Young Neutron Stars and Their Environments
IAU Symposium, Vol. 218, 2004
F. Camilo and B. M. Gaensler, eds.

Orthogonal Polarization Modes in Pulsar Radio Emission

S. A. Petrova

Institute of Radio Astronomy, National Academy of Sciences of Ukraine, 4, Chervonopraporna St., 61002 Kharkiv, Ukraine

Abstract. General features of polarization transfer in the plasma of pulsar magnetospheres are outlined. A technique of plasma density diagnostics based on observed polarization profiles of radio pulses is developed. For the first time, it appears possible to obtain the profiles of the plasma density across the open field line tube from observations. The multiplicities derived are compatible with those predicted by modern theories of pair cascade and show a perfect exponential decrease towards the tube edge. Implications of the results are briefly discussed.

1. Introduction

The diverse and complicated behavior of single-pulse polarization is mainly caused by the presence of orthogonal polarization modes, which are the fundamental property of pulsar radiation. The concept of completely polarized superposed modes has strong observational support (e.g., McKinnon & Stinebring 1998) and is undoubtedly favored by theoretical considerations, since for the partially polarized disjoint modes direct generation and further propagation in the plasma are questionable. The superposed modes are usually identified with the natural waves of the pulsar plasma. As a pulsar's magnetic field is extremely strong and ray propagation is quasi-transverse, the natural waves are linearly polarized, with the polarization plane being adjusted to the local orientation of the magnetic field. Hence, direct representation of the observed superposed modes as the natural waves of the pulsar plasma faces difficulties. Firstly, the observed modes are elliptical, with the degree of circular polarization varying stochastically from pulse to pulse. Secondly, the position angle of linear polarization exhibits a substantial pulse-to-pulse spread; moreover, even on average the modes can be non-orthogonal. These difficulties can be avoided, if one take into account polarization evolution of natural waves in the pulsar plasma.

2. Polarization Transfer in Pulsar Magnetosphere

A rigorous treatment of the polarization evolution of natural waves in a pulsar plasma is discussed by Lyubarskii & Petrova (1999), Petrova & Lyubarskii (2000) and Petrova (2001, 2003). The results can be summarized as follows. In the vicinity of the emission region, the polarization planes of the natural waves follow the local orientation of the ambient magnetic field. As the plasma number density decreases along the trajectory, the scale length for beatings between the modes, $L_b \sim \frac{c}{\omega \Delta n}$, increases and far from the emission region becomes comparable to the scale length for change in the plasma parameters, $L_p \sim r$. Then the polarization planes of the waves have no time to follow the magnetic field direction and wave mode coupling holds. Each of the incident natural waves, independently of the presence of the other, becomes a coherent mixture of the two natural waves peculiar to the ambient plasma, with the amplitude ratio and phase difference varying along the trajectory. As a result, the original natural wave acquires some circular polarization and a shift in position angle, so that it no longer reflects the magnetic field geometry. As the plasma number density decreases considerably, the waves decouple from the plasma and further on propagate as in a vacuum, with the polarization characteristics being fixed. Thus, the final polarization state of outgoing radiation is formed at distances $\sim r_p$, where the condition:

$$r_p \frac{\omega}{c} \Delta n(r_p) = 1 \qquad (1)$$

is satisfied. This is usually called the polarization-limiting effect.

For given plasma parameters, the ordinary and extraordinary waves acquire the same shift in position angle and the same degree of circular polarization of opposite senses. Thus, they become purely orthogonal elliptical modes and match a customary empirical representation of the observational data. It should be noted that the final ellipticity and position angle shift from the geometrically determined value are related to each other, both being conditioned by the efficiency of wave mode coupling, that is, by the physical properties of the plasma in the region of coupling. Then the observed pulse-to-pulse variations of the ellipticity and position angle can be attributed to the fluctuations in the pulsar plasma. On the one hand, incorporating the polarization-limiting effect into the model of pulsar polarization for the first time correctly accounts for the observed ellipticity and position angle spread. On the other hand, the relationship between these quantities provides a basis for diagnostics of pulsar plasmas.

3. General Principles of the Plasma Probing Technique

A rigorous treatment of the polarization-limiting effect (Petrova 2003) shows that the final ellipticity, v_∞, and position angle shift, $\Delta\psi_\infty$, are determined by the two parameters $\eta = -\frac{\Phi \sin\alpha}{\xi - \alpha}$ and $\rho = \frac{r_p}{r_L}\frac{\sin\alpha}{|\xi-\alpha|}$, where Φ is the pulse phase, α and ξ are the angles the rotational axis makes with the magnetic axis and the sight line, and r_L is the light cylinder radius. Note that η is related to the geometric position angle in the customary rotating vector model: $\eta \approx -\tan\psi_0$. Using η and ρ in Equation (1), one can estimate the plasma number density at the polarization-limiting radius:

$$N_p = 1.5 \cdot 10^6 P^{-1} \nu_9 \gamma_2^2 \sin\alpha(\xi - \alpha)\rho^{-1}(1+\eta^2)$$

$$\times \left[\left(1 - \rho\eta/(1+\eta^2)\right)^2 + \left(\mathrm{sign}(\xi-\alpha)\rho/(1+\eta^2)\right)^2\right] \mathrm{cm}^{-3}, \qquad (2)$$

where P is the pulsar period, ν_9 the radio frequency in GHz and γ the plasma Lorentz-factor.

As can be seen from Figure 1, the pair of final polarization characteristics of the wave, $(v_\infty, \Delta\psi_\infty)$, is unambiguously related to the pair of parameters, (η, ρ).

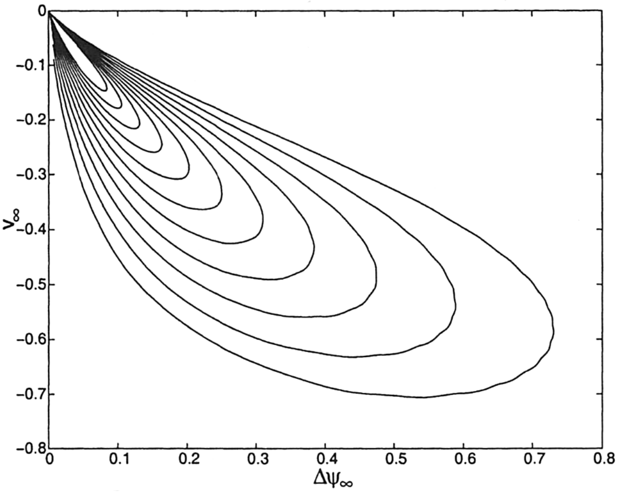

Figure 1. The final ellipticity of the ordinary wave vs. position angle shift for different parameters η and ρ; along each closed line ρ is a constant from the interval 0.1 to 1 and ρ changes from −1 to 1.

On the other hand, if radiation is a mixture of orthogonal elliptical modes, for the dominant mode we have:

$$v_\infty = V/\sqrt{Q^2+U^2+V^2}, \quad 0.5\arctan U/Q = \Delta\psi_\infty - \arctan\eta\,, \tag{3}$$

where (Q,U,V) are the observed Stokes parameters. Thus, proceeding from the observed polarization data, one can derive the parameters η and ρ throughout the pulse and estimate the plasma number density at different distances to the magnetic axis. Then, owing to continuity of the plasma flow, one can extrapolate the number density values along the field lines, $N \propto r^{-3}$, and reconstruct the plasma distribution over a substantial part of the open field line tube. To characterize the density distribution it is convenient to introduce the multiplicity factor of the plasma, $\kappa = NPce/B$, and to transit from pulse phase to the polar angle in the tube, χ, normalized to the tube width, χ_f: $\chi/\chi_f = |\xi-\alpha|\sqrt{r_L/r_p}\sqrt{1+(\eta+\rho)^2}$.

4. Results and Discussion

The plasma density profiles of PSRs B0355+54 and B0628–28 calculated based on the EPN polarization profiles[1] are shown in Figure 2. In both cases the plasma density exhibits a perfect exponential behavior, with the exponent being well fitted by the second order polynomial. The multiplicities range up to a dozen and agree with the predictions of the modern theories of pair cascade (e.g.,

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[1] EPN database is available at `http://www.mpifr-bonn.mpg.de/pulsar/data` .

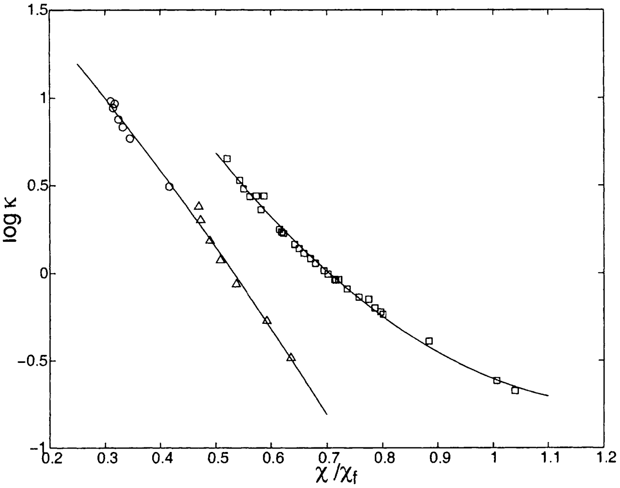

Figure 2. Plasma density profiles of PSR B0355+54 (squares) and PSR B0628–28 (triangles and circles for the polarization data at 0.408 and 0.61 GHz, respectively).

Hibschman & Arons 2001). Note that a marked non-uniformity of the plasma across the tube is an essentially new fact waiting for theoretical explanation. It is also interesting to note that the points in the density profile of PSR B0628–28 obtained from the data at the two distinct frequencies indeed lie on the same curve, testifying to the validity of our technique.

The plasma multiplicities derived directly from observational data can stimulate more detailed studies of the physics of polar gap. Furthermore, an explicit knowledge of the structure of the plasma flow may give new insights into pulsar emission physics. It would be interesting to compare the fluctuations of the total intensity and the plasma density at different time scales. In addition, a rigorous description of the plasma distribution can give a basis for quantitative investigation of propagation effects in the pulsar magnetosphere, in particular, of the effects which can underlie the mechanism of orthogonal polarization modes. Thus, the plasma density profiles can have a number of implications and our plasma probing technique may become a useful tool for studying pulsars.

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