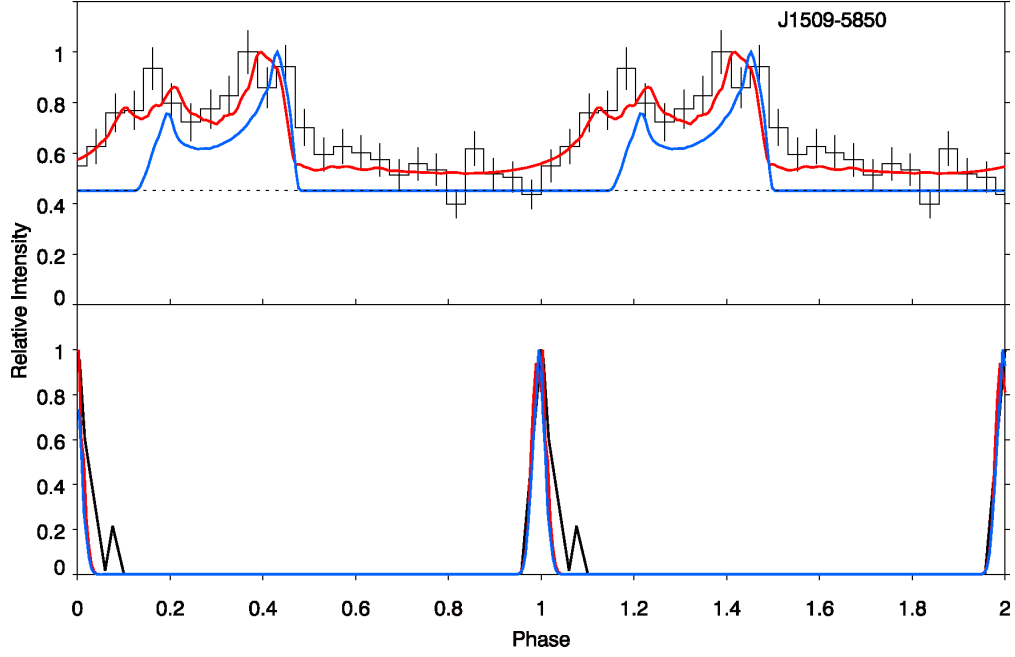


Figure 6.18: OG (blue) and TPC (red) best-fit model pulse profiles for PSR J1509–5850.

6.2.5 PSR J1509–5850

Background

Kramer et al. (2003) reported the discovery of PSR J1509–5850 at radio frequencies (1.4 GHz), resulting from the Parkes multibeam pulsar survey, with $P = 89$ ms, $\dot{P} = 0.92 \times 10^{-14} \text{ s.s}^{-1}$ (corresponding to $\tau_c = 154$ kyr), and $B_0 = 9.14 \times 10^{12}$ G. The pulsar has an associated PWN, as well as a very long tail of emission extending approximately $5.6'$ (corresponding to 4 pc) in the X-ray (Kargaltsev et al., 2008, using *Chandra* observations) and radio (Hui & Becker, 2007) bands. The distance to the pulsar derived by Kramer et al. (2003) using the Cordes & Lazio (2002) model is 2.5 ± 0.8 kpc, with a conservative distance uncertainty of 30%.

Weltevrede et al. (2010) reported the detection of PSR J1509–5850 in γ -rays using *Fermi* LAT. The derived γ -ray efficiency of $\sim 15\%$ is the largest efficiency of all the pulsars considered in this study, but this value isn't well constrained due to the uncertainty in the distance. This pulsar is not to be confused with PSR B1509–58 (a.k.a. PSR J1512–5908), which was seen in soft γ -rays by BATSE, OSSE, and COMPTEL on *CGRO* (Ulmer et al., 1993).

The radio and γ -ray LCs

PSR J1509–5850 is the weakest radio source of the pulsars considered in this study (Weltevrede et al., 2010), and has a roughly triangular, single-peak radio profile, having a small secondary peak following the main peak. The γ -ray profile of PSR J1509–5850 has a single, very broad peak (within current statistics), which could possibly resolve into two peaks with more data. These “two” peaks would lag the radio profile by 0.18 and 0.39 in phase if they corresponded to the locations of the strongest emission in this profile. This would correspond to $\Delta_\gamma = 0.21$ (Weltevrede et al., 2010).

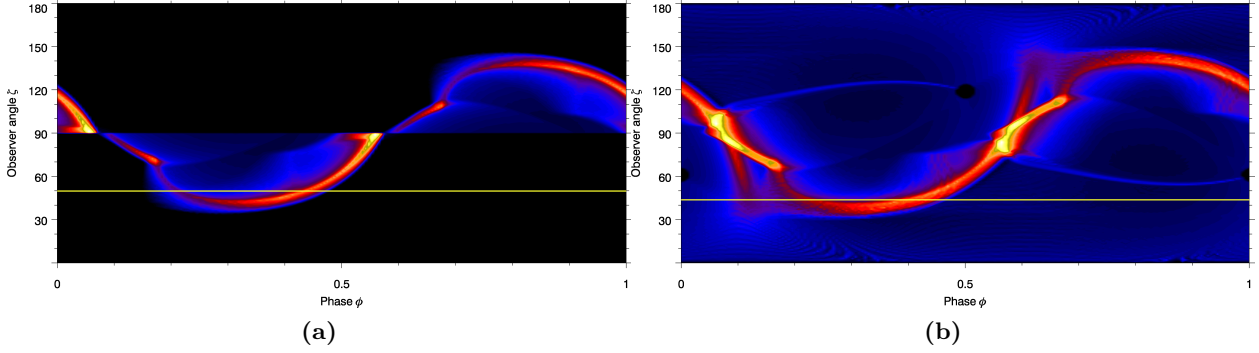


Figure 6.19: Cut phaseplots for the best-fit solutions of PSR J1509–5850. (a): OG, $(\alpha, \zeta) = (66^\circ, 50^\circ)$, and (b): TPC, $(\alpha, \zeta) = (61^\circ, 44^\circ)$.

The best-fit LC solutions

Figure 6.18 shows the best-fit profiles predicted by the OG and TPC models for PSR J1509–5850. The observed radio profile is reasonably well reproduced both in terms of peak multiplicity and width, ignoring the small feature lagging the main peak. The observed radio-to- γ phase lag is also reproduced in both the OG and TPC cases, although the width and structure of the predicted OG profile do not resemble the observed profile to the same degree as the predicted TPC profile.

The predicted OG profile has a main peak around 0.45 in phase, and a secondary peak around 0.2. The predicted OG profile displays quite significant bridge emission between this secondary peak and the main peak. Significantly, the predicted OG profile underpredicts the emission of the observed γ -ray profile, unlike the predicted TPC profile.

The predicted TPC profile shape corresponds remarkably well to the observed γ -ray profile, and also has a secondary structure around the location of the secondary peak predicted by the OG model. This secondary structure is more complex, though, and can roughly be described as being composed of two minor peaks. The first of these, around 0.15 in phase, can be attributed to the “bump” described in Section 6.2.2, while the second of these is produced by cutting the caustic in the same way as in the OG case (see Figure 6.19).

The solution contours for PSR J1509–5850 are shown in Figure 6.20. Boundaries (ii), (v), (vii), and (ix) indicate where the predicted γ -ray peak becomes too narrow; boundaries (i), (iii), and (vi) show where the radio-to- γ phase lag becomes too large; and boundaries (iv) and (viii) show where the bridge emission between the main peak and secondary peak becomes too weak. For a more detailed discussion of the origin of these boundaries, see Chapter 5, where PSR J1509–5850 is used as example to illustrate how these boundaries were obtained.

6.2.6 PSR J1718–3825

Background

Manchester et al. (2001) reported the discovery of PSR J1718–3825 at radio frequencies (1.4 GHz). This detection resulted from the Parkes multibeam pulsar survey, and for PSR J1718–3825 $P = 75$ ms and $\dot{P} = 1.33 \times 10^{-14}$ s.s $^{-1}$. The pulsar has an associated H.E.S.S. source, possibly a pulsar wind nebula (PWN) (Aharonian et al., 2007). Hinton et al. (2007) reported the discovery of an

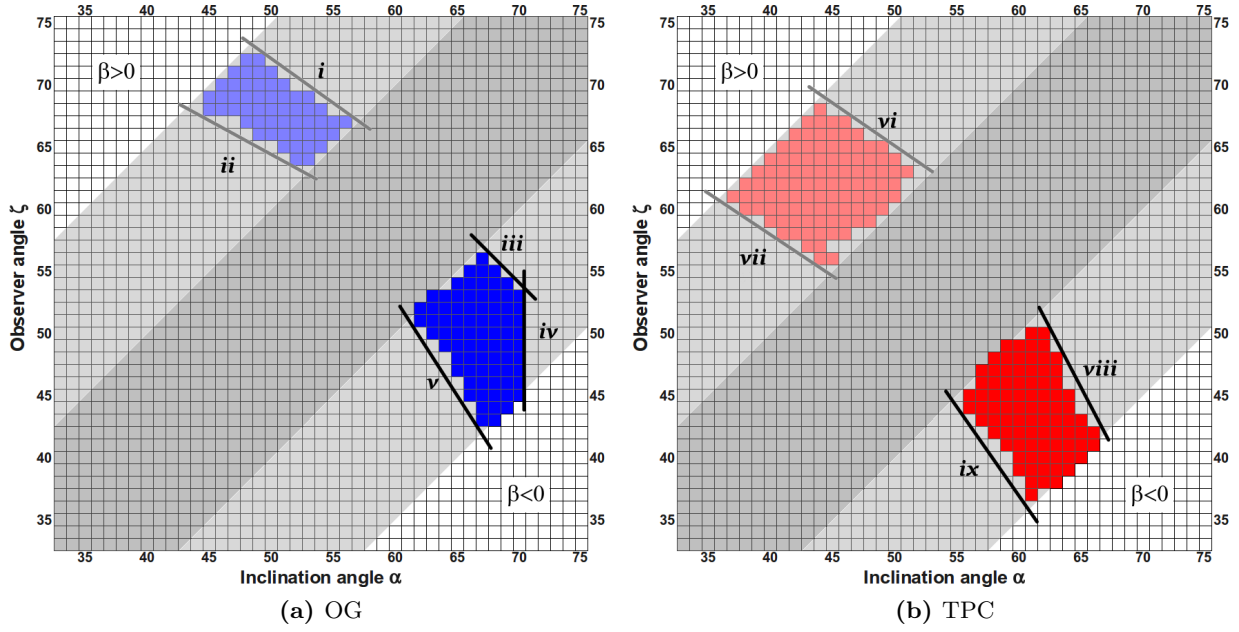


Figure 6.20: The solution contours for PSR J1509-5850.

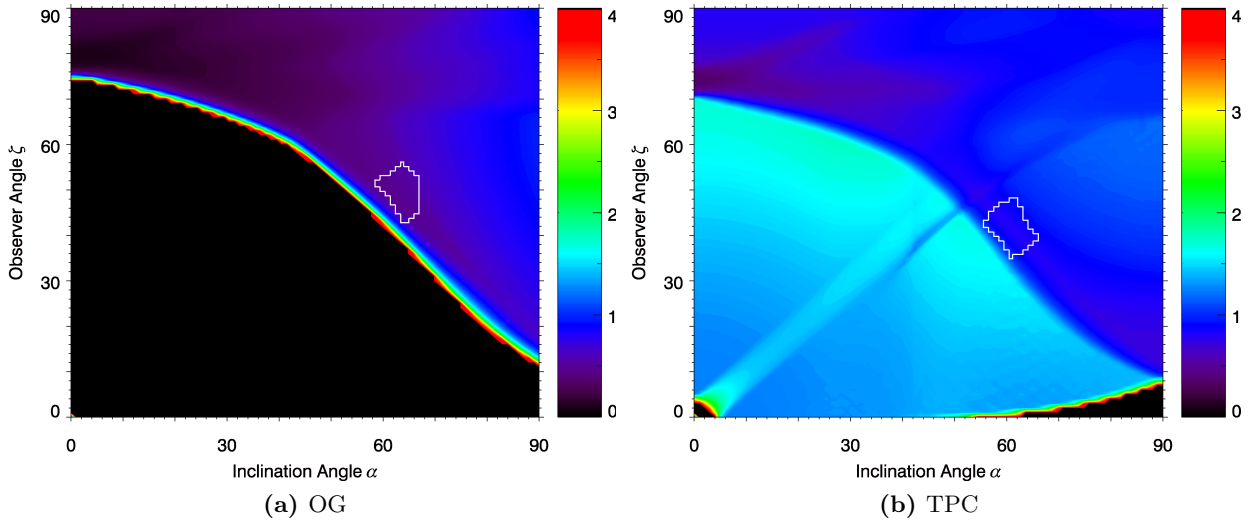


Figure 6.21: The f_{Ω} contours for PSR J1509-5850 with the (α, ζ) solution contours superimposed.

X-ray nebula around PSR J1718-3825 from *XMM-Newton* pointed observation data. Manchester et al. (2001) reported a DM of $247.4 \pm 3 \text{ cm}^{-3} \text{ pc}$, corresponding to a distance of $3.6 \pm 1.1 \text{ kpc}$ according to the Cordes & Lazio (2002) model.

The radio and γ -ray LCs

The radio pulse profile of PSR J1718-3825 consists of a strong peak, followed by a more complex structure extending to about 0.15 in phase. The average intensity of the emission over the extent of this structure is less than a third of that of the main peak.

The γ -ray pulse profile of PSR J1718-3825 has a single, broad peak (FWHM is 0.2 in phase; Weltevrede et al., 2010) lagging the radio profile by 0.42 in phase (see Figure 6.22).

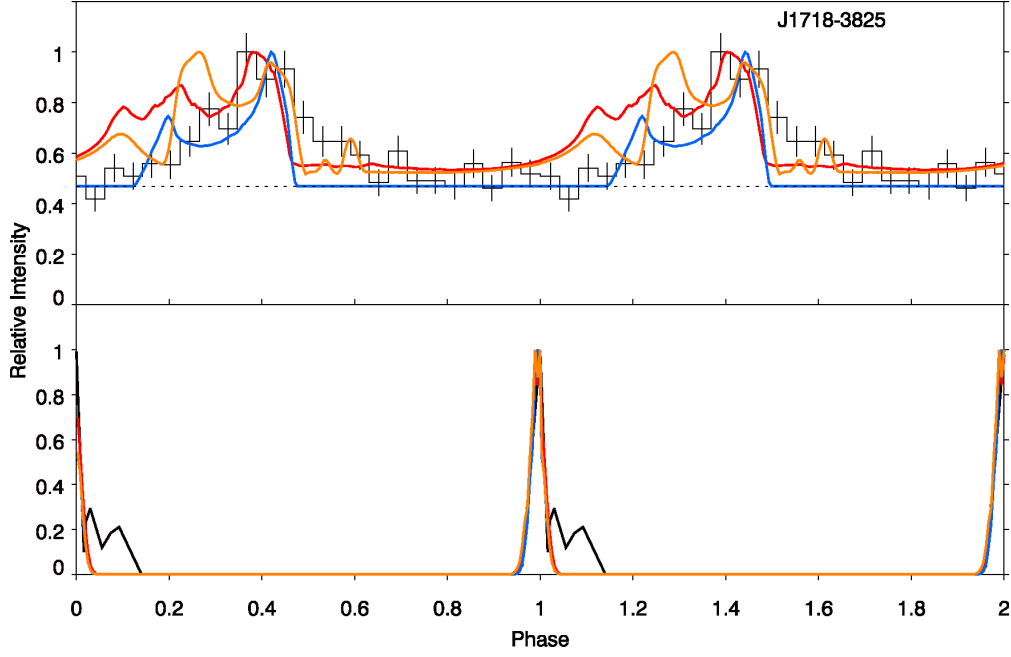


Figure 6.22: OG (*blue*) and TPC (*red* and *orange*) best-fit model pulse profiles for PSR J1718–3825.

The best-fit LC solutions

Figure 6.22 shows the best-fit solutions obtained for PSR J1718–3825. For both the OG and TPC cases, the width of the main radio peak and the radio-to- γ phase lag are reproduced. The requirement of a single-peak radio profile constrains the possible solution space to two bands, $-27^\circ < \beta < -12^\circ$ and $12^\circ < \beta < 27^\circ$. The best-fit profiles predicted by the TPC model both overpredict the intensity of the emission leading up to the main γ -ray peak, and subsequently drop off too sharply. For the fit at $\zeta = (42^\circ, 62^\circ)$ (*orange* in Figure 6.22), the profile can be described as two-peaked with the second of the two peaks corresponding to the main peak in the data. The best-fit profile predicted by the OG model has a small secondary peak at 0.2 in phase, with bridge emission between the two peaks similar to PSR J1420–6048 and PSR J1509–5850.

Figure 6.23 (*a*) shows the phaseplot predicted by the OG model for the best fit to the γ -ray profile of PSR J1718–3825 ($\alpha = 67^\circ$, cut at $\zeta = 48^\circ$). As described in Section 4.1, single-peak profiles are most commonly produced when a tangential cut is made (at $\zeta \sim 40^\circ$ in this case), with the peak located around 0.3 in phase. In the case of PSR J1718–3825, however, the γ -ray peak is located at 0.42 in phase, which means that the profiles produced in this manner underpredict the radio-to- γ phase lag. It also means that, to obtain the correct phase lag, the phaseplot needs to be cut at a higher ζ than where these purely single-peaked profiles are found. Only one region can be identified in (α, ζ) -space within which the location of the main peak corresponds well to that of the data, and that is the region around $(\alpha, \zeta) = (67^\circ, 48^\circ)$, thus disqualifying the diagonal band at positive β in Figure 6.24 (*a*) around $(\alpha, \zeta) = (48^\circ, 67^\circ)$. Furthermore, the width of the observed γ -ray peak also contributes to the disqualification of the majority of these purely single-peak profiles, as they are too narrow, constituting boundary (*ii*) in Figure 6.24 (*a*). The last consideration to provide a useful constraint on the possible OG solution space is whether or not the bridge emission between the main peak and the smaller secondary peak underpredicts the observed profile. It can be seen that when crossing boundary (*i*) in Figure 6.24 (*a*), the bridge emission in

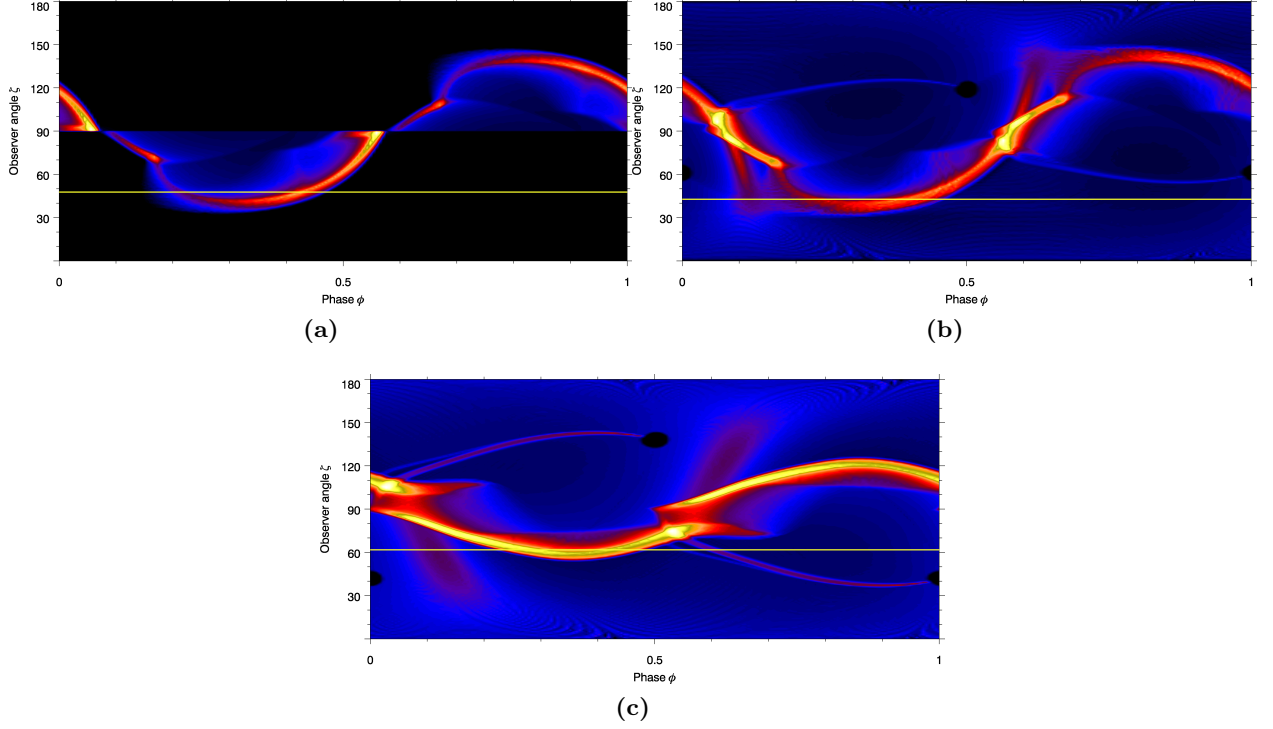


Figure 6.23: Cut phaseplots for the best-fit solutions of PSR J1718–3825. (a): OG, $(\alpha, \zeta) = (67^\circ, 48^\circ)$, (b): TPC, $(\alpha, \zeta) = (61^\circ, 43^\circ)$, and (c): AltTPC, $(\alpha, \zeta) = (42^\circ, 62^\circ)$.

the predicted profiles sufficiently underpredicts the intensity of the observed profile so as to justify their disqualification as possible solutions.

Figure 6.23 (b) and (c) show the phaseplots predicted by the TPC model. Again, a second constraint, in addition to that imposed by the radio visibility and peak multiplicity, is imposed on the possible solution space by the width of the observed γ -ray peak. This yields boundaries (v) and (vii) in Figure 6.24 (b) where the predicted γ -ray peak becomes too narrow. Crossing boundary (vi) in Figure 6.24 (b) along the $\beta \sim -20^\circ$ diagonal, the main peak in the predicted profile appears too late in phase, and the profile as a whole becomes too broad. Crossing boundary (iii) in Figure 6.24 (b), the peak closest in phase to the observed peak shifts too late in phase (in this case it is the second peak in a predicted two-peak profile), but this shift is accompanied by a second change, where the relative intensity of the second peak becomes too low, producing boundary (vi).

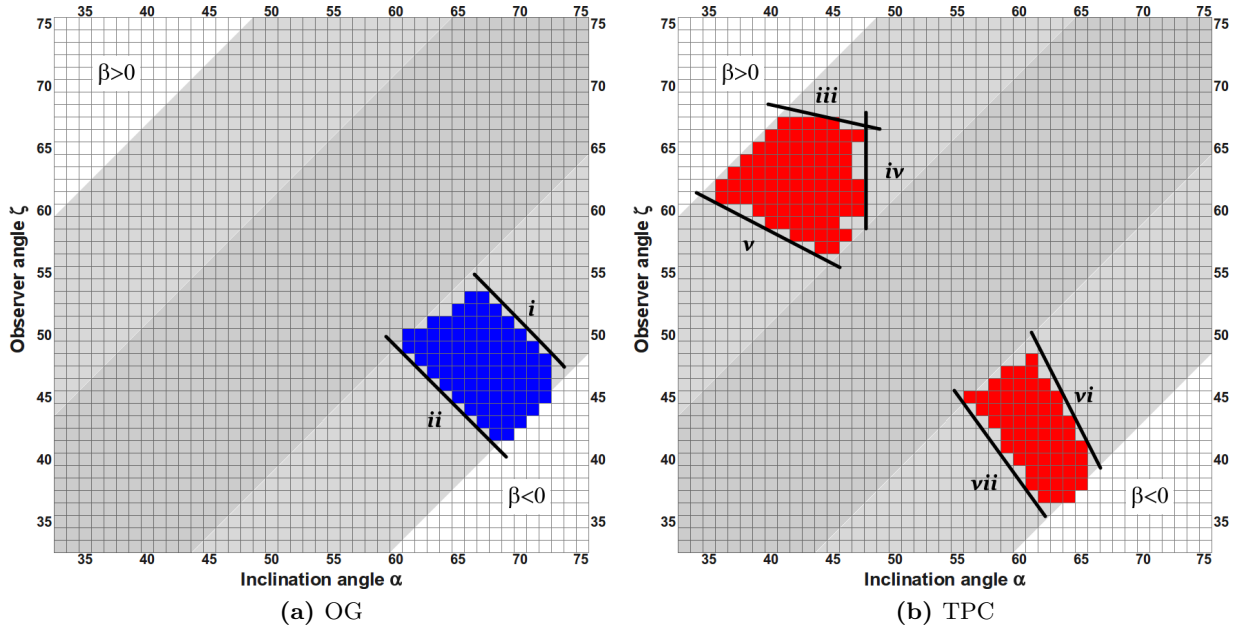


Figure 6.24: The solution contours for PSR J1718-3825.

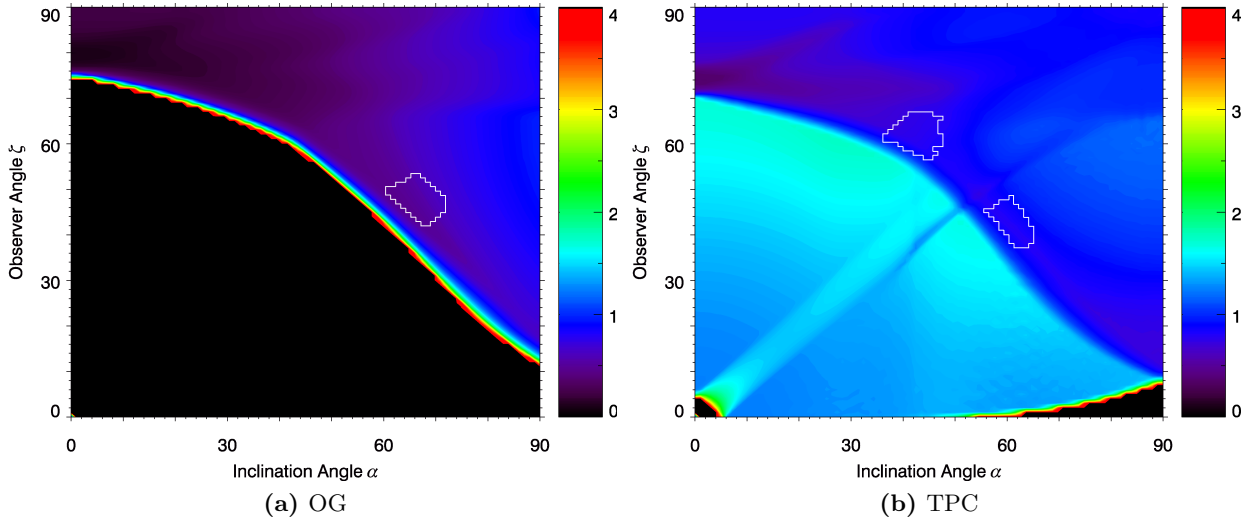


Figure 6.25: The f_{Ω} contours for PSR J1718-3825 with the (α, ζ) solution contours superimposed.