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Propagation Effects on Pulsar Radio Emission

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Abstract: Propagation effects on radio emission within the pulsar magnetosphere are discussed. Widely accepted pulsar models assume that a pulsar magnetosphere is populated with relativistic pair plasmas produced through electron–positron cascades by accelerated primary particles above the polar cap. Any radio emission produced well inside the light cylinder (the radius at which the rotation speed equals c) must propagate through the magnetospheric plasma and be subject to plasma dispersion effects such as refraction and absorption. The observed pulse profiles should contain some features that reflect the influence of the intervening plasma. I discuss particularly the absorption effect due to cyclotron resonance and its possible observational consequences.

Keywords: relativistic plasmas — pulsars: general — radiation mechanisms: non-thermal

1 Introduction

Pulsar radio emission is markedly different from other astrophysical radio sources in that it has an extremely high brightness temperature and is highly polarised. The inferred brightness temperature can be as high as 10^{28} K, implying that the emission must be coherent (cf. review by Melrose 2000). Although various emission models have been proposed, none of them has been widely accepted as a successful model that can account for most observations (e.g. Melrose & Gedalin 1999; Melrose 2000). The most important information we have from observations on the radio emission includes the rapid variability of individual pulses (Manchester & Taylor 1977), the integrated pulse profiles which have very stable shapes but vary from pulsar to pulsar (Lyne & Manchester 1988), and the unique polarisation features such as highly linear polarisation and a large component of circular polarisation (Gould & Lyne 1998; Han, Manchester, Xu, & Qiao 1998). The stable integrated pulse profiles, which are derived by averaging over many individual pulses, suggest that radiating particles are highly collimated and confined to a certain region with well defined geometry. The observed polarisation features include: (1) linear polarisation, which dominates on average; (2) a significant component of circular polarisation, with a sign reversal being observed for some pulsars; and (3) 'mode switch' (from one linear polarisation to another linear polarisation with 90° difference), frequently observed for some pulsars (Lyne & Manchester 1988).

Pulsars are magnetised, rotating neutron stars which emit electromagnetic radiation. The emission from known radio pulsars is thought to be powered by their rotation. A neutron star can be considered as a perfect conductor, and its rotation induces an electric field which has a component parallel to the magnetic field which can accelerate particles (extracted from the star's surface) to ultra high energy. These primary particles move one-dimensionally along the magnetic field lines producing high energy photons through curvature radiation or inverse Compton scattering. These high energy photons can decay into $e^{\pm}$ pairs in strong magnetic fields, which populate the pulsar magnetosphere and outflow along the open field lines (Sturrock 1971; Ruderman Sutherland 1975; Arons & Scharlemann 1979; Daugherty & Harding 1982). The radio emission is believed to be generated in this outflowing plasma (Melrose 2000).

Observations strongly suggest that radio emission from most pulsars comes from the region well inside the light cylinder (LC) (Manchester & Taylor 1977; Blaskiewicz, Cordes, & Wasserman 1991). The radio waves must propagate through the magnetospheric plasma to escape to the interstellar medium. An important issue, regardless of specific emission mechanisms, is how the pulsar magnetospheric plasma affects propagation of the radio emission. There are four main effects that can influence the propagation: these are reflection, refraction, scattering, and absorption. Reflection can occur if waves propagate to a region with a rapid spatial variation in the plasma density. In a smoothly varying inhomogeneous medium, the relevant waves are subject to refraction (slow change in the propagation direction). Waves can also be absorbed through various resonance and scattering processes involving interactions with plasma particles or another wave. Possible resonance processes inside the LC are Cerenkov resonance (e.g. Arons & Barnard 1986), Cerenkov-drift resonance (Kazbegi, Machabeli, & Melikidze 1991; Malov, Malofeev, Machabeli, & Melikidze 1997; Lyutikov, Blandford, & Machabeli 1999), and cyclotron resonance (Blandford & Scharlemann 1976; Mikhailovskii 1979; Mikhailovskii, Onishchenko, Suramlishvili, & Sharapov 1982). Since both Cerenkov and Cerenkov-drift resonances require that waves have a subluminal parallel phase velocity $\omega/k_{\parallel} < c$, absorption of purely or nearly

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transverse waves due to these two processes is not effective (e.g. Volokitin, Krasnosel'skih, & Machabeli 1985; Kazbegi, Machabeli, & Melikidze 1991).

In this paper I discuss specifically the refraction and absorption (due to cyclotron resonance) effects on the propagation of pulsar radio emission inside the LC. In particular, the observable features due to asymmetric cyclotron absorption are considered. Part of the work presented here is the result of my ongoing collaboration with Don Melrose. In Section 2, a brief review on relevant wave modes and their propagation in pulsar plasmas is given with emphasis on those modes that can propagate through the magnetosphere to escape to the interstellar medium. The cyclotron absorption effects on wave propagation and the possible observable features are discussed respectively in Section 3 and in Section 4.

2 Wave Modes

There are extensive discussions in the literature on wave modes in pulsar plasmas (e.g. Volokitin, Krasnosel'skikh, & Machabeli 1985; Arons & Barnard 1986; Lominadze, Machabeli, Melikidze, & Pataraya 1986; Gedalin, Melrose, & Gruman 1998; Lyutikov, Blandford, & Machabeli 1999; Melrose & Gedalin 1999; Kennett, Melrose, & Luo 2000). Here I summarise only those modes which can propagate through the pulsar magnetosphere.

Although the emission mechanism is not well understood, in principle, given a model of pulsar magnetospheric plasmas, one can determine various possible wave modes. Since pulsars have very strong magnetic fields ranging from 10^4 to 10^9 T, electrons or positrons moving in such strong magnetic fields radiate rapidly away their perpendicular energy and their motion is essentially one-dimensional along field lines. In practice, one may derive plasma dispersion by assuming zero perpendicular momentum, $p_\perp = 0$ but allowing transition to the first Landau level (Lominadze, Machabeli, Melikidze, & Pataraya 1986; Melrose & Gedalin 1999; Kennett, Melrose, & Luo 2000). One may make a further assumption of charge neutrality with charge symmetry since the bulk plasma consists mainly of electrons and positrons. (The charge neutrality assumption may not be appropriate in the acceleration region where a non-neutral flow can be dominant.) In these approximations, the dispersion relations can be simplified considerably and one has three distinct modes for oblique propagation: the X mode with the polarisation vector being perpendicular to the **k**–**B** plane, the L–O mode with the polarisation vector in the **k**–**B** plane, and the Alfvén mode with the polarisation vector also in the **k**–**B** plane.

Since the X mode waves with polarisation along $\mathbf{k} \times \mathbf{B}$ cannot effectively interact with particles moving strictly along the magnetic field through Cerenkov resonance, they can only be produced either through cyclotron instability (Machabeli & Usov 1979; Kazbegi, Machabeli, & Melikidze 1991) or some nonlinear processes (Lominadze, Machabeli, Melikidze, & Pataraya 1986). The X mode is subluminal at nearly parallel propagation and becomes superluminal at oblique propagation. Therefore the X mode, which is not Landau damped, can easily propagate through the magnetospheric plasma. However, the X mode can be damped through cyclotron resonance, which is discussed in Section 3.

The L–O mode is a mixed longitudinal–transverse mode, which can interact with particles through Cerenkov resonance provided that the parallel phase velocity is less than c. For parallel propagation the L–O mode is longitudinal corresponding to Langmuir waves, which cannot propagate to underdense regions because of Landau damping. The L–O mode is superluminal and longitudinal in the long wavelength limit, regardless of its propagation angle (between **k** and **B**). The L–O mode has a cutoff frequency $\omega_c = \omega_p \langle 1/\gamma^3 \rangle^{1/2}$, where γ is the particle's Lorentz factor in the pulsar frame, $\langle \ldots \rangle$ denotes the average over the particle distribution, $\omega_p = (e^2 n_p/\varepsilon_o m_e)^{1/2} = 4 \times 10^{11}\ \mathrm{s}^{-1}\ (M/10^2)^{1/2}(0.1\ \mathrm{s}/P)^{1/2}(B/10^8\ \mathrm{T})^{1/2}$ is the plasma frequency, B is the local magnetic field, P is the pulsar period, $n_p = M n_{\mathrm{GJ}}$, M is the multiplicity, and $n_{\mathrm{GJ}} = 7 \times 10^{17} (0.1\ \mathrm{s}/P)(B/10^8\ \mathrm{T})\ \mathrm{m}^{-3}$ is the Goldreich–Julian (GJ) density. For a dipole magnetic field, both B and n_{GJ} decrease as $1/R^3$ where R is the radial distance. This mode crosses the light line to become subluminal at $\omega_{\mathrm{co}} = 2\langle\gamma\rangle\omega_p$ (Arons & Barnard 1986; Melrose & Gedalin 1999). Note that ω_{co} can be much higher than the observed lowest radio frequency unless $\langle\gamma\rangle$ is small or the relevant region is near the LC (Melrose & Gedalin 1999). The L–O mode can be generated in the superluminal frequency region (above the cutoff frequency ω_c) through nonlinear processes.

In the low frequency limit, the Alfvén mode can have a refractive index close to 1 but it cannot propagate away to a very underdense region without being Landau damped. Therefore, for radio emission to escape to infinity, one requires that the emission is produced (1) directly onto the transverse X mode or the nearly transverse L–O mode or their superposition, or (2) onto low frequency modes such as the Alfvén mode which cannot propagate to underdense regions but can be converted, by nonlinear or inhomogeneity effects, to high frequency modes that can propagate through the magnetosphere.

3 Propagation inside the LC

In the following discussion the radio emission is assumed to be produced in waves that can escape (i.e. the X mode or the L–O mode or their superposition). The two mode assumption is favoured by observations (Manchester, Taylor, & Huguenin 1975; McKinnon & Stinebring 1998). In the single-rotating vector model (Radhakrishnan & Cooke 1969; Blaskiewicz, Cordes, & Wasserman 1991), the polarisation vector is fixed relative to the magnetic field line direction. If the emission is linearly polarised, the position angle has an 'S' shape variation as the line of sight sweeps across the open field line flux tube. However, a jump of 90° in the position angle has been observed for some pulsars (Manchester, Taylor, & Huguenin 1975).

Such an abrupt change in the position angle implies switching from one mode to another orthogonal mode. Recent studies have shown that the two modes may occur at the same time so that radio emission is a superposition of these two modes (McKinnon 1997; McKinnon & Stinebring 1998).

3.1 Radiative Transfer Equation

The standard description of refraction and absorption of rays is the geometric optical approximation, in which the characteristic length scale of any inhomogeneity is much larger than the relevant wavelength $\lambda = c/\omega$ (which precludes any reflection). For the frequency above 200 MHz, the approximation is valid for an inhomogeneity length scale much larger than $\lambda = 25$ cm. In this approximation, the local plasma dispersion can be determined in the same way as in a uniform plasma. Propagation of a ray with a specific intensity, I_ν, is determined by the radiative transfer equation (Bekefi 1966; Rybicki & Lightman 1979)

$$n_r^2 \frac{\partial}{\partial s}\left(\frac{I_\nu}{n_r^2}\right) = \alpha_\sigma - \mu_\sigma I_\nu, \tag{1}$$

where $\nu = \omega/2\pi$, $n_r^2 = n_\sigma^2 |v_g(dk/d\omega)(\partial\cos\theta/\partial\cos\theta_r)|$ is the ray refractive index, v_g is the group velocity, n_σ is the refractive index of the σ mode, s is a parameterised distance along the ray path, μ_σ is the absorption coefficient (per unit length), θ and θ_r represent the angles of the wave vector and the ray propagation direction (the group velocity) relative to the magnetic field lines, and α_σ is the energy radiated per unit volume in the frequency range $d\nu$ due to spontaneous emission along the ray path. It is convenient to use the temporal absorption coefficient defined by $\Gamma_\sigma = \mu_\sigma v_g$.

Following Melrose (1979), one defines the polarisation limit region (PLR) along a ray path. The polarisation is affected by the plasma only in the region below the PLR. The PLR location depends on specific wave modes and where the ray starts. The intensity, I_σ, is affected by absorption, which can occur throughout the magnetospheric plasma. Absorption can occur even above the PLR where the plasma density is too low to influence the polarisation.

3.2 Refraction of Rays

Consider two orthogonal modes which initially propagate in the same direction. Due to the difference in their refractive indices, the two rays split. The application of ray refraction to pulsars is shown in Figure 1. The plasma density and magnetic field decrease along the curved field lines. The inhomogeneity associated with this variation has the typical length scale being the radial distance to the star's centre. Since pair production is nonuniform across the polar cap, the pair plasma produced from the cascade must vary spatially across the open field line flux tube with the characteristic length less than the radius of the tube. Assume the X and L–O mode waves are emitted at a in the direction tangential to field lines. The X mode propagates along a nearly straight path because its refractive index, n_X, is very close to 1. In contrast, the L–O mode, which is affected by significant refraction, bends following curved field lines.

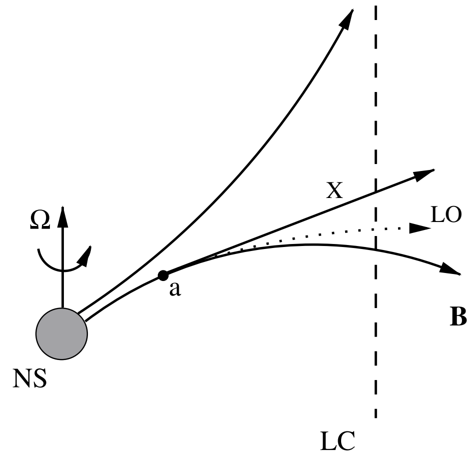

Figure 1 Refraction effects on propagation of the X and the L–O modes. The plasma density is nonuniform in the directions along and perpendicular to the field lines.

The refraction effect on wave propagation in the absence of any absorption or scattering is described by equation (1) by setting the right hand side to zero, i.e. $\partial(I_\nu/n_r^2)/\partial s = 0$. To obtain a ray path it is convenient to use the Hamilton form (Bekefi 1966),

$$\frac{d\mathbf{x}}{d\xi} = \frac{\partial\omega}{\partial\mathbf{k}}, \qquad \frac{d\mathbf{k}}{d\xi} = -\frac{\partial\omega}{\partial\mathbf{x}}, \tag{2}$$

where $\omega(\mathbf{k}, \mathbf{x})$ is the local wave frequency, $\mathbf{k}$ is the wave vector, and $\xi = \int ds/v_g$. Ray bending can occur due to either plasma anisotropy, such as a uniformly magnetised plasma, or inhomogeneous plasmas with the density and magnetic fields varying spatially. For a uniformly magnetised plasma, change of the ray direction is due to the dependence of the wave dispersion on its propagation angle relative to the magnetic field (cf. equation (2)). The angular separation between the two rays is $\Delta\theta_r \approx (\omega_p/\omega)^2\gamma$ (Melrose 1979; Allen & Melrose 1982). Melrose (1979) proposed that this birefringent effect can be an alternative mechanism for an orthogonal mode switch.

Since pulsar magnetospheric plasmas are nonuniform in both directions along and perpendicular to the magnetic field lines, the dominant effect that causes a ray to bend is the inhomogeneity in the plasma density and magnetic field (e.g. Barnard & Arons 1986; Petrova 2000). When inhomogeneity in the transverse direction is dominant, the gradient of ω in equation (2) is perpendicular to $\mathbf{B}$. Then, one has $k_\parallel \approx$ const (Snell's law), and $k_\perp$ has to increase as field lines curve away. Therefore, $\mathbf{k}$ changes little in direction but v_g bends along the field lines.

In principle, given a model of pulsar plasmas, one can derive the dispersion relations of the relevant modes. The corresponding ray path can be found by numerically solving these two equations (Barnard & Arons 1986). So far, there is no comprehensive ray tracing study which includes pulsar rotation. If the refraction occurs at relatively higher altitudes, the rotation may cause distortion in the ray propagation, leading to modification of the pulse profile. This effect has as yet not been fully investigated.

4 Cyclotron Absorption

Cyclotron absorption occurs when the wave frequency in the particle's rest frame equals the cyclotron frequency Ω_e. The pulsar magnetic field can be modelled as a magnetic dipole with the field strength scaled as $1/R^3$ inside the LC, where R is the radial distance to the star. Waves with frequency below the cyclotron frequency must propagate to the region where the cyclotron frequency becomes lower than the wave frequency. Cyclotron resonance must occur within a transition region between the two parameter regimes. It can be shown that at least for some pulsars the cyclotron resonance can occur within the magnetosphere (Blandford & Scharlemann 1976; Mikhailovskii 1979; Mikhailovskii, Onishchenko, Suramlishvili, & Sharapov 1982; Lyubarskii & Petrova 1998; Luo & Melrose 2001), and more pulsars can have cyclotron resonance if a broad distribution of pair plasmas is allowed.

The cyclotron resonance condition is

$$\omega - k_{\parallel} v_{\parallel} - \Omega_e/\gamma = 0, \tag{3}$$

where $k_{\parallel} = k\cos\theta$, θ is the angle between the wave vector, $\mathbf{k}$, and the magnetic field line direction, and $v_{\parallel}$ is the parallel velocity. Since Ω_e varies with the radial distance as $1/R^3$, given a frequency of emitted radio waves and a particle's Lorentz factor, the cyclotron resonance condition is satisfied only at a particular radius, called the cyclotron absorption radius, denoted by R_c. Here I only discuss the resonance inside the LC, that is $R_c < R_{\rm LC}$, where $R_{\rm LC} = c/\Omega$. Since the pulsar plasma has a distribution, the cyclotron absorption radius R_c is distributed over an extended region.

To concentrate on the cyclotron absorption, I ignore emission and set $\alpha_\sigma = 0$ in equation (1). Then, from equation (1) one obtains the intensity as a function of the propagation distance,

$$I_\nu = \frac{I_{0\nu}}{n_{r0}^2}\exp(-\tau_\sigma), \qquad \tau_\sigma = \int_0^s ds'\,\Gamma_\sigma(s'), \tag{4}$$

where $n_r \approx 1$ at s, τ_σ is the optical depth for the σ mode, $I_{0\nu}$ is the intensity at $s' = 0$, and the integration is along the ray path. The absorption coefficient can be derived from the local plasma dispersion (e.g. Melrose 1986). In the approximation that waves are considered as transverse, the X and L–O modes have a similar absorption rate given by $\Gamma \approx \pi(\omega_p^2/\omega) f(\gamma_c\beta_c)$ where $f(\gamma\beta)$ is the plasma distribution, and $\beta_c = (1-\gamma_c^{-2})^{1/2}$ is the velocity of the resonant particles (Blandford & Scharlemann 1976).

The simplest case is the monoenergetic distribution with γ_0. One finds the optical depth (e.g. Blandford & Scharlemann 1976; Lyubarskii & Petrova 1998; Luo & Melrose 2001)

$$\tau = \frac{\pi}{3} M\theta^2 \frac{R_c}{R_{\rm LC}}, \tag{5}$$

where θ is the propagation angle (between $\mathbf{k}$ and $\mathbf{B}$), $R_c/R_{\rm LC} = (2\Omega_{e,{\rm LC}}/\omega\gamma_0\theta^2)^{1/3}$, and $\Omega_{e,{\rm LC}}$ is the cyclotron frequency at the LC. Here, I consider only the parameter regime with $R_c/R_{\rm LC} \le 1$. For a dipole magnetic field, the angle θ can be as large as 0.1–0.4. In the conventional polar cap models (Ruderman & Sutherland 1975; Arons & Scharlemann 1979) M can be very large (say 10^2–10^3), implying a very large optical depth, $\tau \gg 1$. To avoid strong absorption, one requires that either the plasma in the wave propagation region has a much lower density than predicted by the conventional polar cap models (Blandford & Scharlemann 1976), or the waves propagate along nearly straight field lines close to the magnetic axis (in which case θ is very small).

Calculation of the optical depth for a broad distribution was recently given by Luo & Melrose (2001). Consider a relativistic distribution with a bulk Lorentz factor Γ (e.g. Weatherall 1994)

$$f(u_\parallel) = N^{-1}\exp\left[-\varrho_{\rm T}\gamma\Gamma(1-\beta\beta_\Gamma)\right], \tag{6}$$

where $\Gamma = 1/\sqrt{1-\beta_\Gamma^2}$, $u_\parallel = \gamma\beta$, $\varrho_{\rm T}$ is the inverse temperature, and N is the normalisation factor. Examples of relativistic distributions are shown in Figure 2 with $\varrho_{\rm T} = 0.2$, $\Gamma = 100, 500$. Optical depth for the distribution equation (6) and a monoenergetic distribution is plotted as a function of frequency, shown in Figure 3.

Allowing a wide range of the bulk Lorentz factor and the spread of distribution in the parallel momentum ($u_\parallel$), it can be shown that the majority of pulsars including young pulsars can have cyclotron resonance inside their LC. One possibility is that cyclotron resonance only partially affects the radio emission in the sense that only part of the radio beam is absorbed and in most cases the absorption is marginal. This possibility has a major observational consequence as partial absorption can produce asymmetric pulse profiles, in particular when the rotation effect is considered (Luo & Melrose 2001), and differential absorption on different modes can lead to observable polarisation features.

5 Observational Consequences

If propagation effects are important the observed pulses must carry some features that arise from the propagation. I consider marginal absorption due to cyclotron resonance and discuss its observational signature.

5.1 Asymmetric Pulse Profiles

The cyclotron absorption strongly depends on the propagation angle and the local plasma density, n_p, through $\tau \propto M\theta^2$, which can be significantly modified by the star's rotation. Therefore, the absorption is in general asymmetric about the rotation axis (as well as the magnetic axis), leading to potentially observable absorption features.

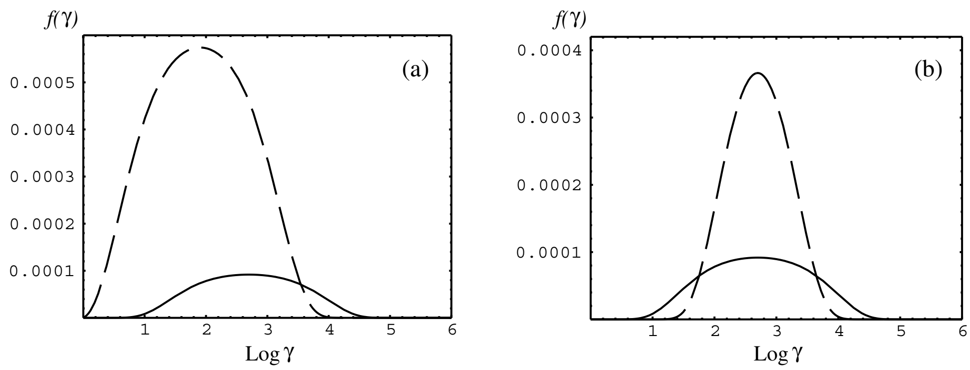

Figure 2 Relativistic distributions. (a) The inverse temperature is assumed to be $\varrho_{\rm T} = 0.1$ for two different bulk Lorentz factors, $\Gamma = 80$ (dashed) and 500 (solid). (b) Assume $\Gamma = 500$ for $\varrho_{\rm T} = 0.1$ (solid) and 0.5 (dashed).

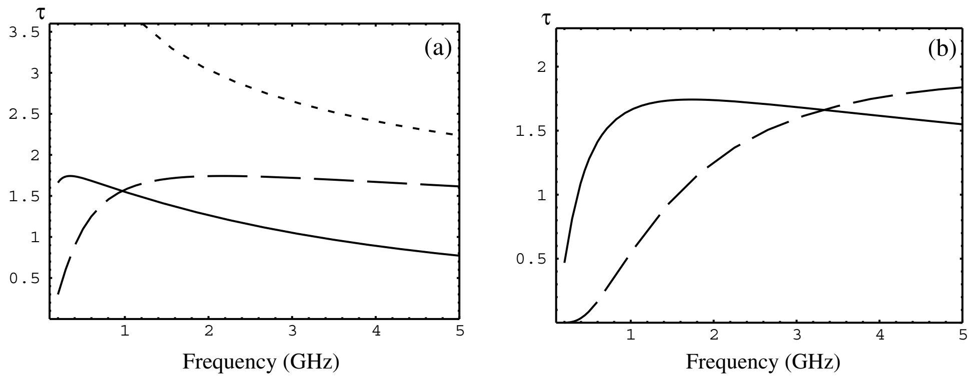

Figure 3 Optical depth against frequency with $M = 100$, $B_* = 10^8$ T, $P = 0.15$ s, and $\theta = 0.2$. The dotted curve is plotted with a monoenergetic distribution with $\gamma = 500$. The ray is assumed to start at $0.2R_{\rm LC}$ and the integration is from $0.2R_{\rm LC}$ to $0.8R_{\rm LC}$. (a) The distributions are as in Figure 2(a) with $\Gamma = 80$ (dashed) and 500 (solid). (b) Two different temperatures, $\varrho_{\rm T} = 0.1$ (solid) and 0.5 (dashed) with the distributions given in Figure 2(b).

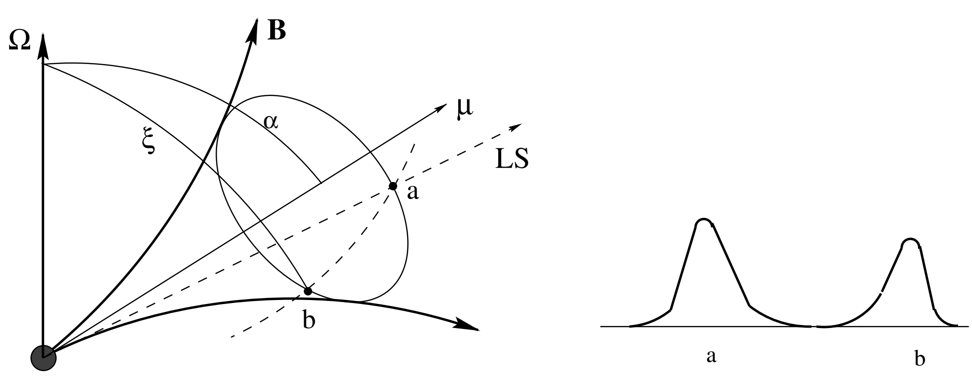

Figure 4 A cone emission model. The angles of the line of sight (LS) and the magnetic pole relative to the rotation axis are respectively ξ and α. As the star rotates, the LS (dashed arrow line) follows a trajectory shown as the dashed curve on the spherical surface at the emission radius. Rays emitted at a and b form two peaks. As the two rays propagate through different parts of the rotating magnetosphere, they are subject to differential cyclotron absorption, resulting in asymmetry in the intensity of the two peaks.

To discuss the observational consequences of this asymmetric absorption, consider a wide cone with the radio emission originating from a narrow ring. As shown in Figure 4, as the line of sight (LS) cuts across the cone one observes a pulse with two widely separated subpulses emitted from the two opposite sides of the cone. Consider two components with intensity given by $I_a = I_0 \exp(-\tau_a)$ and $I_b = I_0 \exp(-\tau_b)$ where we assume the two beams have the same initial intensity, I_0, but with different optical depths due to the difference in the propagation angle

θ and the local plasma density M (in the GJ density) along the two ray paths. The asymmetry in intensity is given by

$$\frac{I_b}{I_a} = \exp\left[-\left(\frac{M_b\theta_b^2}{M_a\theta_a^2} - 1\right)\tau_a\right], \qquad (7)$$

where the subscripts a and b correspond to the two ray paths originating from the two sides. Assume the first component with the intensity I_a has marginal absorption with $\tau_a \leq 1$. For $(M_b/M_a)(\theta_b/\theta_a)^2 > 1$, the ratio can have a wide range of values from 1 to less than a few percent. The relative intensity is determined by the inclination angle and the angle, ξ, of the LS relative to the rotation axis. The strong asymmetry occurs for an oblique inclination angle $\alpha \approx \xi$ (Figure 4).

There seems to be a class of pulsars with pulse profiles having a distinct conical structure (Lyne & Manchester 1988). In the rotating vector model (Radhakrishnan & Cooke 1969; Blaskiewicz et al. 1991), such double peak profiles can be interpreted as the emission from opposite sides of the cone. Some pulsars with very widely separated double peak pulse shapes may be regarded as extreme cases of the usual cone emission (wide cone) (Lyne & Manchester 1988). Then, the observed asymmetry of the double peak profile (in which one peak is stronger than the other) can be interpreted as due to one component being more strongly absorbed through cyclotron resonance.

5.2 Frequency Dependence

The best chance to test the predicted asymmetric absorption effect against observations is to consider pulsars with profiles with widely separated double peaks, such as pulsars with interpulses. There are two interpretations for interpulses. In the two-pole model, the main pulse and interpulse are due to emission from two opposite poles. Double peak pulses are common features of light curves of pulsar high energy, which leads to an alternative interpretation that observed double peak radio pulses are due to the emission from one pole (Manchester & Lyne 1977; Manchester 1996). In the cone model, the emission is produced on a single wide cone with an oblique inclination angle. The intensity ratio of the two components can be less than a few percent and depends on frequency. Figure 5 shows plots of I_b/I_a as a function of frequency. For a monoenergetic distribution, the ratio decreases with increasing frequency as $\tau \propto 1/\omega^{1/3}$ (the dotted curve). For a broad distribution, the absorption peaks at the frequency at which resonance particles are at the peak of the distribution. In general, if the resonance occurs on the negative slope of the distribution, the absorption increases for increasing frequency, leading to a decrease in the ratio. On the positive slope the absorption decreases for increasing frequency. Both cases appear to be seen in observations, suggesting that the resonance occurs for both $df/du_\parallel > 0$ and $df/du_\parallel < 0$.

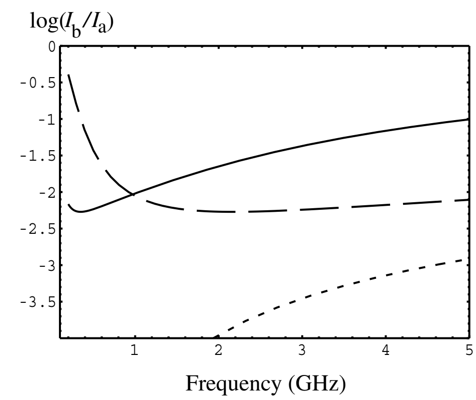

Figure 5 Intensity ratio against frequency for $(M_b/M_a)^{1/2}$ $(\theta_b/\theta_a) = 2$. The parameters are as in Figure 3(a).

6 Summary

Radio emission produced well inside the LC must propagate through relativistic pair plasmas and is subject to refraction and absorption. Influence on rays by plasma dispersion should produce observable features of pulse profiles. Identifying these features can provide important information on pulsar magnetospheric structures and emission processes. Among various damping processes, cyclotron absorption is considered as an important absorption process which can lead to observable asymmetric features of pulse profiles. For pulsars with double peak profiles, one expects that one component (the leading peak) is stronger in intensity than the other as the later peak has strong cyclotron absorption. The asymmetry in the intensity ratio of the two peaks depends on frequency. This frequency dependence can be tested against observations and be used to infer whether the resonance occurs on the $df/du_\parallel > 0$ or $df/du_\parallel < 0$ part of the plasma distribution. Work on the details of the frequency dependence of cyclotron absorption and its relation to the plasma distribution is currently in progress.

Acknowledgements

It is my great pleasure to dedicate this paper to Don Melrose with whom I have had many fruitful collaborations on pulsar emission theory.

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