Simulations of the light curves of an orthogonal radio pulsar

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Abstract

The recently-constructed theory [1] of radio wave propagation in pulsar magnetosphere outlined the general aspects of the radio light curve and polarization formation. It allowed us to describe general properties of mean profiles, such as the position angle of the linear polarization, p.a., and the circular polarization for the realistic structure of the magnetic field in the pulsar magnetosphere. In this poster we present application of our theory to the radio observations of PSR J1906+0746 (M. Kramer, private communication). This pulsar is particularly interesting because observations of relativistic spin-precession in a binary system allowed to put strong constraints on the geometry of the pulsar. The fact that pulsar is a nearly orthogonal rotator allowed to observe both magnetic poles, which as we show is crucial for testing our theory and obtaining constraints on the parameters of magnetospheric plasma. Our results show that plasma parameters are qualitatively consistent with theories of pair plasma production in polar cap discharges, e.g. plasma multiplicity λ ~ few x 10^3 and lorentz factor of secondary plasma γ ~ few hundreds.

Introduction

In this poster we simulate the general properties of radio profiles, such as the position angle of the linear polarization p.a. and the circular polarization V along the mean profile, of a nearly orthogonal rotator. Our aim is to improve some predictions of the 'hollow cone' model which could not explain observational data. The main theoretical prediction found in [1] is the correlation of signs of the circular polarization, V, and derivative of the position angle with respect to pulsar phase, dp.a./df, for both radio emission modes. The PSR J1906+0746 was discovered in a binary pulsar system in 1998 and was observed for 13 consecutive years. Relativistic spin-precession in binary pulsars, which arises from the misalignment of the spin vector of the pulsar with respect to the total angular momentum vector, led to a change in viewing geometry and to observed significant changes in polarization profiles. Observations show simultaneous switch of signs of circular polarization and dp.a./df of it's interpulse in the moment when the line of sight crosses the magnetic axis. This prediction is broadly consistent with the prediction of radio propagation theory [1]. However, understanding several observed features such as a second switch of sign of circular polarization and general morphology of the radio light curve require a more detailed modeling. Here we present the result of a detailed radiative transfer calculation under the same framework as in [1]. We take into account the distribution of pair production zones in the magnetosphere of a nearly orthogonal rotator [2], limiting polarization effect, realistic structure of the magnetic field, aberration and cyclotron absorption. As we show below, these calculations allow us to reproduce many observational features.

Propagation Theory. Limiting Polarization

The limiting polarization is a well-known propagation effect [3]. When the radiation escapes into the region of rarefied plasma, the wave polarization ceases to depend on the orientation of the external magnetic field. In the case when the dielectric tensor can be presented as $\varepsilon_{ij} = \varepsilon\delta_{ij} + \chi_{ij}$, where the anisotropic part χ_{ij} is much smaller than the isotropic one, we can write down the following evolution equations for the complex angle $\Theta = \Theta_1 + i\Theta_2$

$$\frac{\mathrm{d}\Theta_1}{\mathrm{d}l} = \frac{\omega}{2c}\mathrm{Im}\left[\varepsilon_{x'y'}\right] -\frac{1}{2}\frac{\omega}{c}\Lambda\cos[2\Theta_1 - 2\beta_B(l) - 2\delta(l)]\sinh 2\Theta_2,$$

$$\frac{\mathrm{d}\Theta_2}{\mathrm{d}l} = \frac{1}{2}\frac{\omega}{c}\Lambda\sin[2\Theta_1 - 2\beta_B(l) - 2\delta(l)]\cosh 2\Theta_2.$$

where Θ_1 is a position angle and Θ_2 determines the circular polarization : $V = I\tanh 2\Theta_2$. Here l is a coordinate along the ray propagation, and the angle $\beta_B(l)$ defines the orientation of the external magnetic field in the picture plane. Further,

$$\Lambda = \mp\sqrt{(\mathrm{Re}\left[\varepsilon_{x'y'}\right])^2 + \left(\frac{\varepsilon_{x'x'} - \varepsilon_{y'y'}}{2}\right)^2}$$

$$\tan(2\delta) = -\frac{2\mathrm{Re}\left[\varepsilon_{x'y'}\right]}{\varepsilon_{y'y'} - \varepsilon_{x'x'}}$$

where the signs correspond to the regions before/after the cyclotron resonance and the aberration angle δ results from electric drift motion $U_{\rm dr}$.

For homogeneous media (β_B = const, ε_{ij} = const) the parameters of polarization ellipse Θ_1 and Θ_2 remain constant if the following conditions are valid:

$$\Theta_1 = \beta_B + \delta, \qquad \sinh 2\Theta_2 = \frac{\mathrm{Im}\left[\varepsilon_{x'y'}\right]}{\Lambda} = -\frac{1}{Q},$$

$$\Theta_1 = \beta_B + \delta + \pi/2, \quad \sinh 2\Theta_2 = -\frac{\mathrm{Im}\left[\varepsilon_{x'y'}\right]}{\Lambda} = \frac{1}{Q}$$

In other words, it becomes true for eigenmodes. Here

$$Q = i\,\frac{\epsilon_{y'y'} - \epsilon_{x'x'}}{2\epsilon_{x'y'}}$$

In inhomogeneous medium one can put $\mathrm{d}\Theta_1/\mathrm{d}l \approx \mathrm{d}(\beta_B+\delta)/\mathrm{d}l$. It takes place up to so-called escaping radius $r_{\rm esc}$ [1]

$$r_{\rm esc} \sim 10^3 R \cdot \lambda_4^{2/5}\gamma_{100}^{-6/5}B_{12}^{2/5}\nu_{\rm GHz}^{-2/5}P^{-1/5}$$

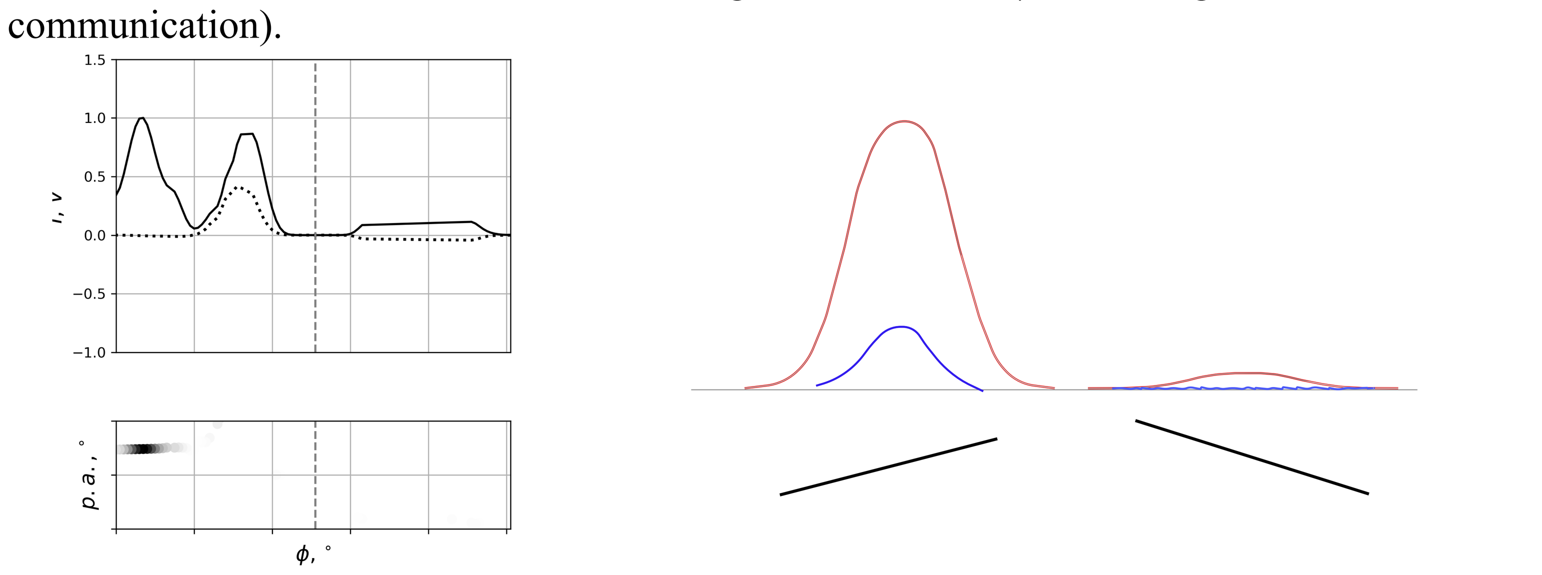
where the polarization characteristics freezes. Hence, for high enough shear of the external magnetic field along the ray propagation when the derivative $\mathrm{d}(\beta_B+\delta)/\mathrm{d}x$ is high enough, the first term in the r.h.s. of the first equation may be neglected.

For large enough total turn $\Delta(\beta_B + \delta) \sim 1$ (i.e., for large enough shear of the magnetic field) within the light cylinder $R_{\rm L} = c/\Omega$, and for small angle of propagation to the magnetic field $\theta << 1$ through the relativistic plasma ($v_{\parallel}/c \sim 1$) (and assuming that $U/c << 1$ and $U_x/c \approx U/c \approx \theta$) one can obtain that the Stokes parameter V is to be much larger than $V_0 = \pm I/Q$ resulting from standard evaluation [4]. As a result, the following predictions were formulated [1]:

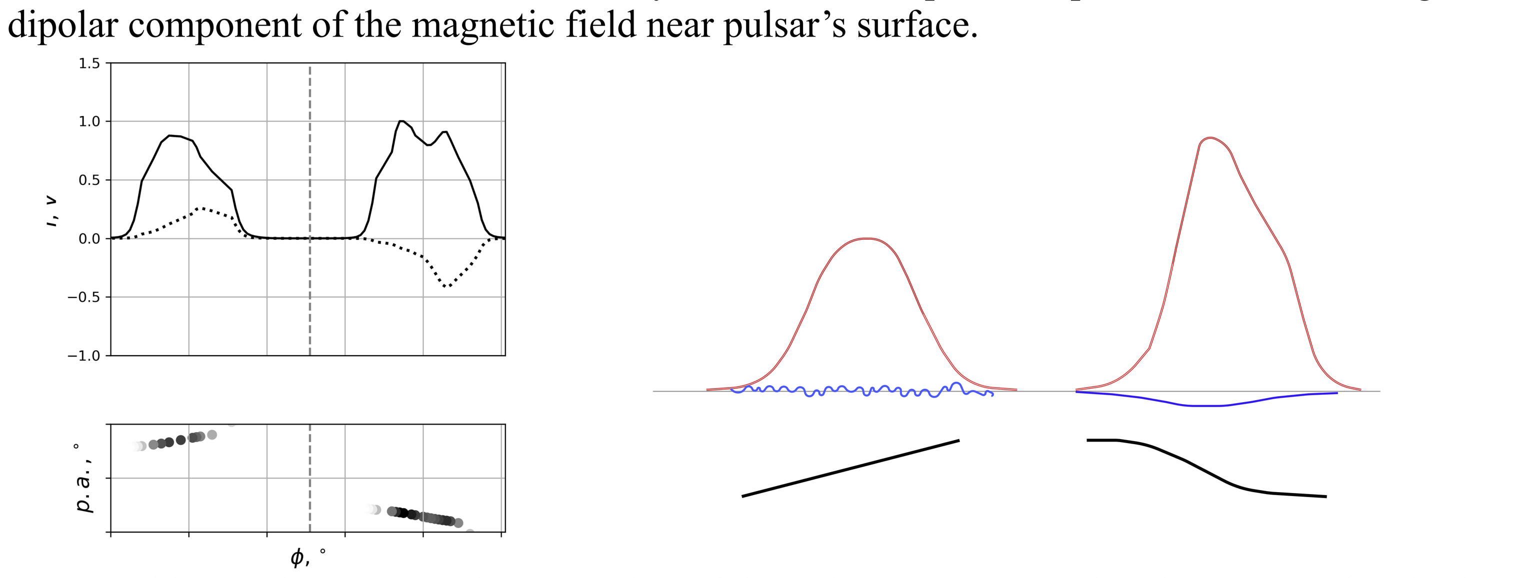
- **For the X-mode the signs of the circular polarization V and the derivative $\mathrm{d}p.a./\mathrm{d}\phi$ should be the SAME.**
- **For the O-mode the signs of the circular polarization V and the derivative $\mathrm{d}p.a./\mathrm{d}\phi$ should be OPPOSITE.**

Simulations&Observations

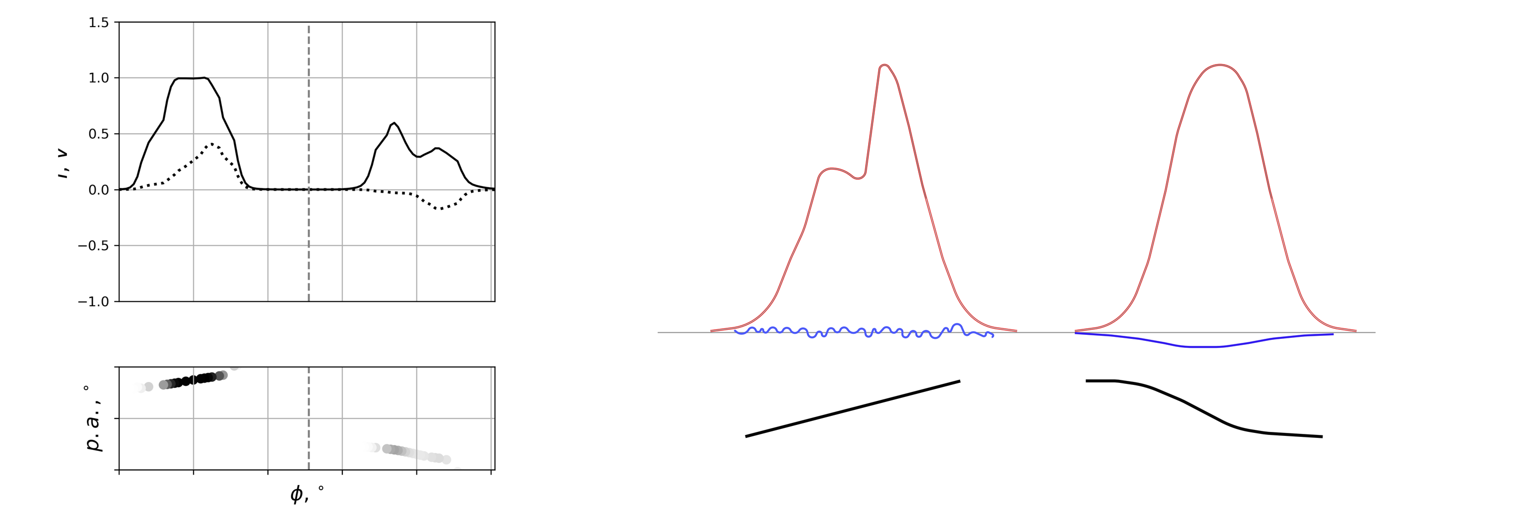
Left column: simulations with inclination angle 85, λ = 1000, γ = 300. Right column: schematic representations of observations of PSR J1906+0746 (Kramer, in preparation, private communication).



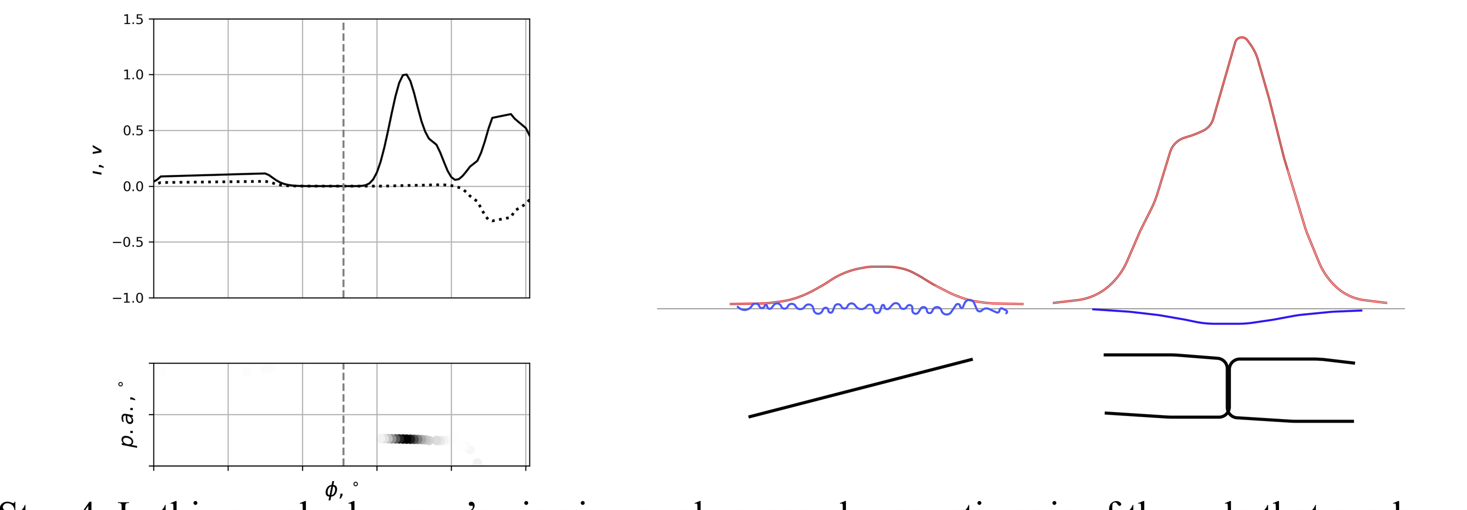
Step 1: The correlation of the signs of V and dp.a./df in the main pulse (both positive) is reproduced, however the single-peaked shape of the main pulse is not in agreement with simulations. This can be due to extra synchrotron absorption or presence of the strong non-dipolar component of the magnetic field near pulsar's surface.



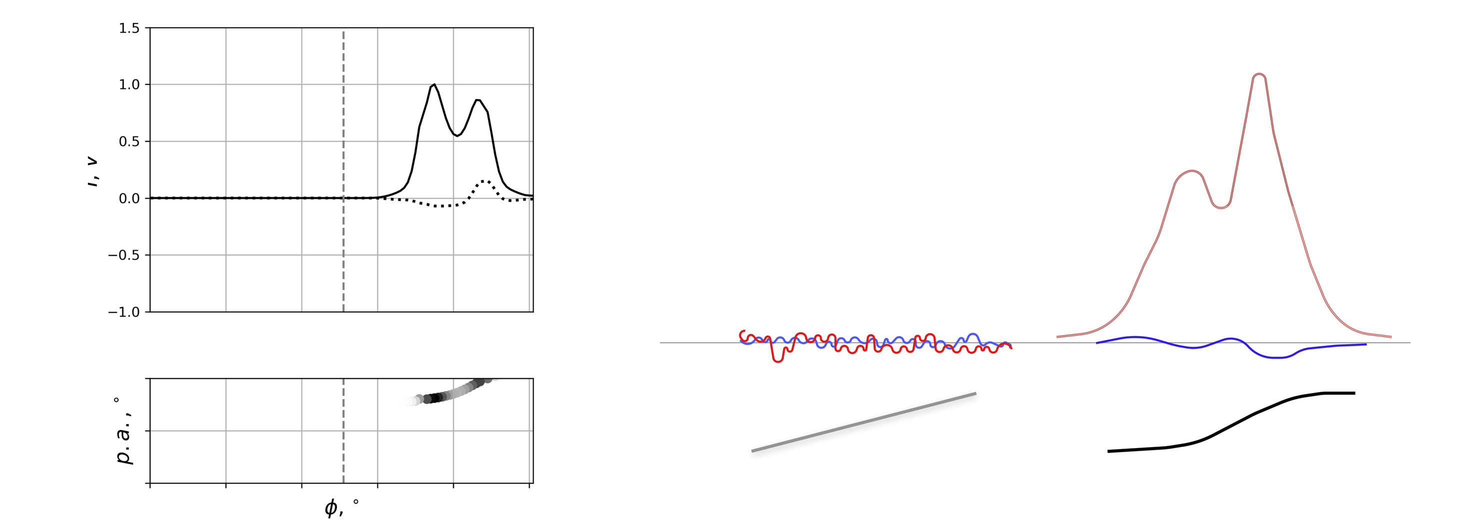
Step 2: This epoch corresponds to crossing of the polar cap near rotational equator, when both main pulse and interpulse should be identical. Observed difference may be attributed to the presence of a strong non-dipolar component of the magnetic field near pulsar's surface.



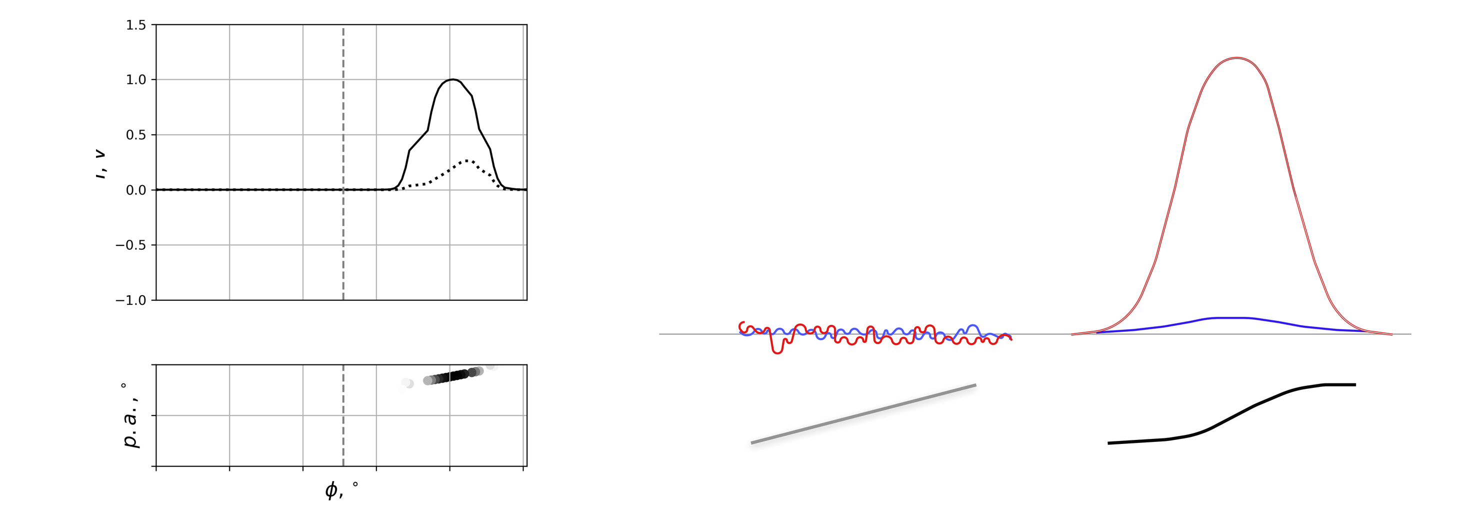
Step 3: The main pulse remains single-peaked, and the inter pulse becomes stronger. Simulated signs of V and dp.a./df are both positive in the main pulse, and are both negative in the interpulse; in an agreement with observations.



Step 4: In this epoch observer's viewing angle crossed magnetic axis of the pole that produces interpulse, so the slope of p.a changes it's sign. The main pulse is weak.



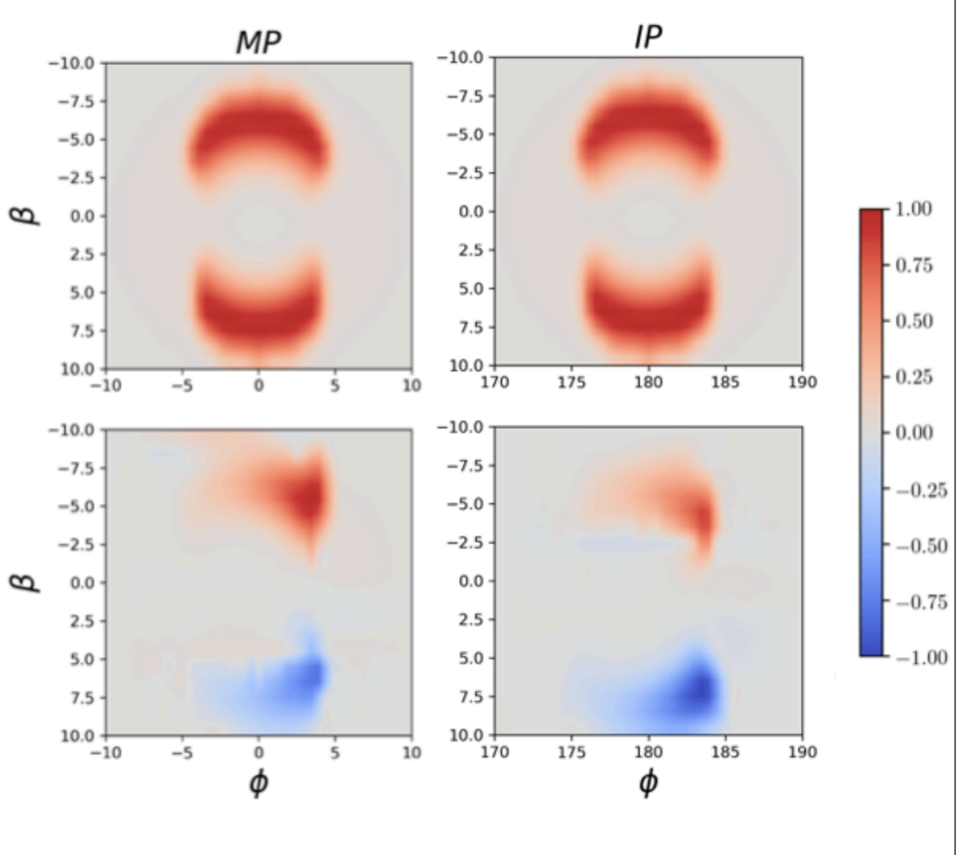
Step 5: After crossing of the magnetic axis, signs of circular polarization and dp.a./df are again correlated (now both negative). Also one of the sub-peaks in the interpulse has a 'wrong' sign of the circular polarization, which is in agreement with simulations.



Step 6: The interpulse becomes single-peaked, signs of the circular polarization and dp.a. / dphi are correlated similar to the observational epochs before crossing of the magnetic axis (now both signs are positive).

Simulated beam maps

Top row: Radio emission intensity for the main pulse (left column) and inter pulse (right column). Absence of the radio emission near magnetic axis (center of the plot) and around β=0 line reflects absence of high-energy curvature photons near magnetic axis and absence of particle acceleration on field lines that carry sub-Goldreich-Julian current (β=0 line, [2]). Bottom row: Same for the circular polarization. Note the second change of sign of V at negative observer's viewing angle in the interpulse which is in agreement with observations (see Step 5)



Conclusion

In this work we demonstrate that complex behavior of radio lightcurves and polarization profiles of a nearly orthogonal pulsar in the binary pulsar system can be explained by the radio wave propagation theory developed in [1]. In particular, one can understand observed correlation of signs of circular polarization and the slope of position angle of the linear polarization with respect to the pulsar phase, their simultaneous switch after passing the magnetic axis and presence of the "wrong" sign of the circular polarization in the interpulse at some observed phases. The exact shape of the main pulse and the difference between interpulse and mainpulse observed for an equatorial crossing of the line of sight can be potentially explained by an additional non-dipolar magnetic field component [2].

References

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