Polarization characteristics of radiopulsars

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Abstract

It is widely known that the most important observational characteristics that depend strongly on pulsar inclination angle α is its mean profile and the plot of the position angle of linear polarization. They provide the most basic ideas about the geometric properties of the directivity pattern. But they appear to be non-reliable to determine the inclination angle. In Beskin & Philippov (2012) the method was proposed taking into account the circular polarization as well. This method is based on Kravtsov-Orlov equations, that allows to determine the plots of Stokes parameters in the neutron star magnetosphere along the ray trajectory, depending on local plasma parameters and magnetic field structure. Observations together with numerical simulation of the ray propagation in the magnetosphere allows us to determine the unknown parameters more accurately. Using this method, we firstly studied the influence of strong toroidal magnetic field on polarization characteristics of the radiation. This sort of toroidal field can be the consequence of a strong asymmetric current, that are obtained in MHD numerical simulations in Philippov, Tchekhovskoy & Li (2014). We also study the polarization characteristics of pulsars with interpulses, giving an additional argument to what angles best describe these pulsars' observational characteristics.

Hollow cone model

There are two modes in pulsar magnetosphere that determine the directivity pattern and the mean profiles of radiopulsars (see Figure 1):

- X-mode (extraordinary mode) propagates along a straight line;
- O-mode (ordinary mode) declines in the regions of strong magnetic field.

These modes are indistinguishable from the point of view of the mean profile. Also the creation of particles is suppressed for regions close to the pole (straight field lines) and near the edges of the polar cap.

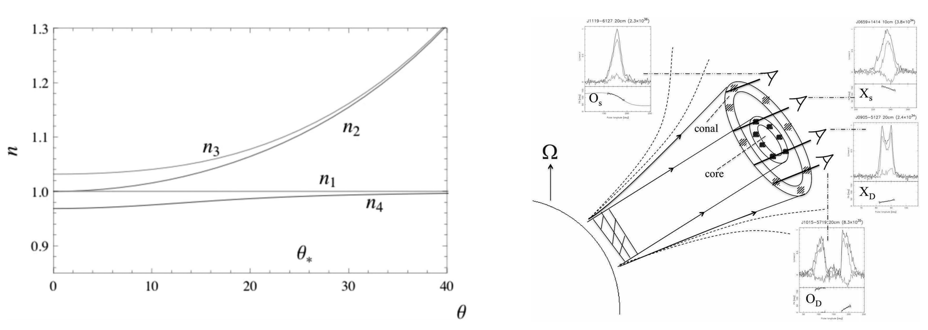

Figure 1: The refraction coefficients for plasma modes (n_1 - X-mode, n_4 - O-mode), and the schematic illustration of directivity pattern in hollow cone model.

As it is well known, the main assumptions of the Hollow cone model are:

- the radiation is being generated deep near the surface, where the magnetic field is close to dipole;
- the emission propagates along a straight line;
- no cyclotron absorption;
- the polarization is formed at the point of emission (no limiting polarization), which gives us the so-called RVM curve for a position angle (Radhakrishnan & Cocke 1969) $p.a. = \arctan\left(\frac{sin\alpha \sin\phi}{\sin\alpha\cos\zeta\cos\phi - \sin\zeta\cos\alpha}\right)$, where α is the inclination angle, ζ is the angle to the line of sight, ϕ is the pulse phase.

However, accurate observations of $p.a.$ and circular polarization showed, that this model is not working for most of pulsars, as anomalous p.a. plot shifts and other phenomena were being obtained.

More accurate approach

The working method to combine all these effects and provide a numerical approach was given in [1]. Effects taken into account:

- the refraction of O-mode;
- the non-dipole magnetic field with a "split-monopole" solution for pulsar wind;
- the cyclotron absorption, which in the region of the singularity of dielectric tensor $\omega_B \sim \gamma\gamma_U\tilde{\omega}$, with ω_B being the cyclotron frequency, γ - gamma-factor of secondary particles, γ_U - transversal (to the field) gamma-factor and $\tilde{\omega} = \omega - \mathbf{k}.\mathbf{v}$.
- limiting polarization effect, that describes the fixation of the radiation polarization characteristics at the point where it escapes into the region of rarefied plasma.

The main results of [1] were the following:

1. peak suppression in case of double-peaked pulsars because of synchrotron absorption, which is observed in the majority of mean profiles;
2. signs of $\mathrm{d}p.a./\mathrm{d}\phi$ and V for X-mode are the same and O mode - opposite;
3. $(\mathrm{d}p.a./\mathrm{d}\phi)_{\max}$ shift to the right from the center of the profile, which is also observed.

Enhancements

This work is the third in line of two already published papers studying the characteristics of pulsars based on polarization data, with the first one [1] giving primary theoretical basis, and the second one analysing the statistics (in preparation). In this work the improvements to the method were made to allow us to broaden the possibilities of the program and do numerical calculations for the most interesting cases.

- For inclination angle about 90° the effect of asymmetrical plasma density must be taken into account instead the one used in [1]. This effect is taken empirically as an exponential suppression along a line, where $\rho_{\mathrm{GJ}} = 0$ (see Figure 2). The cases of $\sim 90^\circ$ and $\sim 0^\circ$ are extremely interesting for the study of pulsars with interpulses, as it is not yet well understood, whether it is perpendicular to the line of sight, or it looks straight at us.

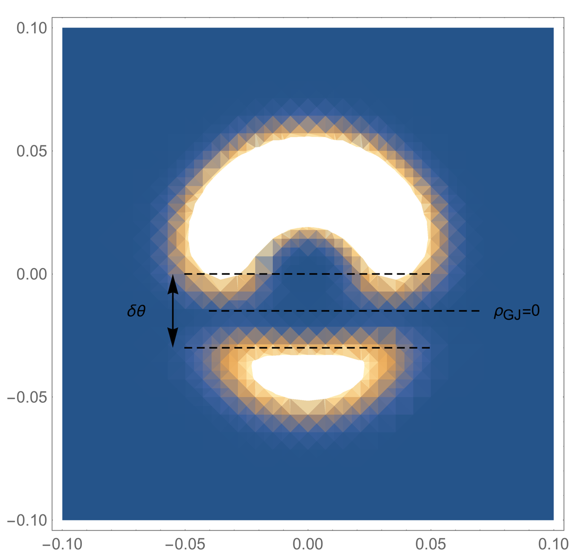

Figure 2: The asymmetrical profile density.

- The possibility to put any magnetic field was also added to the method, as it was interesting to study the case of the strong toroidal field (see Figure 3), because of the anomalous asymmetrical current density, obtained in [2]. Toroidal field is larger than an ordinary dipole field, so the polarization will be strongly affected by this field at r_{esc}.

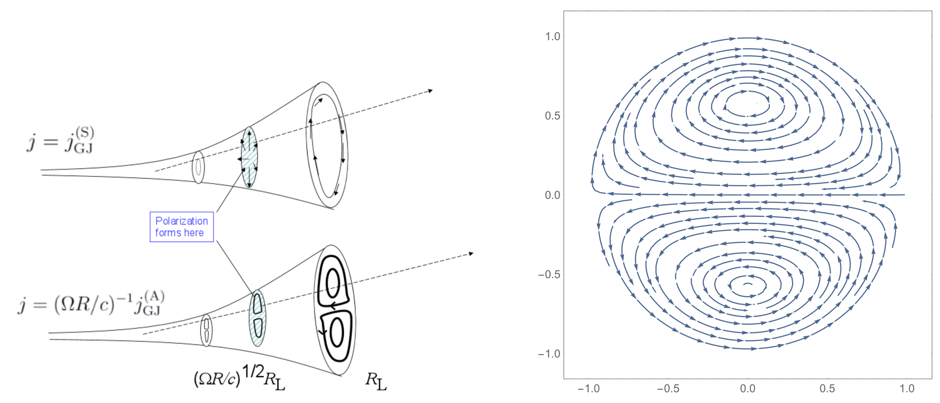

Figure 3: The large toroidal field structure, because of anomalous (by the factor of R/R_{LC}) asymmetric current.

Results

The whole simulation lies on several geometric and plasma parameters that characterize pulsar magnetosphere:

1. inclination angle α and the angle to the observer ζ;
2. period P (~ 1 sec) and the surface magnetic field B_0 ($\sim 10^{12}$ G);
3. the emission frequency ν, which is usually ~ 1 GHz;
4. plasma parameters, such as multiplicity λ, characteristic gamma-factor γ_0 and the hollow cone parameter f_0;
5. emission radius $R_{\mathrm{em}} \sim 10R$.

First of all, let us review the resulting plots for standard pulsar for angles near 10° and 90° (see Figure 4). The 45° angle pulsars are studied in [1]. As one can notice, the near 0° mean profile (left) is five times wider, but has lower circular polarization.

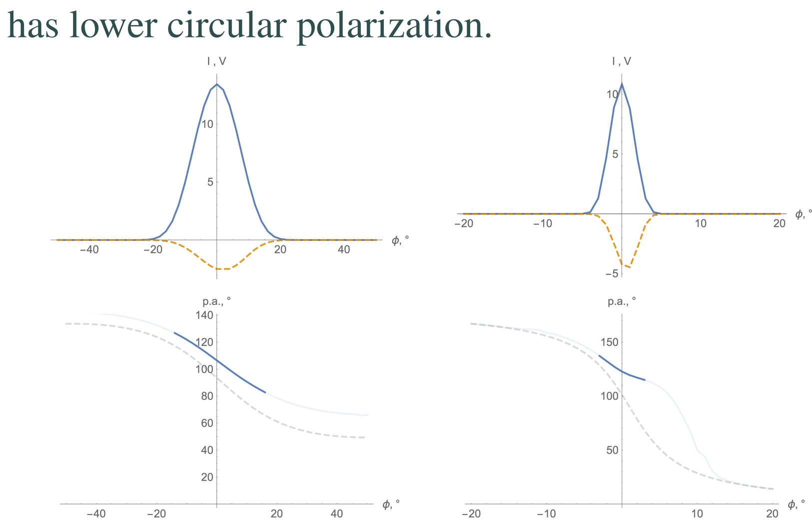

Figure 4: I - blue line, V - orange dashed line and $p.a.$ - blue line below. The dashed $p.a.$ is the RVM.

We also can try to recreate the profiles for a given pulsar with interpulse, and say whether the angle is near 0° or 90°. We took PSR J1302-6350 observation on a 1398 MHz, with a period of 0.05 sec and surface magnetic field $\sim 3 \cdot 10^{11}$ G. The profile from the observations is very wide and the $p.a.$ plot is nearly flat, which, assuming from the simulations given in the right, may mean, that this pulsar's angle is near to 0°.

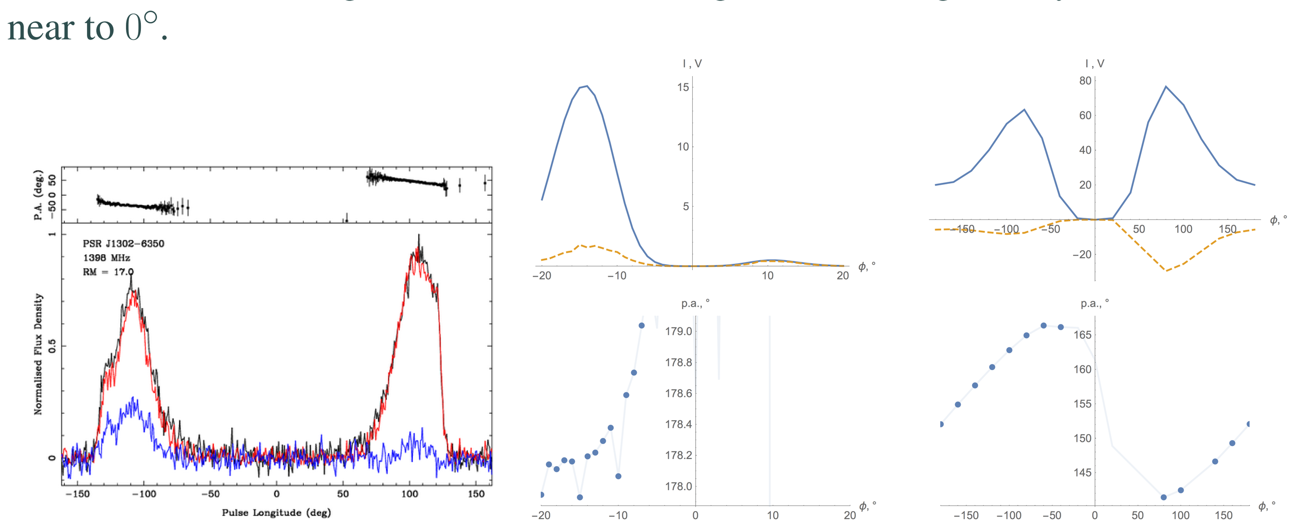

Figure 5: The observations of PSR J1302-6350, the near 90° plot and near 0° plot.

In [3] the angle of B0943+10 pulsar is estimated (15°) using the RVM curve fitting. However, considering the large uncertainty of data, we show, that the angle cannot be found using this method. The uncertainty of data is about $\pm 20^\circ$, but from the simulation we see, that both 15° and 30° can be considered as they are shifted by about 20° (see Figure 6).

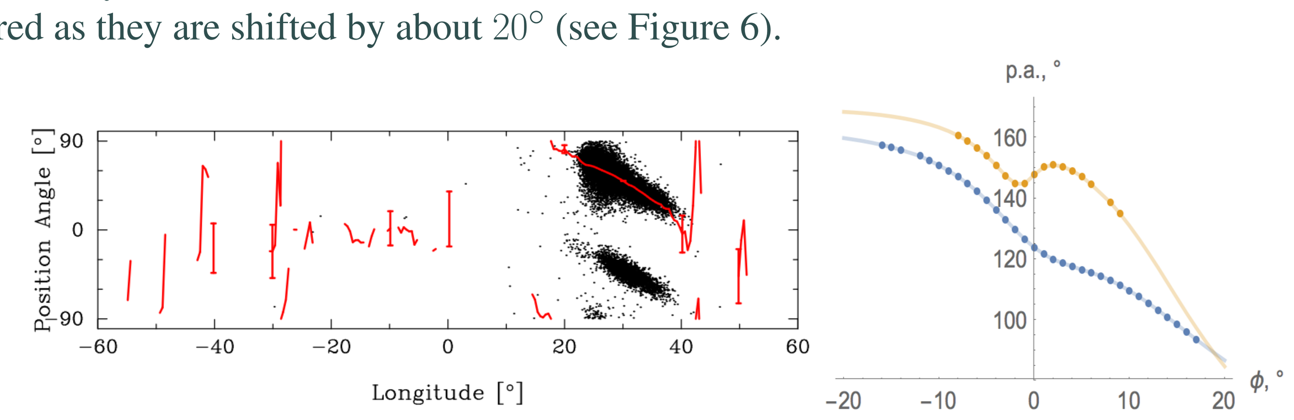

Figure 6: The observations of PSR B0943+10 with a fitted curve and the simulations for 15° (blue) and 30° (orange).

When turning on the large toroidal field from [2], the plots change drastically, as it can be seen from Figure 7.

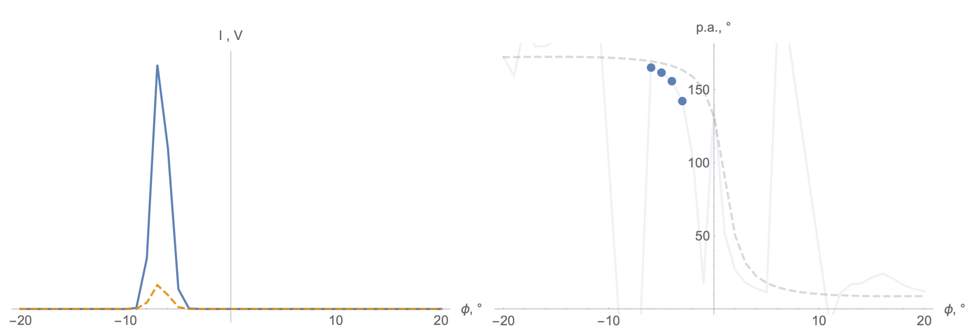

Figure 7: Simulations with large toroidal field for $\sim 60^\circ$.

References

[1] *Beskin V.S., Philippov A.A.*, On the mean profiles of radio pulsars - I. Theory of propagation effects // MNRAS. 425. 2. P. 814-840. (2012).

[2] *Philippov A., Tchekhovskoy A., Li J.G.*, Time evolution of pulsar obliquity angle from 3D simulationsof magnetosphere // MNRAS. 441. 3. P. 1879-1887. (2014).

[3] *Backus I., Mitra D., Rankin J.M.*, The beam topology and dynamic emission properties of pulsar B0943+10 VI. Discovery of a Q-mode precursor and comparison with pulsar B182209 // MNRAS. 404. 1. P. 30-41. (2010)