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

A S Seyffert[1], **C Venter**[1], **A K Harding**[2] **and T J Johnson**[3,4]

[1] Centre for Space Research, North-West University, Potchefstroom Campus, Private Bag X6001, Potchefstroom 2520, South Africa

[2] Astrophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

[3] National Research Council Research Associate

[4] High-Energy Space Environment Branch, Naval Research Laboratory, Washington, DC 20375, USA

E-mail: `20126999@nwu.ac.za`

Abstract. Guillemot *et al.* recently reported the discovery [1] 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 (LC) of pulsar A has 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 (its inclination and observer angles α and ζ): 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 geometric 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 LC fits may be improved by adapting the standard geometric models in order to reproduce the profile 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 [2]. 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 [3]. The fact that both stars are observed as radio pulsars, a kind of system that had not yet been found, further added to this system's uniqueness and allowed very sensitive, and famous, confirmation the predictions

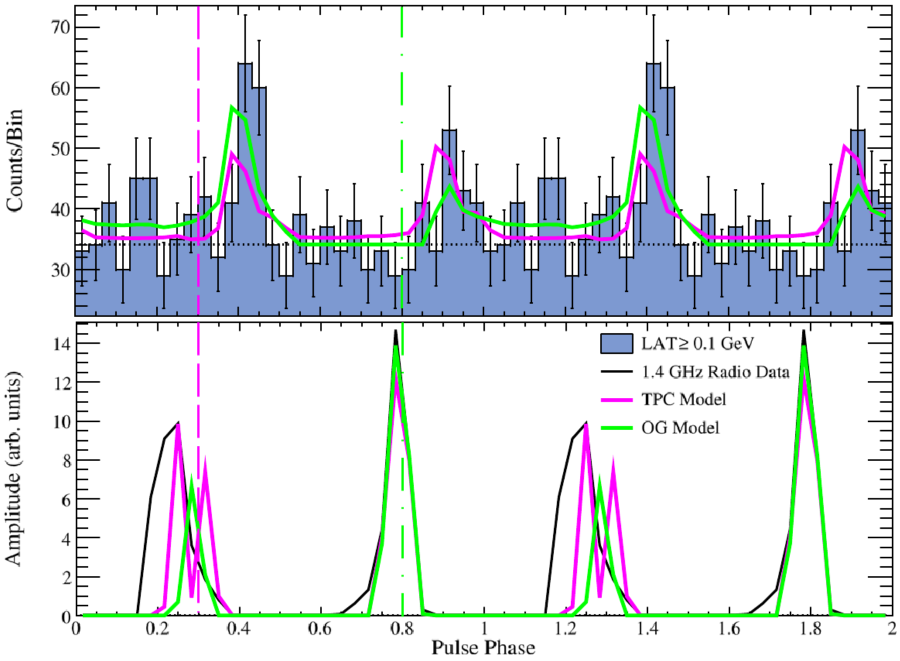

Figure 1: The observed radio (bottom) and γ-ray (top) LCs for PSR J0737−3039A with best-fit solutions for the OG (green) and TPC (pink) geometric models. The vertical dashed and dash-dotted lines indicate the closest approach to the magnetic axis under the best-fit TPC and OG models respectively [1].

of Einstein's General Relativity using high precision measurements of the orbital motions of the two stars [4].

The discovery of pulsed γ-ray radiation from the millisecond pulsar PSR J0737−3039A [1] further added to the value of this system as PSR J0737−3039A occupies a region on the P-$\dot{P}$ diagram relatively devoid of γ-ray pulsars. PSR J0737−3039A is the first mildly recycled millisecond pulsar yet observed to emit in γ-rays. Figure 1 shows the radio and γ-ray light curves (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.

2. Geometry of PSR J0737−3039A

The first constraint on the viewing geometry of PSR J0737−3039A derives from the fact that the two radio peaks are most likely associated with opposite magnetic poles, as the peaks 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 model simulations.

Figure 1 shows the best-fit LCs obtained for PSR J0737−3039A using the outer gap (OG [5, 6]) and two-pole caustic (TPC [7]) models for the γ-ray emission, alongside an empirical conal model [8] for the radio emission [1]. As can be seen in the bottom panel, the biggest difficulty when trying to fit these 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

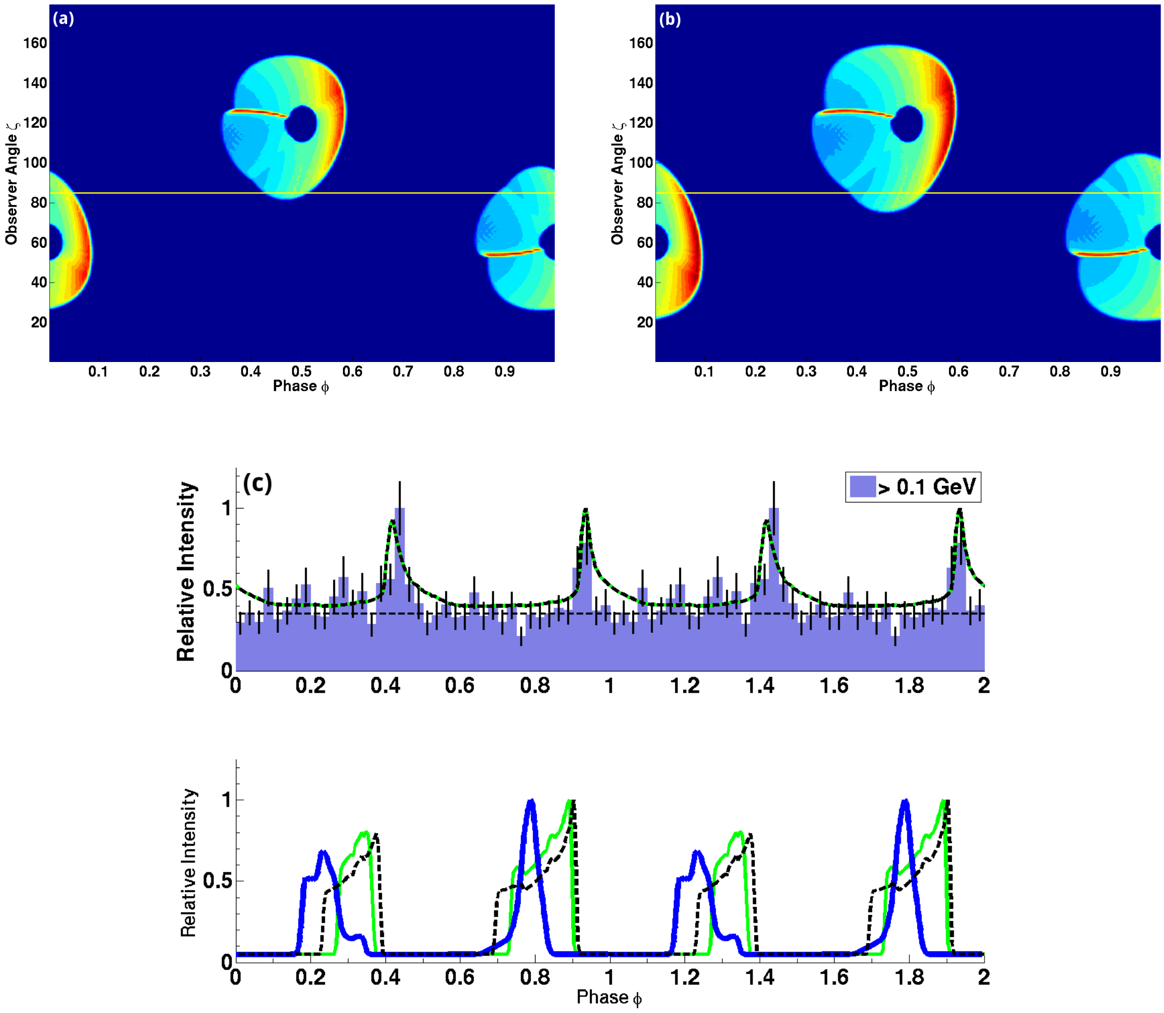

Figure 2: Fits obtained using the alternative model discussed in Section 3. The top panels show phaseplots for a low-altitude slot gap extending to a radius $R_{\rm max} = 0.15R_{\rm LC}$ (panel (a)), and for $R_{\rm max} = 0.20R_{\rm LC}$ (panel (b)), where $R_{\rm LC}$ is the light cylinder radius. The yellow line indicates a cut along $\zeta = 85^\circ$, yielding the LCs in panel (c). The green radio LC corresponds a radius $R_{\rm max} = 0.15R_{\rm LC}$, and the black dashed LC corresponds to $R_{\rm max} = 0.20R_{\rm LC}$. In both cases the large radio-to-γ phase lag cannot be reproduced. For illustration, we used $\alpha = 60^\circ$ and $\zeta = 85^\circ$.

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]. The results of their study agree very well with the results of the other two approaches discussed above.

3. Improving the geometric fits

The good agreement between the results yielded by the three independent approaches, as summarized in Table 1, increases our confidence in the identification of PSR J0737−3039A as an orthogonal rotator, but simultaneously poses a challenge to the geometric models employed.

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

Method	α (°)	ζ (°)	Source
Geometic modelling	80^{+9}_{-3}	86^{+2}_{-14}	[1]
Polarisation data fitting	$98.8^{+8.0}_{-1.5}$	$95.8^{+13.2}_{-4.3}$	[9]
Radio analysis	$90.2^{+16.3}_{-16.2}$	$90.8^{+0.27}_{-0.46}$	[10]

Neither the OG nor TPC γ-ray models, when coupled with the conal radio model, are able to reproduce the large radio-to-γ phase lag. A refinement of the current models is clearly necessary, and we have already 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 motivation behind this proposed geometry was to study the effect of lowering radio emission altitude. We probed the phase space spanned by four model parameters in this case: α, ζ, $R_{\rm min}$, and $R_{\rm max}$. The profiles produced by this model still could not reproduce the radio-to-γ phase lag satisfactorily, even though the LC shapes were still reasonable. Figure 2 shows fits obtained using this alternative model.

The second alternative model proposed, 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 (specifically the peak separation) simultaneously within the context of this model, leading us to abandon this scenario.

4. Future work

In this paper, we discussed the geometry of the double pulsar system, noting that three independent methods yielded similar results for α and ζ. A remaining issue that needs to be resolved is reproducing the relative phase lag between the radio and γ-ray pulse profiles. Pursuant to this, we investigated two alternative geometric models. Although the LC fits obtained using these preliminary models still could not provide correct radio peak positions, they do point to interesting avenues of model refinement. For example, we will investigate non-uniform emissivities, provided by patchy or one-sided radio cones, or misaligned 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 this pulsar finds itself, suggests that there may be some form of interaction between the two pulsars, perhaps through their stellar winds. Such an interaction may be observable through changes in the LCs at the orbital period, but thus far no such periodic phenomenon has been observed. It may also be the case that the stellar winds, and specifically the currents they constitute, perturb the usual magnetic field structure of the pulsars, and hence the geometry of the emitting regions. Such perturbations are 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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