Modelling the γ-ray and radio light curves of the double pulsar system

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Abstract. Guillemot et al. recently reported the discovery of γ-ray pulsations from the 22.7 ms pulsar (pulsar A) in the famous double pulsar system J0737−3039A/B. The γ-ray light curve of pulsar A exhibits two peaks separated by approximately half a rotation, and these are non-coincident with the observed radio and X-ray peaks. This suggests that the γ-ray emission originates in a part of the magnetosphere distinct from where the radio and X-ray radiation is generated. Thus far, three different methods have been applied to constrain the viewing geometry of pulsar A (the inclination angle between its magnetic and rotation axes, and the observer angle): geometric modelling of the radio and γ-ray light curves, modelling of the position angle sweep in phase seen in the radio polarisation data, and independent studies of the time evolution of the radio pulse profile of pulsar A. These three independent, complementary methods have yielded consistent results: pulsar A's rotation axis is likely perpendicular to the orbital plane of the binary system, and its magnetic axis close to lying in the orbital plane (making this pulsar an orthogonal rotator). The observer is furthermore observing emission close to the magnetic axis. Thus far, however, current models could not reproduce all the characteristics of the radio and γ-ray light curves, specifically the large radio-to-γ phase lag. In this paper we discuss some preliminary modelling attempts to address this problem, and offer ideas on how the light curve fits may be improved by adapting the standard geometric models in order to reproduce the profile peak positions more accurately.

1. Introduction

Using the Parkes multibeam receiver Burgay et al. reported the discovery of a 22 ms pulsar, PSR J0737−3039A, in a close binary system. The derived orbital parameters implied that the system consists of two neutron stars [1]. The short orbital period (roughly 2.4 hr) coupled with the high orbital eccentricity (0.88) made this system the most rapidly merging neutron star binary yet discovered, with the eventual merger predicted to occur in approximately 85 Myr. This discovery was soon followed by the discovery of radio pulsations from pulsar A's binary companion, PSR J0737−3039B, with a pulsation period of 2.8 s [2]. The fact that both stars are observed as radio pulsars made this system the first of its kind and allowed very sensitive,

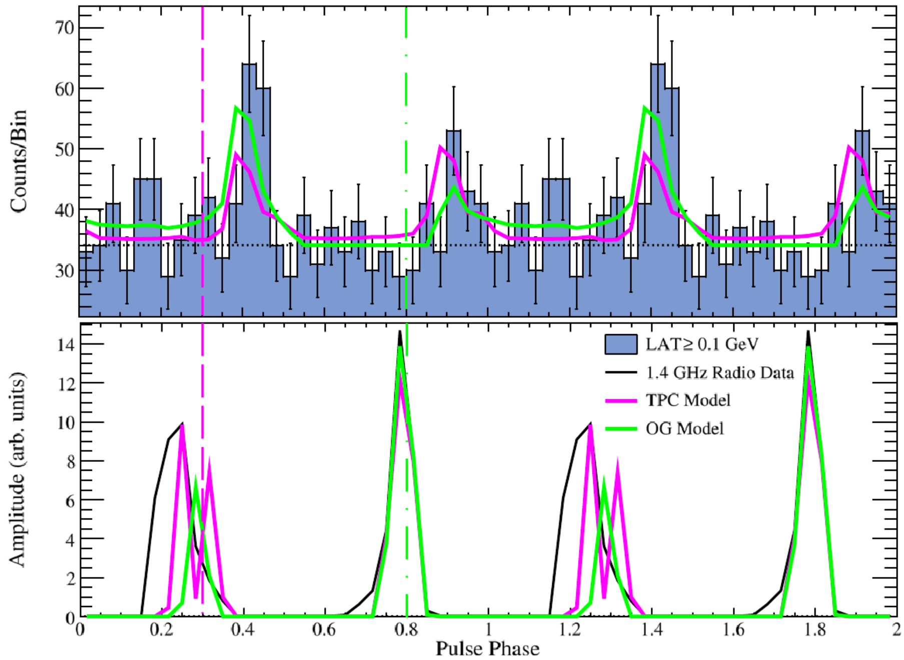


Figure 1: The phase-averaged observed radio (bottom; black; rebinned) and γ-ray (top; histogram) LCs for PSR J0737−3039A with best-fit solutions for the OG (green) and TPC (pink) geometric models. The horisontal dotted line on the γ-ray LC shows the estimated background level associated with PSR J0737−3039A. The vertical dashed and dash-dotted lines indicate the point in phase where the observer's line of sight is in the plane defined by the magnetic and rotation axes of the pulsar (the fiducial plane) for the the best-fit OG and TPC model LCs respectively [4]. The geometric parameters associated with these best-fit LCs are listed in Table 1.

and famous, confirmation of the predictions of Einstein's General Relativity using high precision measurements of the orbital motions of the two stars [3].

The discovery of pulsed γ-ray radiation from the millisecond pulsar PSR J0737−3039A [4] further added to the value of this system as there are relatively few pulsars with periods and period derivatives (with respect to time) similar to those of PSR J0737−3039A. PSR J0737−3039A is the first mildly recycled millisecond pulsar observed to emit in γ-rays.

2. Constraining the Geometry of PSR J0737−3039A

The first constraint on the viewing geometry of PSR J0737−3039A that can be obtained from the γ-ray and radio light curves (LCs) is that the two radio peaks are most likely associated with opposite magnetic poles as they are separated by about half a rotation in phase. This means that the inclination angle α between the magnetic and rotation axes of this pulsar is most likely close to 90°. Furthermore, the large radio-to-γ phase lag suggests that the radio and γ-ray radiation are produced in different regions of the magnetosphere. This large radio-to-γ phase lag is, however, very troublesome when trying to reproduce these LCs through standard model simulations.

Figure 1 shows the radio and γ-ray LCs observed for PSR J0737−3039A at 1.4 GHz and $\geqslant$0.1 GeV respectively. Both LCs display a widely-spaced two-peak structure. Note that two rotations of the pulsar are shown in the interest of clarity. Two sets of best-fit LC solutions are also shown. These were obtained using the outer gap (OG [5, 6]; green) and two-pole caustic

(TPC [7]; pink) geometric models for the γ-ray emission alongside a semi-empirical conal model [8] for the radio emission [4]. As can be seen in the bottom panel, the biggest difficulty when trying to fit the observed LCs is reproducing the large radio-to-γ phase lag, with the leading radio peak in the predicted LCs still lying too close to the trailing peak.

In addition to the radio and γ-ray LCs there are also high quality radio polarisation data available for PSR J0737−3039A with which the viewing geometry can be constrained. Fitting these data using a modified rotating vector model [9] yields a geometry consistent with the one found using the geometric models, with PSR J0737−3039A being an almost orthogonal rotator (see Table 1).

The last estimate of the geometric parameters to mention here is the one obtained by Ferdman et al., who studied six years of radio observations of PSR J0737−3039A [10]. By modelling the time-varying pulse widths they were able to constrain the geometry of PSR J0737−3039A. The results of their study agree very well with the results of the other two approaches discussed above (see Table 1).

3. Improving the geometric fits

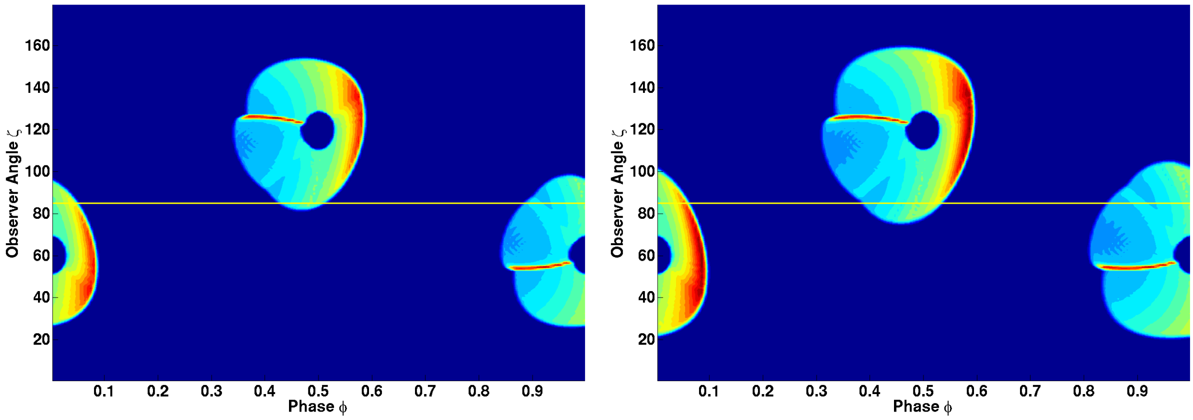
The good agreement between the results yielded by the three independent approaches increases our confidence in the identification of PSR J0737−3039A as an orthogonal rotator, but simultaneously poses a challenge to the geometric models employed. Neither geometric γ-ray model (OG or TPC) is able to reproduce the large radio-to-γ phase lag when coupled with the conal radio model. A refinement of the current models is clearly necessary, and we have made some attempts to rectify the problem.

The first alternative model invoked a low-altitude slot gap geometry for the radio emission (see [11] for the original slot gap model), coupled with the usual TPC model for the γ-rays. This geometry is proposed in the context of a radio cone producing radio peaks that lead the caustic γ-ray peaks. The profiles produced by this model still could not reproduce the radio-to-γ phase lag satisfactorily, even though the LC shapes were reasonable. Figure 2 shows fits obtained using this alternative model.

The second alternative model considered, instead, a conal structure for both the radio and γ-ray emitting regions, with the γ-ray region lying *lower* than the radio region. This configuration was motivated by the idea that the radio may indeed have a dominating leading peak, with the γ-ray LC leading the radio LC. It was however found that it is not possible to reproduce both the radio and γ-ray profile shapes simultaneously within the context of this model, leading us to abandon this scenario.

Table 1: The geometric parameters of PSR J0737−3039A as determined by three independent methods.

Method	α (°)	ζ (°)	Ref.
Geometric LC modelling (TPC)	80^{+9}_{-3}	86^{+2}_{-14}	[4]
Geometric LC modelling (OG)	88^{+1}_{-17}	74^{+14}_{-4}	[4]
Polarisation data fitting	$98.8^{+8}_{-1.5}$	$95.8^{+13.2}_{-4.3}$	[9]
Radio width analysis	$90.2^{+16.3}_{-16.2}$	$90.8^{+0.27}_{-0.46}$	[10]



(a) $R_{\rm max} = 0.15 R_{\rm LC}$ (b) $R_{\rm max} = 0.20 R_{\rm LC}$

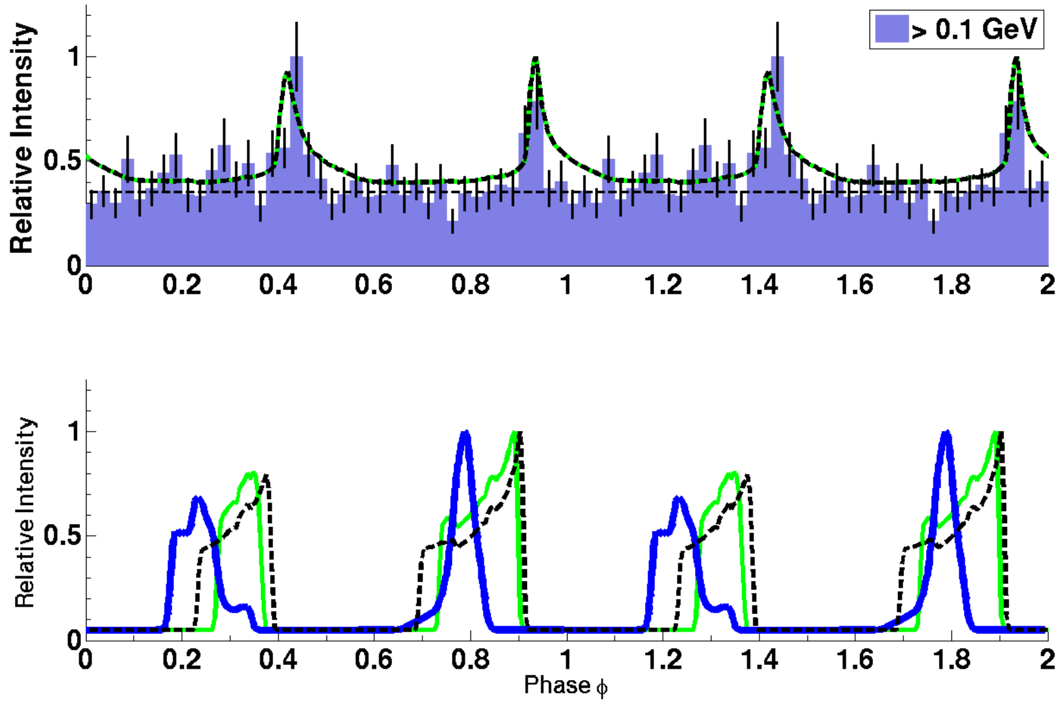


Figure 2: Best-fit LC solutions obtained using the first alternative model discussed in Section 3. For our fits we used the observed γ-ray LC weighted by the spectrum (histogram in the middle panel) and the 1.4 GHz radio LC (solid blue line in the lowest panel). The coloured plots at the top are radio intensity maps (or phaseplots) plotting relative intensity per solid angle as a function of rotational phase ϕ and observer angle ζ (the angle between the observer's line of sight and the rotation axis). The best-fit LCs are obtained from these phaseplots by cutting along lines of constant ζ (the yellow horisontal lines shown). The green radio LCs (obtained from phaseplot *(a)*) correspond to an emission gap extending from the pulsar's surface to a radius $R_{\rm max} = 0.15 R_{\rm LC}$, where $R_{\rm LC}$ is the radius of the light cylinder (where the corotation speed is c), and the black dashed radio LC (obtained from phaseplot *(b)*) corresponds to a gap extending from the pulsar's surface to $R_{\rm max} = 0.20 R_{\rm LC}$. In both cases the large radio-to-γ phase lag cannot be reproduced. For illustration, we used $\alpha = 60^\circ$ and $\zeta = 85^\circ$.

4. Future work

The fits obtained using the preliminary alternative models discussed in Section 3 may not be satisfactory, but they do point to interesting avenues of model refinement, e.g., the investigation of non-uniform emissivities, such as patchy or one-sided radio cones, or non-aligned radio and γ-ray cones. The fact that these LCs are hard to fit using the established geometric models, coupled with the unique characteristics of the system within which PSR J0737−3039A finds itself, suggests that there may be some form of interaction between the two pulsars, perhaps through their pulsar winds. Such an interaction may be observable through changes in the γ-ray LCs at the orbital period, but thus far no such periodic phenomenon has been observed. It may also be the case that the pulsar wind eminating from PSR J0737−3039B, and specifically the currents it constitutes, interacts with the magnetosphere of PSR J0737−3039A. This would mean that the structure of PSR J0737−3039A's magnetosphere may be different from what it would be if it was not a member of a binary pulsar system. Such a perturbed magnetosphere structure would mean that the geometry of the emitting regions may also be different. Such perturbations are currently not included in the geometric models employed thus far, and an investigation into how these two pulsars interact may lead to valuable refinements to the current geometric models.

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References

[1] Burgay M et al. 2003 *Nature* **426** 531–3
[2] Lyne A G et al. 2004 *Science* **303** 1153–7
[3] Kramer M 2006 *Science* **314** 97–102
[4] Guillemot L et al. 2013 *Astrophys. J.* **768** 169–77
[5] Cheng K S, Ho C and Ruderman M 1986 *Astrophys. J.* **300** 500–22
[6] Cheng K S, Ho C and Ruderman M 1986 *Astrophys. J.* **300** 522–39
[7] Dyks J and Rudak B 2003 *Astrophys. J.* **598** 1201–6
[8] Story S A, Gonthier P L and Harding A K *Astrophys. J.* **671** 713–26
[9] Craig H A and Romani R W 2012 *Astrophys. J.* **755** 137–44
[10] Ferdman R D et al. 2013 *Astrophys. J.* **767** 85–95
[11] Arons J 1983 *Astrophys. J.* **266** 215–41