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Polarization sounding of the pulsar magnetosphere

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Abstract. The possibility of a polarization sounding of the pulsar magnetosphere is examined, using intrinsic pulsar emission as a probe signal, for modern radio telescopes operating in the meter and decameter wavelength range. Different models of the pulsar magnetosphere at altitudes higher than a radius of critical polarization are used. The propagation medium besides magnetosphere is described by the stratified model, in which each layer has its own density of free electrons and vector of magnetic induction, as well as the spatial and temporal fluctuation scales of these parameters.

The frequency dependence of the polarization parameters of the pulsar radio emission, obtained in the broad band for a selected pulse phase, will enable a sounding deep into the pulsar magnetosphere.

Keywords. Magnetic fields, plasma, polarization, pulsar.

1. Introduction

The pulsar magnetosphere is a region where radio emission is generated. Studying the properties of radio-emitting region is of primary importance for understanding both the nature of pulsar radio emission, and the nature of the neutron star as a whole. There are several models of pulsar magnetosphere, but still there is no unified explanation of physical processes occurring in a pulsar magnetosphere.

The main purpose of this work is to sound the pulsar magnetosphere by studying the polarization properties and characteristics of a pulsar radio emission. The decameter range is the most difficult for polarization studies: there the influence of all known propagation effects is becomes apparent with the highest contrast. It is in this range the anomalously powerful pulses from pulsars B0809+74, B0943+10, B0950+08, B1133+16 (Ul'yanov *et al.* 2006) and the giant pulses from PSR B0531+21 (Popov *et al.* 2006) are registered.

Furthermore, due to the Faraday effect the bandwidth of intensity modulation of the elliptically polarized radiation in this range narrows down to several tens of kilohertz. It is supposed that this property of radio emission of pulsars (REP) will be used to obtain the polarization parameters of REP via observations on radio telescope UTR-2 which is composed from linearly polarized broadband dipoles. For a moment the observations of REP polarization using this effect were reported for the radio-telescopes DKR 1000 and BCA 100 (Suleymanova & Pugachev 2002). Determination of the polarization parameters requires consideration of both direct and inverse problems. To achieve the assigned task we consider a model of polarized radiation and a model of the propagation medium. Solving the inverse problem allows for the recovery of Stokes parameters in the reference frame of the pulsar using registered REP at the receiver side. In our work the direct and inverse problems are solved as applied to the case of UTR-2 telescope.

2. Model

To solve the assigned task we model a medium of propagation as a layered structure. The most important parts of the propagation medium are the upper pulsar magnetosphere, the interstellar medium (ISM), the interplanetary medium, the Earth's ionosphere and the underlying surface of a radio telescope. The layers are characterized by their own transmission coefficients and by their own the longitudinal and transverse magnetic field components on the line of sight, etc. We assume that propagation of a radiation along a line of sight in each layer is described by a eikonal equation, which includes separate refractive coefficients for the ordinary and extraordinary waves. These coefficients we determine via the mean values of the electron concentration in the selected layer on the line of sight and the average values of magnetic field vector component parallel to the line of sight.

At present stage the propagation of the radio waves in the ISM is considered, since modeling of this medium is the most simple. A radiation point source located at infinitely large distance from the receiving antennas and emitting elliptically polarized radiation in a wide frequency range is considered. We will assume that at distances of a critical radius of polarization the two orthogonal modes of the pulsar radio emission have fixed amplitudes.

Pulsar radiation is modeled by a set of the noise circular frequencies ω with the Gauss shape of the envelope. In the model we specify a variation of a position angle (PA) χ along the average profile of the pulse envelope. Influence of the propagation medium is taken into account by eikonal equation $\nabla\varphi(\omega) = n(\omega)\vec{k}(\omega)$, where $\varphi(\omega)$ is the phase of the signal at circular frequency ω , $n(\omega)$ is the ISM refractive coefficient, $\vec{k}(\omega)$ is the wave vector. In this case the equation for the phase of the analytical signal at arbitrary frequency ω will have the form :

$$\varphi(\omega)_{O,X} \approx \omega\frac{L}{c} - \frac{1}{\omega}\frac{2\pi e^2}{m_e c}\int_0^L N_e(z)dz \mp \frac{1}{\omega^2}\frac{2\pi e^3}{{m_e}^2 c}\int_0^L N_e(z)\beta(z)dz, \qquad (2.1)$$

where c is the speed of light, e is the electron charge, m_e is the electron rest mass, L is the layer thickness, $N_e(z)$ is the electron concentration on the line of sight, $\beta(z)$ is the value of the projection of the magnetic induction vector onto that line of sight.

The rotation of the polarization plane is connected with the different refraction coefficients for the orthogonal modes that have the opposite directions of rotation. These waves are the so-called ordinary (O) and extraordinary (X) waves (Zheleznyakov 1997). For O and X waves refractive coefficients can be written as: $n_{O,X} = \sqrt{1 - [{\omega_p}^2/\omega(\omega \mp \omega_H)]}$,

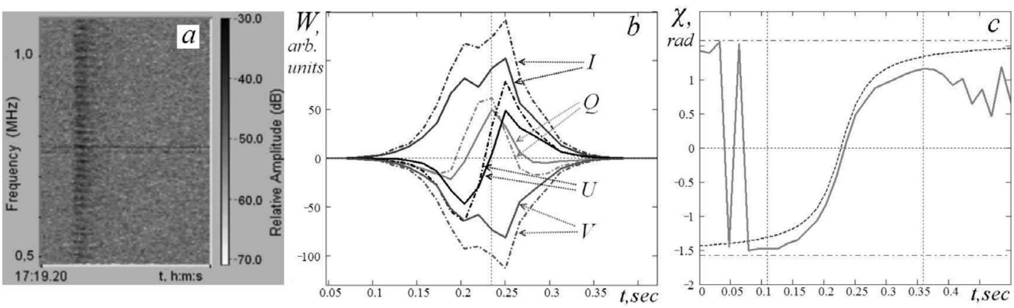

Figure 1. a) the dynamic spectrum of the elliptically polarized radiation from PSR B0809+74, detected using UTR-2 ($F_c = 23.7$ MHz, $\Delta F = 1.53$ MHz); b) the Stokes parameters I, Q, U, V; c) the position angle χ.

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where ω_p and ω_H are the plasma and the cyclotron frequencies, respectively, subscripts O and X correspond to the ordinary $(-\omega_H)$ and extraordinary $(+\omega_H)$ waves.

An example of registering the polarization ellipse of PSR B0809+74 pulse on the radio telescope UTR-2 can be seen in the Fig. 1a. The central recording frequency is $F_c = 23.7$ MHz. Period of the Faraday intensity modulation is $\Delta F_F \approx 20$ kHz. We have made the simulations for the similar spectra. These spectra were generated for a given value of the rotation measure (RM = -234 rad/m^2) at frequencies $F_c = 20$ MHz and $F_c = 30$ MHz ($\Delta F = 4$ kHz). For the given model signals the Faraday periods of intensity modulation were found. Using these values the magnitude of the rotation measure was estimated. The accuracy of this method is lower than $0.5/N_{max}(f)$, where $N_{max}(f)$ is the number of harmonic, which has the maximal intensity. This number depends on ΔF_F.

3. Results

We can construct a polarization tensor (Zheleznyakov 1997) for a signal registered in two orthogonal polarizations. From polarization tensor the polarization parameters (Stokes parameters) and the variation of PA can be found (see Fig. 1).

In Fig. 1b, the Stokes parameters of the restored signal (the continuous line) and the original signal (dashed line) are presented. The variation of the PA in the pulse window at the receiving end (Fig. 1c) is almost identical to the variation of the model PA. The PA is determined only up to an arbitrary constant.

The developed algorithms were used for processing the real data. For three different anomalously intensive pulses of PSR B0809+74 registered near the center frequency $F_c = 23.7$ MHz in the same observation session of one hour duration the variations of the values of the rotation measure of about 1 rad/m^2 were detected. The values of the observed variations are 13 times larger than the errors of determination of the rotation measure values. These variations were observed during nighttime for undisturbed ionosphere. Comparison of the RM value obtained in the decameter range with RM values obtained in the 250-500 MHz frequency range (Manchester 1972) allows us to suppose that regular component of the interstellar medium magnetic field and dipole component of the emitting pulsar pole of PSR B0809+74 have opposite directions.

4. Conclusions

The direct and inverse problems of determining the polarization parameters of elliptically polarized signal propagating through ISM were solved by numerical methods. An eikonal equation gives an opportunity to take into account both the Faraday effect and cold plasma influence on the signal properties.

A method of estimating the rotation measure and position angle was proposed. It allows us to recover all Stokes parameters in the reference frame associated with a pulsar.

It was found that ISM magnetic field and visible pulsar magnetic field have opposite directions.

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