ON THE NATURE OF THE CIRCULARLY POLARIZED COMPONENT OF PULSAR RADIO EMISSION

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Abstract

It is shown that circular polarization occurs in the region of cyclotron resonance because the group velocities of right-hand and left-hand polarized waves are different with respect to the direction of the magnetic field. Due to the dependence of the intensity of radio emission on the coordinates across the polar cap, this difference in group velocities leads to noncompensated circular polarization proportional to the derivative of the total intensity as a function of longitude. The indicated dependence corresponds to observations of the so-called core component of pulsar radio emission.

In the frequency band $\omega \ll \omega_B$, (ω_B is the cyclotron frequency) the eigen electromagnetic modes in the magnetized plasma have linear polarization. Only in the band $\omega \geq \omega_B$ do the modes have a marked circularly polarized component. However, in an electron-positron plasma the polarization vector rotation is absent because of the opposite signs and similar masses of the charges. This is valid for a nonrelativistic plasma. In the relativistic case circularly polarized waves can exist owing to the different values of the energies of the electrons and positrons. This situation takes place in the pulsar magnetosphere in the region of open magnetic field lines. The electron-positron plasma, moving along the magnetic field, consists of a beam of fast particles (electrons if the angle χ between the stellar rotation axis and magnetic dipole is less than 90°, *i.e.* $\chi < \pi/2$, and positrons for the case $\chi > \pi/2$), and this secondary plasma has a considerable density. The distribution functions of the relativistic electrons and positrons are different although they have the similar shapes.

Figure 1 shows this difference for the case $\chi < \pi/2$ when the electrons possess less energy than the positrons. The minimum value of the Lorentz-factor $\gamma^+_{\rm min}$ for the positrons is of the order of 4×10^2, just as for the electrons $\gamma^-_{\rm min} = \lambda^{1/2} \simeq 10^2$ (Beskin, Gurevich, and Istomin 1988b). The parameter λ is the multiplicity of the secondary plasma. It is the ratio of the plasma density n to the Goldreich-Julian (1969) density $n_G = -\boldsymbol{\Omega} \times \boldsymbol{B}/2\pi ec$

$$n = \lambda n_G \qquad \lambda = 10^3 - 10^5 .$$

The radio emission is generated in the polar regions of the pulsar magnetosphere at distances not so far above the neutron-star surface $z/R \leq 10^2$–10^3 (Beskin, Gurevich, and Istomin 1988b). The polarization of the radiation is linear. The direction of the electric field vector in the wave depends on the eigen mode. For the extraordinary wave the

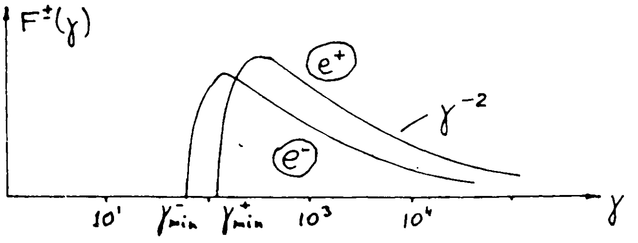

Figure 1

electric field is orthogonal to the plane in which the magnetic field line lies. This mode propagates along a straight line, and the radiation has a narrow beam pattern. The extraordinary mode is identified with the core component of pulsar radio emission.

While propagating into the external regions of the magnetosphere where the magnetic field strength decreases, the extraordinary linearly polarized waves become circularly polarized.

One kind of wave, in which the wave vectors lie in the plane of the magnetic field line, becomes the left-hand polarized mode. The other kind, in which the wave vector is orthogonal to this plane, becomes the right-hand polarized mode. By this the UKB approximation is not violated. The quasi-classical parameter is less than unity

$$\frac{dk/dz}{K(n_1 - n_2)} \simeq \frac{\gamma_{\rm min}}{\Delta\gamma K R} \ll 1 .$$

Here K is the polarization, $\Delta\gamma$ is the width of the distribution function at $\gamma \sim \gamma_{\rm min}$, $\Delta\gamma/\gamma_{\rm min} > 10^{-1}$, R is the neutron-star radius $\approx 10^6$ cm, $\boldsymbol{k}$ is the wave vector, and $n_{1,2}$ are the refractive indices of the two circularly polarized modes.

Now we calculate the effect of the appearance of the circularly polarized component of the core emission intensity.

The refractive indices and polarization of the

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two modes are

$$n_{1,2}^2 = 1 + \delta\varepsilon_{11} - \theta\varepsilon_{xz} + \frac{\theta^2}{2}\delta\varepsilon_{zz} \pm \frac{1}{2}[(\theta^2\delta\varepsilon_{zz} - 2\theta\varepsilon_{xz})^2 - 4(\varepsilon_{xy} + \theta\varepsilon_{yz})^2]^{1/2}$$

$$\left(\frac{E_x}{E_y}\right)_{1,2} = -\{\theta^2\delta\varepsilon_{zz} - 2\theta\varepsilon_{xz} \pm [(\theta^2\delta\varepsilon_{zz} - 2\theta\varepsilon_{xz})^2 - 4(\varepsilon_{xy} + \theta\varepsilon_{yz})^2]^{1/2}\}/2i|\varepsilon_{xy}|.$$

The quantities $\delta\varepsilon_{11}$, $\delta\varepsilon_{zz}$, ε_{xy}, ε_{xz}, ε_{yz} are the components of the dielectric permitivity tensor

$$\begin{aligned}
\delta\varepsilon_{11} &= \left\langle \frac{\omega_p^2\gamma\tilde{\omega}^2}{\omega^2(\omega_B^2 - \gamma^2\tilde{\omega}^2)} \right\rangle \\
\delta\varepsilon_{zz} &= -\left\langle \frac{\omega_p^2}{\gamma^3\tilde{\omega}^2} \right\rangle + \left\langle \frac{\omega_p^2\gamma\theta^2}{(\omega_B^2 - \gamma^2\tilde{\omega}^2)} \right\rangle \\
\varepsilon_{xy} &= i\left\langle \frac{\omega_p^2\omega_p\tilde{\omega}}{\omega^2(\omega_B^2 - \gamma^2\tilde{\omega}^2)} \right\rangle \\
\varepsilon_{xz} &= \left\langle \frac{\omega_p^2\gamma\theta\tilde{\omega}}{\omega(\omega_B^2 - \gamma^2\tilde{\omega}^2)} \right\rangle \\
\varepsilon_{yz} &= -i\left\langle \frac{\omega_p^2\omega_B\theta}{\omega(\omega_B^2 - \gamma^2\tilde{\omega}^2)} \right\rangle \\
\omega_p^2 &= 4\pi ne^2/m \\
\omega_B &= eB/mc. \qquad (1)
\end{aligned}$$

In eq.(1) we consider that the wave vector $\boldsymbol{k}$ lies in the plane ZX, and the angle θ between $\boldsymbol{k}$ and $\boldsymbol{B}$ is small enough. The quantity $\tilde{\omega} = \omega - k_z V_{\parallel} = (\omega/2)(\theta^2 + \gamma^{-2})$ and the angle brackets imply integration over the distribution functions of the particles—that is, the electrons and positrons. As the distribution functions are different, the components ε_{xy} and ε_{yz} are not equal to zero.

The region of cyclotron resonance is defined by the condition

$$\frac{|\omega_B|}{\gamma} \approx \frac{\omega}{2}(\theta^2 + \gamma^{-2}). \qquad (2)$$

Because of magnetic field-line deflection (due to curvature) the value θ becomes greater than $\gamma^{-1}(\leq 10^{-2})$. Changes in the angle θ through a distance z near the pulsar surface are described by the following expression

$$\frac{d\theta}{dz} = \frac{1}{\rho_0}\left(\frac{z}{R}\right)^{-1/2},$$

where ρ_0 is the radius of the curvature of magnetic field line near the surface $\rho_0 = 9 \times 10^7 P^{1/2} f^{-1/2}$. Eq.(2) is valid for a dipole magnetic field. The dimensionless coordinate f enumerates the magnetic field tube ($0 < f < f_*(\chi)$, $f_* \approx 1.6$), and P is the period of the pulsar. Thus

$$\theta = \frac{2R}{\rho_0}\left(\frac{z}{R}\right)^{1/2}.$$

Substituting this value in eq.(2) we get the distance z_p where the cyclotron resonance occurs.

$$\begin{aligned}
\frac{z_p}{R} &= \left(\frac{\omega_{B0}}{2\omega}\right)^{1/2}\left(\frac{\rho_0}{R}\right)^{1/2}\gamma^{-1/4} \\
&\approx 580\left(\frac{B_{12}P}{\nu_{GHz} f \gamma_{100}}\right)^{1/4},
\end{aligned}$$

where

$$\begin{aligned}
B_{12} &= B \times 10^{-12}\,\mathrm{G}, \\
\nu_{GHz} &= \nu \times 10^{-9}\,\mathrm{GHz}^{-1}, \\
\gamma_{100} &= \gamma \times 10^{-2}.
\end{aligned}$$

In the region of cyclotron resonance the polarization of the eigen modes becomes circular

$$\left(\frac{E_x}{E_y}\right)_{1,2} = \pm i.$$

The refractive indices for the left- and right-hand polarized modes are not equal

$$n_{1,2} = 1 \pm \left\langle \frac{\omega_p^2\theta^2}{4\omega(\omega_B \mp \gamma\tilde{\omega})} \right\rangle.$$

This difference results in the Faraday effect—the rotation of the polarization vector after leaving the resonance region. However, we are interested in the appearance of circular polarization due to nonuniform profile emission intensity. Indeed, the group velocities of the two modes are different also

$$V_{g_{1,2}} = c\left[\frac{\boldsymbol{k}}{k} \pm \left\langle \frac{\omega_p^2}{2\omega(\omega_B \mp \gamma\tilde{\omega})} \right\rangle \boldsymbol{b}\right] \qquad (3)$$

($\boldsymbol{b}$ is the unit vector along the direction of the magnetic field line). Because of this the left and right-hand polarized waves come to the observer from

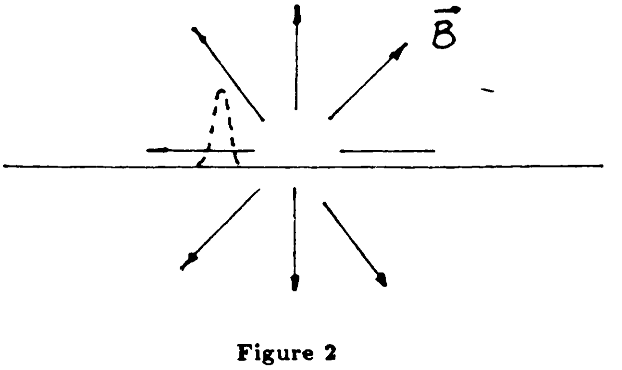

Figure 2

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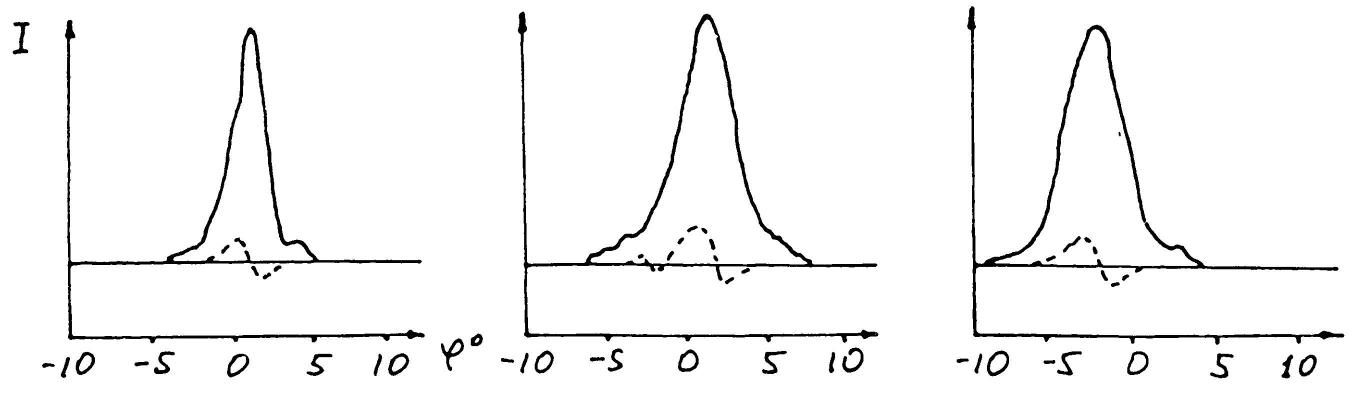

Figure 3a PSR 2002+31 **Figure 3b** PSR 1907+02 **Figure 3c** PSR 1933+16

different regions of the magnetosphere where their intensities are different. If we designate the intensity of the circularly polarized wave as I_V, then

$$I_V(x) = I(x_1) - I(x_2) = \frac{dI}{dx}(x_1 - x_2). \quad (4)$$

The x coordinate lies in the plane of the page (see figure 2).

From eq.(3) it follows that

$$\frac{d(x_1 - x_2)}{dz} = \left\langle \frac{\omega_p^2 \omega_B b_x}{\omega(\omega_B^2 - \gamma^2 \tilde{\omega}^2)} \right\rangle. \quad (5)$$

Integrating over dz and dy we find from eqs.(4) and (5) the formula

$$I_V(\varphi) = \frac{4\lambda}{P\nu} \left|\cos\chi e_e \gamma^+_{\min}/\gamma^-_{\min}\right| \frac{dI}{d\varphi}. \quad (6)$$

Figure 3 shows the profiles of several pulsars with core component emission PSR 2002+31, 1907+02, and 1933+16 (Rankin 1983a). The behavior of the circularly polarized component is in agreement with eq.(6). From eq.(6) it is possible to determine the quantity λ

$$\lambda_4 \ln\left(\frac{\lambda_4 \Delta\varphi_{10}}{1.6}\right) \approx 22\, P\, \nu_{\mathrm{GHz}}\, \Delta\varphi_{10} \left(\frac{I_V}{I}\right).$$

For the pulsars 2002+31, 1907+02, and 1933+16, shown above, the multiplicity parameter λ_4 is equal to 25, 20, and 15, respectively. These correspond to the expected values, which follow from the theory of particle reproduction $\lambda \sim 10^4$–10^5 (Gurevich and Istomin 1985a).

Let us note that we do not take into account the cyclotron absorption. As was shown by (Mikhailovskii *et al.* 1982b) and (Beskin, Gurevich, and Istomin 1988b), the absorption is small for the actual parameters of pulsars and it can be negligible.

We have discussed the possibility of explaining the circular component of pulsar radio emission as a result of propagation effects. This model does not depend on a concrete theory of radio pulsar emission; only the presence of a dense plasma in the pulsar magnetosphere is necessary.

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