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Coherent radio emission from pulsars

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The high brightness temperature of pulsar radiation requires that the emission process be coherent. There are three possibilities in principle: emission by bunches; reactive instability, due to an intrinsically growing wave mode; and kinetic instability, which is maser action. The emission may be direct or indirect, depending on whether the radiation can escape to infinity through the pulsar magnetosphere, or must first be converted into another wave mode. Early models favoured either direct curvature emission by bunches or indirect emission due to a reactive beam instability, but before about 1980 it was realized that there are serious problems with both mechanisms. There are strong physical arguments against emission by bunches being viable, and the first detailed analysis suggested that the seemingly plausible alternative of maser curvature emission is impossible. Also the growth rates for beam instabilities were found too small to allow waves to grow effectively. Alternative emission mechanisms, including cyclotron and linear acceleration emissions, and variants on the existing mechanisms have been considered. In this paper the suggested emission mechanisms are reviewed from a plasma-physical viewpoint, and they are then compared to see how they might fit into a phenomenological model for pulsar radio emission.

1. Introduction

Pulsar radio emission has a very high brightness temperature which implies that the emission mechanism must be coherent; that is, the emission cannot be explained in terms of individual particles radiating independently (incoherently) of each other. There are three general forms of coherent emission: emission by bunches, a reactive instability and a maser mechanism. In its simplest form *emission by bunches* involves N particles radiating as a macroparticle, so that the power radiating in N^2 times the power per individual particle. A *reactive instability* corresponds to an intrinsically growing wave in which growth occurs due to phase bunching. *Maser emission* corresponds to negative absorption which causes waves with arbitrary or random phases to grow. These three require that the distribution of particles have the following properties, respectively: localization in both coordinate and momentum space (a monoenergetic bunch), localization only in momentum space (a monoenergetic distribution), a positive gradient in momentum space (an inverted energy population). All three types of coherent emission have been invoked in models for pulsar radio emission. However, although there are many specific examples of maser emission in space physics and astrophysics, there is no convincing case of a reactive instability, and *a fortiori*, no case of emission by bunches. Some form of maser

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emission is intrinsically the most plausible for any coherent emission from an astrophysical source.

There is another general classification of emission processes in plasmas. This arises from the fact that waves in only two specific wave modes can escape from an astrophysical plasma to infinity; waves in all other wave modes encounter either a stop band, from which they are reflected, or a region where the wave are absorbed completely. This leads to the distinction between a *direct emission mechanism*, in which the waves are generated in one or both of the modes that can escape, and an *indirect emission*, in which the waves that are generated initially are in a wave mode that cannot escape and so must be transformed into one of the modes that can escape. Relevant direct processes for pulsar radio emission are curvature, cyclotron and linear acceleration emissions. An example of an indirect maser mechanism in another context is plasma emission in solar radio bursts: the maser process is a beam instability that generates Langmuir turbulence (longitudinal electron plasma waves), and nonlinear processes in the plasma lead to escaping radiation at the fundamental and the second harmonic of the plasma frequency, ω_p (Melrose 1986, p. 94). Relevant indirect processes for pulsar radio emission also invoke some form of beam instability and conversion due to scattering, wave–wave processes or mode coupling in the inhomogeneous plasma. Here such indirect emission processes are referred to as *relativistic plasma emission* processes.

Coherent emission by bunches is discussed critically in §2 and is then not considered further. Four possible emission mechanisms are discussed: masar curvature emission in §3, cyclotron emission and linear acceleration emission in §4 and relativistic plasma emission in §5. The application of these mechanisms to the interpretation of phenomenological aspects of the pulsar radio emission is discussed in §6. It is concluded that relativistic plasma emission is the most plausible mechanism, but that none of the other three mechanisms can be ruled out.

2. Curvature emission by bunches

In the superstrong magnetic field, $\boldsymbol{B}$, of a pulsar, gyromagnetic emission by electrons and positrons causes them to radiate away all their perpendicular momentum. The perpendicular momentum is quantitized with $p_\perp^2 = 2n\hbar eB$, where n is an integer and is said to label the *Landau levels*. As a result of gyromagnetic emission, the particles fall to the lowest Landau level, so that the motion is one dimensional along the field lines with Lorentz factor $\gamma = (1+p_\parallel^2/m^2c^2)^{\frac{1}{2}}$ determined solely by the parallel momentum, $p_\parallel$. Particles propagating along curved magnetic field lines must experience an acceleration to cause them to follow the curved path, and this acceleration may be attributed to a Lorentz force $\pm e\boldsymbol{v}_d \times \boldsymbol{B}$, where $\pm e$ is the charge and $\boldsymbol{v}_d$ is the curvature drift velocity. As a result of the accelerated motion the particles radiate so-called *curvature emission*. Curvature emission may be described in terms of emission by a relativistic particle moving around the arc of a circle, chosen such that the actual acceleration corresponds to the centripetal acceleration.

Coherent curvature emission by bunches was favoured in some early theories (Gunn & Ostriker 1971; Sturrock 1971; Ginzburg & Zheleznyakov 1975; Benford & Buschauer 1977; Kirk 1980; Buschauer & Benford 1983). Three criticisms of this mechanism are (Melrose 1981, 1992): there is no general theory for emission by bunches; there is no adequate bunching mechanism; and, even if bunches did form they would disperse too rapidly. A theory for emission by bunches exists only for a distribution of particle all with the same momentum. Qualitatively, if a mono-energetic bunch were to be created initially, then one effect of the coherent emission would be to induce a spread in momentum which would lead to a dispersion of the bunch. As a result of such backreaction, one expects coherent emission by bunches to evolve into a reactive instability and, as the momentum spread increases further, into maser emission. The latter evolution is understood in detail for specific plasma instabilities (Melrose 1986, p. 37), but the first stage cannot be discussed in detail due to the lack of a general theory for emission by bunches.

Let us ignore the difficulties for the present and assume that emission by bunches is efficient as possible and consider its implications. The existing theory for coherent emission by a bunch all with the same momentum (Sturrock *et al*. 1975) relates the power $P_{\text{bun}}(\boldsymbol{k})\,\mathrm{d}^3\boldsymbol{k}/(2\pi)^3$ emitted by the bunch in the range of wavevectors $\boldsymbol{k}$ to $\boldsymbol{k}+\mathrm{d}^3\boldsymbol{k}$ to the same quantity $P_{\text{par}}(\boldsymbol{k})\,\mathrm{d}^3\boldsymbol{k}/(2\pi)^3$ for a single particle by

$$P_{\text{bun}}(\boldsymbol{k}) = |n(\boldsymbol{k})|^2 P_{\text{par}}(\boldsymbol{k}), \tag{1}$$

where $n(\boldsymbol{k})$ is the spatial Fourier transform of the number density of particles in the bunch. The simple case where N particles radiate N^2 times the power per particle corresponds to the limit of an arbitrarily small bunch: $\lim_{k\to 0} n(\boldsymbol{k}) = N$.

The main difficulties with coherent curvature emission by bunches is that there is no effective mechanism for formation of the bunches (Melrose 1978; Asséo *et al*. 1981). Suppose one ignores this and postulates some unidentified mechanism which produces adequate bunching. The following difficulties remain.

1. Efficient coherent emission requires that $n(\boldsymbol{k})$ be close to N when $\boldsymbol{k}$ corresponds to the wave vector of the emitted radiation. Put another way, for a bunch to emit coherently, $n(\boldsymbol{k})$ must be approximately equal to the number of particles per coherence volume, that is, $n(\boldsymbol{k}) = n_{\mathrm{e}} V_{\mathrm{c}}$, where n_{e} is the particle number density. The emission has $k_\perp \lesssim k_\parallel/\gamma$, $k_\parallel \approx \omega/c$, where $\omega = 2\pi c/\lambda$ is the frequency and λ is the wavelength of the emission, corresponding to a coherence volume $V_{\mathrm{c}} = 8\pi^2/k_\perp^2 k_\parallel \approx \lambda^3/\pi\gamma^2$. This implies a pancake-shaped bunch with the normal within an angle $\approx 1/\gamma$ of $\boldsymbol{B}$, and with the ratio of the thickness to the radius of the pancake of the same order. The angle between the normal to such a bunch and $\boldsymbol{B}$ changes due to the curvature of the field line, and the bunch would cease radiating coherently after propagating a distance R_{c}/γ, because the direction of the dominant $\boldsymbol{k}$ values in the bunch are then no longer within an angle $1/\gamma$ of $\boldsymbol{B}$.

2. For a very small bunch, with dimensions perpendicular to $\boldsymbol{B}$ of order the dimension c/ω parallel to $\boldsymbol{B}$, the foregoing difficulty is avoided, but at the expense of reducing the volume of the bunch to which the N particles are confined by a factor γ^2. Even in this extreme case, a dispersion in momentum develops due to the radiation reaction to the coherent emission and this leads to a spatial dispersion that ultimately destroys the bunch, and hence limits the time that the bunch can radiate coherently. An order of magnitude estimate suggests that coherent emission ceases after the bunch has propagated a distance $(R_{\mathrm{c}}/\gamma)(R_{\mathrm{c}}/r_{\mathrm{e}}N)^{\frac{1}{2}}$, where r_{e} is the classical radius of the electron.

It follows that even if an appropriate bunch were formed initially it would quickly cease to radiate coherently, so that the bunches must be continually reformed. This places a severe demand on an acceptable bunching mechanism, and no effective bunching mechanism has been identified. This practical difficulty with the bunching mechanism compounds the uncertainties associated with the absence of a theory for emission by bunches that allows the effect of dispersion in momentum to be included. In view of these difficulties emission by bunches should be regarded as untenable.

3. Maser curvature emission

Maser action requires that the absorption coefficient, Γ, be negative, and this is not possible for curvature emission in the simplest approximation (Blandford 1975; Melrose 1978). Let $\eta(\gamma;\omega,\theta)$ be the emissivity, which is the power per unit frequency range and per unit solid angle about the direction at angle θ to $\boldsymbol{B}$, and let $f(\gamma)\,\mathrm{d}\gamma$ be the number density of particles between $\gamma(\gg 1)$ and $\gamma+\mathrm{d}\gamma$. Then for

$$\Gamma(\omega,\theta) = -\frac{(2\pi c)^3}{2\omega^2 mc^2}\int \mathrm{d}\gamma\,\eta(\gamma;\omega,\theta)\frac{\mathrm{d}f(\gamma)}{\mathrm{d}\gamma}, \tag{2}$$

to be negative requires that both the following conditions be satisfied simultaneously:

$$\mathrm{d}f(\gamma)/\mathrm{d}\gamma > 0, \quad \mathrm{d}\eta(\gamma;\omega,\theta)/\mathrm{d}\gamma < 0. \tag{3}$$

The latter condition cannot be satisfied for curvature emission. The reason may be seen from figure 1*a*; as γ is increased the power emitted at a fixed frequency, ω, and angle, θ, increases monotonically.

This proof that maser curvature emission is impossible is not valid when the curvature drift motion, $\boldsymbol{v}_{\mathrm{d}}$, is taken into account (Zheleznyakov & Shaposhnikov 1979; Shaposhnikov 1981). The curvature drift for a relativistic particle defines an angle $\theta_{\mathrm{d}} = v_{\mathrm{d}}/c$ between the velocity vector and $\boldsymbol{B}$:

$$\theta_{\mathrm{d}} = c\gamma/\omega_B R_{\mathrm{c}}, \tag{4}$$

with $\omega_B = eB/m$. The inclusion of this drift implies that the emission is centred about an angle $\theta = \theta_{\mathrm{d}}$, rather than strictly along the field lines in the absence of this drift. The emissivity in this case may be obtained from that for $\theta_{\mathrm{d}} = 0$ (denoted $\bar{\eta}$) by writing

$$\eta(\omega,\theta,\gamma) = \bar{\eta}(\omega,\theta-\theta_{\mathrm{d}},\gamma). \tag{5}$$

Then the second inequality in (3) becomes

$$\frac{\partial\eta}{\partial\gamma} = \frac{\partial\bar{\eta}}{\partial\gamma} - \frac{\theta_{\mathrm{d}}}{\gamma}\frac{\partial\bar{\eta}}{\partial\theta}. \tag{6}$$

The derivative with respect to θ allows maser emission in principle, as may be seen from figure 1*b*.

Although maser curvature emission is possible in principle, earlier estimates of the maximum growth rate (Chugunov & Shaposhnikov 1988) seem overoptimistic. Luo & Melrose (1992) discussed the conditions for effective growth, and found a sensitive dependence on B. As a result, maser emission can be ruled out for the relatively modest fields ($B \approx 10^4$ T) in millisecond pulsars. Although the arguments against the mechanism are not compelling for slower pulsars, with fields $B \gtrsim 10^8$ T, it would seem unsatisfactory to invoke this emission mechanism for slower pulsars and an entirely different emission mechanism for millisecond pulsars.

Another form of coherent curvature emission was proposed by Beskin *et al.* (1988). This suggested mechanism has been criticized on fundamental grounds (Nambu 1989; Machabeli 1991), and appears to be a spurious result of the way that the inhomogeneity of the system is incorporated in the theory.

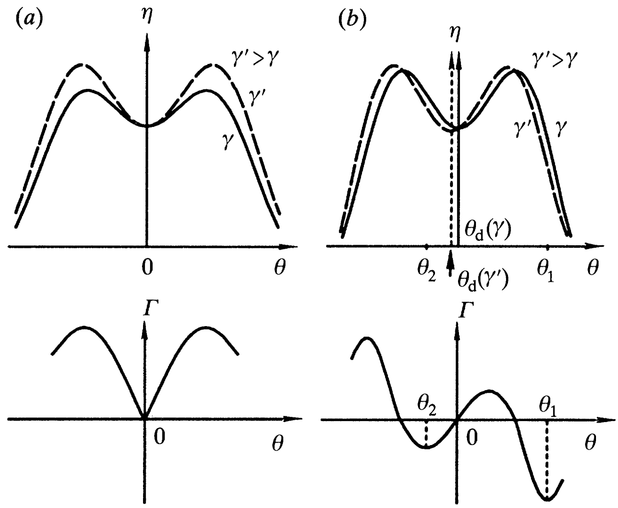

Figure 1. (*a*) The emissivity is plotted as a function of angle of emission (upper curve) for two different particle energies in the absence of any drift; the absorption coefficient (lower curve) is strictly positive. (*b*) When the drift is included, the dependence of θ_d on γ allows the absorption coefficient to be negative; the growth rate has two maxima, at θ_1 and θ_2 on opposite sides on $\boldsymbol{B}$.

4. Cyclotron emission and linear acceleration emission

Two other direct emission mechanisms have been explored as possible pulsar emission mechanisms: cyclotron emission and linear acceleration emission.

A cyclotron emission mechanism for pulsars was suggested by Tsytovich & Kaplan (1974), criticized by Mikhailovskii (1979) and proposed in a different form by Machabeli & Usov (1979). This mechanism is different from the ECME that operates in planetary emissions and from the mechanism that operates in laboratory gyrotrons, which is a reactive version of ECME (Melrose 1986, p. 187). In the pulsar case the emission must occur far from the star, where the magnetic field is weak enough for the cyclotron frequency to be in the radio band. Although it has been argued that this model can account for most of the observational features of pulsar radio emission (Machabeli & Usov 1989), including the circular polarization (Kazbegi *et al.* 1991), there are observational arguments against the source being located so far from the star (Cordes 1978).

An important feature, which distinguishes the cyclotron model for pulsar emission from ECME in other contexts, is that the emission is due to the anomalous Doppler effect. In other contexts the ECME is driven by an overpopulation in the higher Landau levels and is due to transitions $n \rightarrow n-1$ between Landau levels. In the cyclotron model for pulsars the maser emission is attributed to transitions $n = 0 \rightarrow 1$, in which energy from the parallel motion is converted into perpendicular motion. Such transitions are possible only when the emitted waves have refractive index greater than unity, and such waves cannot escape directly from the plasma. Hence, although the usual form of ECME is a direct emission process, the specific form of cyclotron maser emission invoked in the context of pulsars is an indirect emission process. The waves produced in the maser emission need to be converted into escaping radiation, as for the forms of relativistic plasma emission discussed below.

A further possible direct mechanism is linear acceleration emission (Melrose 1978; Rowe 1992). If there is an electric field component parallel to the magnetic field then the electrons and positrons are accelerated and so radiate. Maser emission is possible if the parallel electric field is oscillatory. One may compare linear acceleration emission with the relativistic plasma emission processes discussed below. In one sense, linear acceleration emission is a limiting case of the indirect emission processes, such that the waves generated by a beam instability are replaced by a large-amplitude oscillatory parallel electric field. In another sense, the mechanisms are quite different in that the power in the escaping emission comes from different sources. One may regard the physical process involved in linear acceleration emission as being analogous to free-electron maser emission, with the oscillatory electric field playing the role of the 'wiggler' field in a free-electron maser. In linear acceleration emission the power is provided primarily by the relativistic electrons or positrons, with the oscillatory electric field playing a passive role from an energetic viewpoint. In contrast, in relativistic plasma emission the power comes primarily from the plasma turbulence, with the pair plasma playing an energetically passive role in converting the wave energy into energy in escaping radiation.

5. Indirect emission mechanisms

An indirect emission mechanism for pulsars corresponds to some form of relativistic plasma emission. One may define a specific plasma emission process in terms of three ingredients: the instability mechanism, usually assumed to be a beam instability; the wave mode of the resulting turbulence, assumed to be Langmuir waves in solar radio bursts; and the conversion mechanism that partly converts this turbulence into escaping radiation. The theory of beam or stream instabilities in a relativistic pair plasma involves a straightforward generalization of the non-relativistic theory, but how this is to be applied in detail is uncertain. The wave modes in such a plasma (Arons & Barnard 1986; Beskin *et al.* 1988) are quite different from those in a non-relativistic plasma. The waves that grow may be in a Langmuir-type mode, that is a mode that is approximately longitudinal, or they may be in an Alfvén-type mode. Both types of wave mode have been invoked in the literature (cf. Asséo *et al.* 1990; Beskin *et al.* 1988).

The main qualitative difference between models based on these two types of wave mode concerns the details of the conversion process into escaping radiation. Longitudinal waves have small group velocities, and so the conversion process must occur close to where the waves are generated. One suggestion involves the formation of solitons which, it is argued, radiate directly (Asséo *et al.* 1990). Alfvén-type waves propagate away from the source region, and may be converted into escaping radiation through scattering, wave–wave interaction or through mode coupling due to plasma inhomogeneity. The details of some possible conversion mechanisms were discussed (Istomin 1988), but this aspect of the relativistic plasma emission process has been given relatively little attention. Another process that can have an important effect on the escaping radiation is cyclotron absorption (Mikhailovskii *et al.* 1982): emission that occurs within the magnetosphere is below the cyclotron resonance, and as the waves propagate outward their frequency must ultimately pass through the cyclotron resonance. It is possible that preferential absorption of one mode might produce the circular polarization in some sources. However, the observational significance of this has yet to be explored in detail.

The growth of a beam instability requires some relative streaming motion. At least three components are present in a polar cap model (Ruderman & Sutherland 1975):

a primary beam, and secondary distributions of electrons and positron which, although generated as pairs, may have a relative motion resulting from any electric field with a component along the magnetic field. An additional intermediate 'tail' component is invoked in some models (Machabeli & Usov 1989). An early suggestion (Ruderman & Sutherland 1975) is based on the streaming motion of the primary beam through the pair plasma, and an alternative is based on the relative streaming of electrons and positrons (Cheng & Ruderman 1980). However, these and other specific models for the beam instability have been found to have growth rates that are inadequate to account for the required turbulence (Buschauer & Benford 1976; Asséo *et al.* 1981). One suggestion that appears to overcome this difficulty is that the generation of the pair plasma is non-stationary, resulting is spatially separated clumps of plasma, and that the instability results when the faster particles from a following clump overtake the slower particle from a preceding clump (Usov 1987; Ursov & Usov 1988). Another suggestion is that the waves grow and then the energy is further concentrated through the formation of solitons, thereby enhancing the effect of nonlinear plasma processes (Asséo *et al.* 1990).

Some form of relativistic plasma emission seems the most plausible mechanism for pulsar radio emission, despite the uncertainties that remain in the detailed understanding of the growth mechanism, of the properties of the waves that grow, and of the conversion mechanism into escaping radiation. Although the specific details must be very different, this leads to the overview that pulsar radio emission may be regarded as an extreme variant of the emission mechanism that produces type III solar radio bursts. This has the unfortunate practical implication that the emission is due to a multistage process, thereby introducing a variety of different possibilities for interpreting specific aspects of the observational data.

6. Phenomenological models for radio emission

There are many features of the data on pulsar radio emission that should be explained by any complete theory, but at our present stage of understanding it would be unrealistic to expect any theory to explain all the data. The choice of which observations must be explained and which might be ignored is a matter of opinion. Here emphasis is placed on the following features: the high brightness temperature, the frequency–radius mapping, the sweep of linear polarization, the existence of a circularly polarized component and orthogonally elliptically polarized modes in some pulsars. In addition, an acceptable mechanism should be capable of accounting for similar emission from millisecond pulsars and from slower pulsars, despite the large difference in angular speed, Ω, and in B.

As already argued, the high brightness temperature, T_b, requires some form of coherent emission. The quantitative implications of this requirement are subject to considerable uncertainty both from the observational side, related to the estimation of T_b, and also from the theoretical side, due to the uncertainty concerning the emission mechanism. Estimates suggest T_b in the range 10^{25}–10^{31} K (Cordes 1981). Suppose the coherence is due to emission by particles with number density n_e and Lorentz factor $\gamma \gg 1$. Then the maximum brightness temperature that could result from incoherent emission is $\approx \gamma mc^2/\kappa$, where κ is Boltzmann's constant, and any coherent emission is enhanced over this by a factor corresponding to the effective number of particles that radiate in phase. This effective number cannot exceed the total number of particles per coherence volume, $n_e V_c$. The ratio $\kappa T_b/V_c \gamma n_e mc^2$, which

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is also the ratio of the energy density in the radiation to the energy density in the particles causing the emission, is a measure of the efficiency of the coherent emission. Observational estimates suggest T_b in the range 10^{25}–10^{31} K (Cordes 1981), placing a restriction that $n_e V_c$. Specifically, for $\gamma = 10^2$, one requires that $n_e V_c$ times the efficiency factor (which may be quite small) must be in the range 10^{13}–10^{19}. For example, using the estimate $V_c \approx \lambda^3/\pi\gamma^2$ made in §2, for $\lambda = 0.1$ m and an efficiency factor 10^{-4}, one requires n_e in the range 3×10^{24}–3×10^{30} m^{-3}. This value can exceed the Goldreich–Julian number density,

$$n_{GJ} = -2\epsilon_0 \boldsymbol{\Omega}\cdot\boldsymbol{B}/e, \tag{7}$$

especially if the source is far from the star. Thus this argument may place a significant constraint on acceptable models. However, tighter observational limits are required to draw useful conclusions from such arguments.

The frequency–radius mapping is based on the assumptions that (*a*) the emission from a given radius, r, is restricted to a narrow frequency range, and (*b*) that the central frequency, $\omega(r)$, varies with r. Granted these assumptions, a plausible fit to the data can be achieved, provided that the emission comes from well inside the light cylinder (Cordes 1978). This fit provides one argument against theories based on emission near the light cylinder: it is suggested above that this is an argument against the cyclotron theory for pulsar radio emission. Both curvature emission and relativistic plasma emission imply a frequency–radius mapping, but with different dependencies on r. For curvature emission, one has $\omega(r) \propto r^{-1}$ for a dipole field. For relativistic plasma emission, with the emission frequency determined by the local plasma frequency and with $n_e \propto n_{GJ}$, then one has $\omega(r) \propto r^{-\frac{3}{2}}$ for a dipole field. Although it is not possible to use such estimates to distinguish between the mechanisms in any simple way, one would expect microstructures in the emission to reflect this underlying dependence on r.

The sweep of the linear polarization through a pulse is expected in any model in which the emission has a linearly polarized component whose orientation is determined by the direction of the magnetic field, and this is the case for all emission mechanisms discussed here. The orientation of the electric vector in the radiation, relative to the projection on the sky of the magnetic vector in the source region, is different for different mechanisms; for example, the two are orthogonal for curvature emission and parallel for relativistic plasma emission due to longitudinal waves. As the absolute orientation of the projection of the magnetic field on the sky is not well determined, it does not seem possible to use this difference to distinguish between different mechanisms.

There are two alternative explanations for the presence of a circularly polarized component in some pulsars (Radhakrisknan & Rankin 1990). One is that the circular polarization is intrinsic to the emission process, and the other is that the circular polarization is imposed as a propagation effect. A circularly polarized component is difficult to explain in terms of curvature emission or relativistic plasma emission due to longitudinal waves, both of which should lead to linearly polarized emission. A circularly polarized component is expected in a cyclotron model, and this is perhaps the strongest argument for such a model (Kazbegi *et al*. 1991). Relativistic plasma emission due to Alfvén-type waves, which are themselves elliptically polarized, can have a circularly polarized component in principle. Imposition of a circularly polarized component as a propagation effect may be understood by analogy with a quarter-wave plate: the birefringence of the ambient plasma can cause a linearly polarized wave to become elliptically polarized. By using a simple model for the wave properties of the pair plasma, this effect was discussed by Melrose & Stoneham (1977), Melrose (1979) and Allen & Melrose (1982). Despite a specific criticism of this idea by Kazbegi *et al.* (1991), the jumps between oppositely elliptically polarized components seen in some pulsars (Manchester *et al.* 1975) is strongly suggestive of a splitting into two orthogonal modes as the radiation propagates through the pulsar magnetosphere. A possible alternative mentioned above involves cyclotron absorption of the escaping radiation. Further detailed modelling of the propagation is needed to test these suggestions in detail.

A more controversial observational point concerns whether there are distinct 'core' and 'conal' components in the emission (Rankin 1983, 1986) or not (Lyne & Manchester 1988). If the suggestion of two distinct components is accepted, then this would favour an emission mechanism or combination of mechanisms which allows two distinct components in the emission from the one distribution of particles. Both the cyclotron model (Kazbegi *et al.* 1987) and linear acceleration emission (Rowe 1992) imply two components with appropriate properties. However, the controversy over the existence of two distinct components in the data needs to be resolved before any conclusions are drawn about this favouring these mechanisms over others.

7. Conclusions

From the following discussion one may draw the following conclusions.

1. Curvature emission by bunches encounters both fundamental difficulties (no theory that includes dispersion in momentum) and practical difficulties that render it untenable.

2. Maser curvature emission is possible in principle when the curvature drift is taken into account; the growth rate is sensitive to the value of B, and the mechanism is not viable for millisecond pulsars.

3. Some form of relativistic plasma emission seems the most plausible mechanism. The details of the initial wave mode (longitudinal or Alfvénic) and of the conversion mechanism into escaping radiation are uncertain.

4. Linear acceleration, or free electron maser emission, may be regarded as a limiting form of relativistic plasma emission.

5. Cyclotron emission, due to the anomalous Doppler effect, is not a direct emission mechanism and needs a second stage conversion mechanism, as for plasma emission. The cyclotron theory requires that the source be far from the star and near the light cylinder.

The discussion of observational features, such as the actual brightness temperature, the frequency–radius mapping, the seep of linear polarization and the presence of a circularly polarized component in some sources, has yet to provide compelling evidence for one mechanism over the others.

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