Reconstruction of Light-curve Anomalies of Radio Pulsars

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Abstract

The wave propagation theory [1] based on Kravtsov & Orlov approach outlined the general aspects of the theory of radio light curve and polarization formation for radio pulsars. 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. However, some radio pulsars indicate clear deviation from that correlation. In this work we apply the theory of the radio wave propagation in the pulsar magnetosphere for the analysis of anomalous light curves and polarization profiles. We show that within our theory the circular polarization of a given mode can switch its sign, without the need to introduce a new radiation mode or other effects.

Introduction

In this poster on the ground of quantitative theory of the radio waves propagation [1] based on Kravtsov & Orlov approach [2] we analyze the general properties of mean profiles such as the position angle of the linear polarization *p.a.* and the circular polarization V along the mean profile. Our aim was to enhance some predictions of 'hollow cone' model which could not explain observational data on the ground of the theory mentioned above. Remember that 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, d*p.a.*/dϕ for both emission modes: for X-mode the signs of the circular polarization and the derivative d*p.a.*/dϕ should be the same, and for O-mode these signs should be opposite. However, some radio pulsars indicate clear deviation from that correlation. In this poster the additional effects resulting in the polarization formation are studied. It allowed us to describe the anomalous properties of mean profiles for the most pulsars using the realistic structure of the magnetic field in the pulsar magnetosphere.

Propagation Theory. Limiting Polarization

The limiting polarization is a well-known propagation effect [3]. When radio emission 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 $\Theta = \Theta_1 + i\Theta_2$

$$
\begin{aligned}
\frac{d\Theta_1}{dl} &= \frac{\omega}{2c}\mathrm{Im}\left[\varepsilon_{x'y'}\right] \\
&\quad -\frac{1}{2}\frac{\omega}{c}\Lambda\cos[2\Theta_1 - 2\beta_B(l) - 2\delta(l)]\sinh 2\Theta_2, \\
\frac{d\Theta_2}{dl} &= \frac{1}{2}\frac{\omega}{c}\Lambda\sin[2\Theta_1 - 2\beta_B(l) - 2\delta(l)]\cosh 2\Theta_2.
\end{aligned}
$$

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. 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 different signs correspond to the regions before/after the cyclotron resonance, and the angle δ describes aberration effects due to $\mathrm{E}\times\mathrm{B}$ motion of plasma particles.

In 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 is satisfied for eigenmodes. Here

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

In inhomogeneous medium one can estimate $d\Theta_1/dl \approx d(\beta_B+\delta)/dl$. This holds up to the so-called escaping radius r_{esc} [1]

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

where polarization characteristics freezes. Hence, for high enough shear of the external magnetic field along the ray the derivative $d(\beta_B+\delta)/dx$ is large, and the first term in the r.h.s. of the first equation can be neglected.

For large enough variation $\Delta(\beta_B + \delta) \sim 1$ within the light cylinder $R_L = c/\Omega$, 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 $U_x/c \sim U/c \sim \theta$ at the escaping radius) 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 d*p.a.*/dϕ should be the SAME.**
- **For the O-mode the signs of the circular polarization V and the derivative d*p.a.*/dϕ should be OPPOSITE.**

Deviations from the predicted mode sequence

According to [1], if two orthogonal modes are detected in the three-component mean profile, one can expect O-X-O sequence. However, some pulsars (PSR J2048-1616) demonstrate polarization profiles that poorly fit into this simplified model.

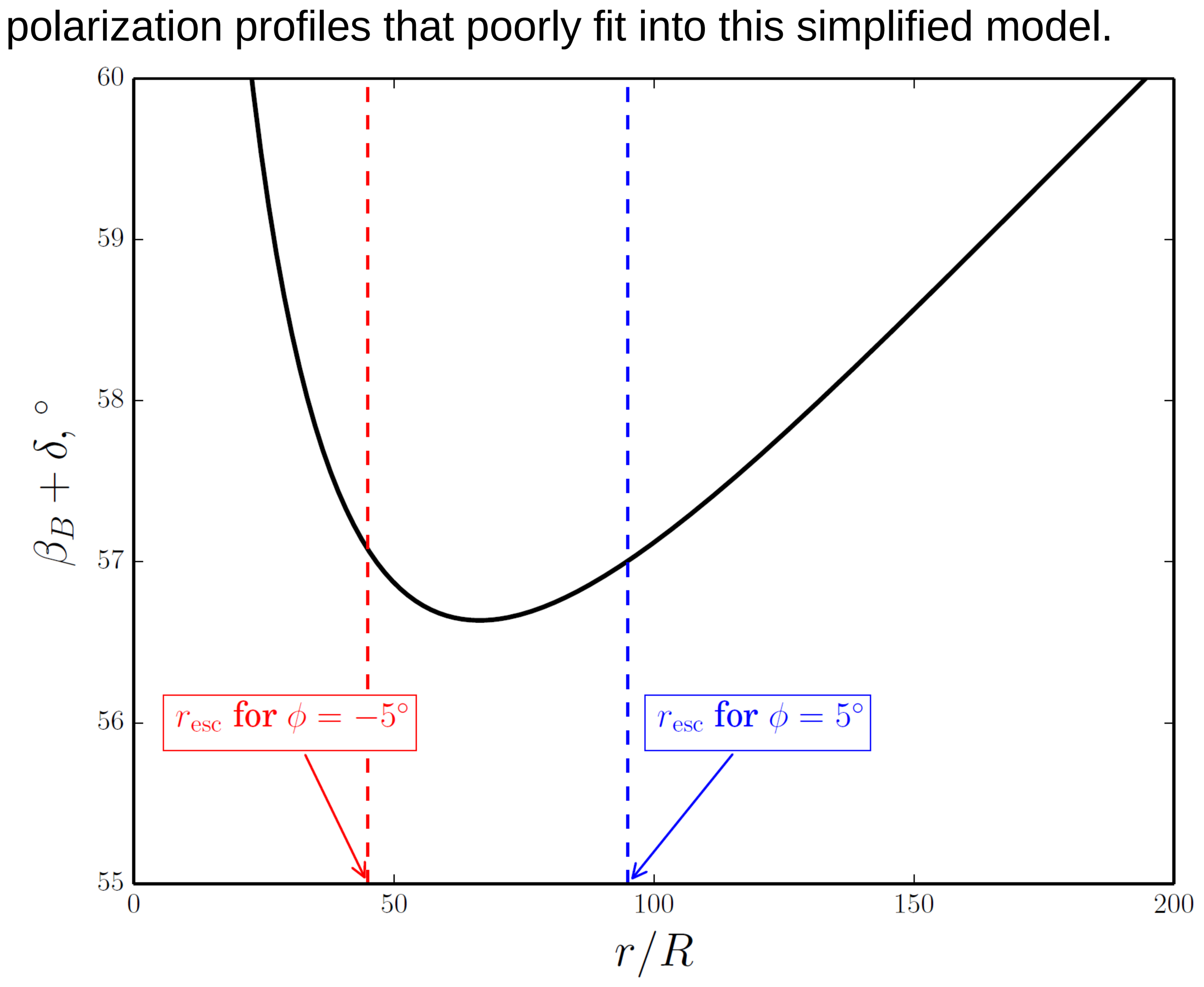

Figure 1. Dependence of $\beta_B + \delta$ along the ray, which shows a clear minimum at $r \sim 70R_*$. If polarization is formed below this minimum, the sign of V is governed by the derivative of β_B, and by the derivative of δ if it is formed above.

To explain this property, we investigated the propagation process in more detail and found that in general the sign V is sensitive to escape radius r_{esc}. If this radius is well above the position of the extremum of $\beta_B + \delta$ (see Figure 1), then the sign V is fixed during the whole profile. However, when escape radius r_{esc} is near the extremum, polarization can be formed slightly below or above this altitude, since plasma density along the ray can vary with phase (see Fig. 2 for example of such behavior).

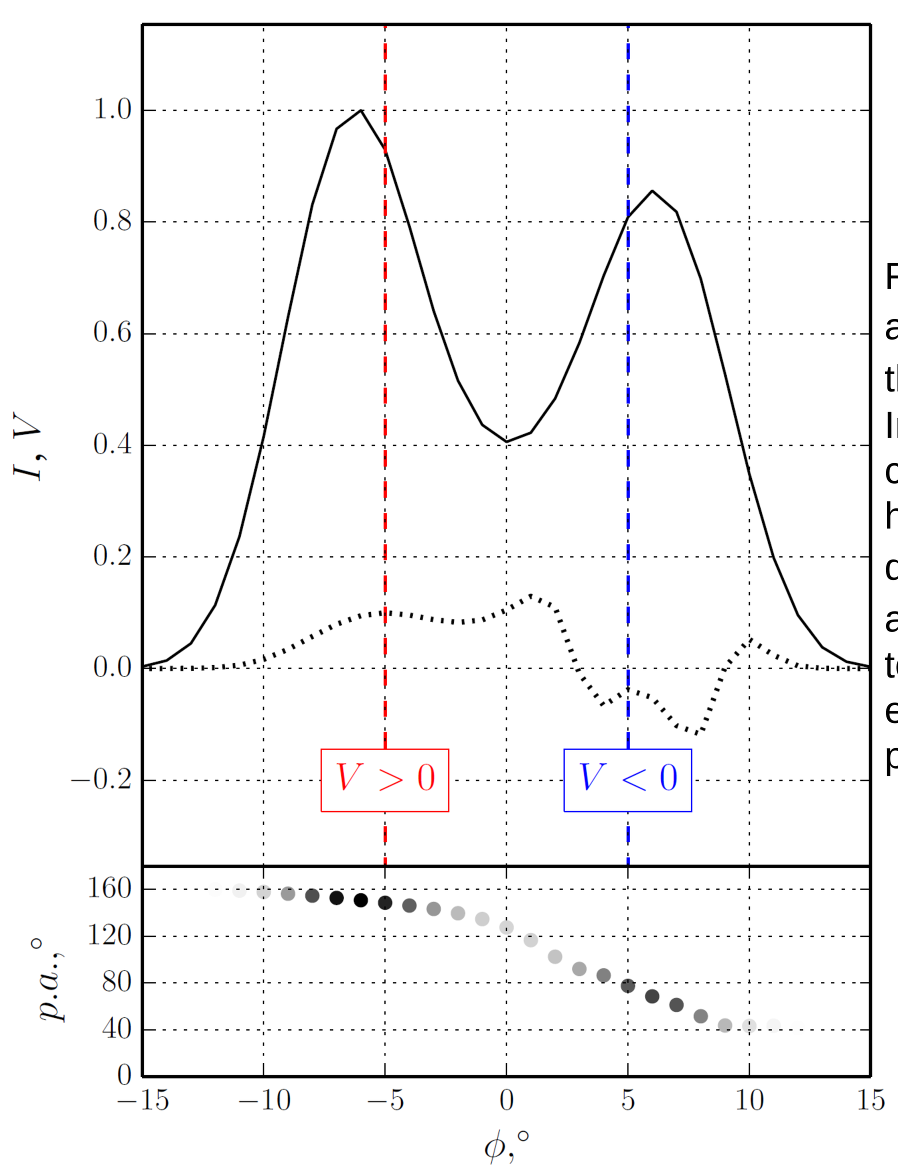

Figure 2. The profile of a pulsar with r_{esc} near the minimum of $\beta_B + \delta$. In this case the circular polarization has different signs at different phases ϕ=−5° and ϕ=5°, due to the variation of the escape radius with phase.

Width of the emitting region

Analyzing the width of the *p.a.* curve obtained in [5] we formulate a method which allows us to determine the radius-to-frequency mapping. Indeed, assuming that the width of this curve results from different radiation radii for the given frequency, we can evaluate the height and characteristic depth of the radiation region. To do that, we compare the results of our simulation with the corresponding observational data obtained in [5].

In Fig. 3 we show simulated mean profile corresponding to O-mode double profile. As one can see, the width of the *p.a.* curve is slimmer in the center of a profile and wider near the pulse edges. On the other hand, for the single-peaked X-mode pulsar the *p.a.* curve is wider in the center of integrated profile (due to the intensity suppression near the edges). Both these are in a good agreement with observational data.

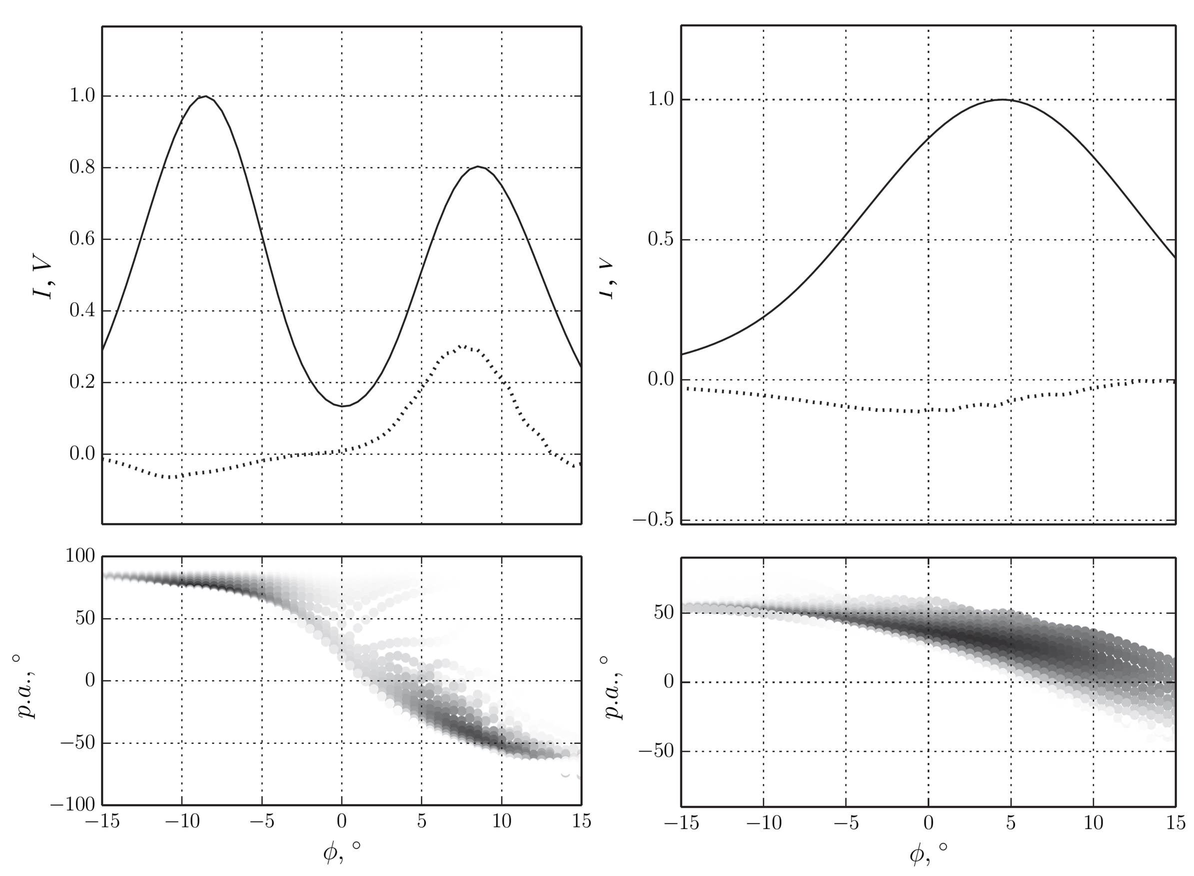

Figure 3. Simulated profiles for O-mode pulsar PSR B0301+19 at 430 MHz (left) and for X-mode pulsar PSR B0540+23 at 430 MHz (right). The scattering of the polarization angle curve is due to the generation at a wide range of altitudes. For both cases the width of the curve is smaller near the edges, since the intensity is suppressed there.

Concluding Remarks

In this work we demonstrate that complex behavior of pulsar lightcurves and polarization profiles can be explained by propagation theory developed in [1]. In particular, one can understand different signs V at different phases for the same polarization mode. In addition, our method provides direct information about the width of the radiating region.

References

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