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The Models for Radio Emission from Pulsars – The Outstanding issues

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Abstract. The theory of pulsar radio emission is reviewed critically, emphasizing reasons why there is no single, widely-accepted emission mechanism. The uncertainties in our understanding of how the magnetosphere is populated with plasma preclude predicting the properties of the emission from first principles. Some important observational features are incorporated into virtually all the proposed emission mechanisms, and other observational features are either controversial or fail to provide criteria that clearly favor one mechanism over others. It is suggested that the criterion that the emission mechanism apply to millisecond, fast young, and slow pulsars implies that it is insensitive to the magnetic field strength.

It is argued that coherent emission processes in all astrophysical and space plasmas consist of emission from many localized, transient subsources, that any theory requires both an emission mechanism and a statistical theory for the subsource, and, that this aspect of coherent emission has been largely ignored in treatments of pulsar radio emission. Several specific proposed emission mechanisms are discussed critically: coherent curvature emission by bunches, relativistic plasma emission, maser curvature emission, cyclotron instability and free electron maser emission. It is suggested that some form of relativistic plasma emission is the most plausible candidate although one form of maser curvature emission and free electron maser emission are not ruled out. Propagation effects are discussed, emphasizing the interpretation of jumps between orthogonal polarizations.

1. Introduction

The pulsar radio emission mechanism is still poorly understood. Reasons for our lack of success in identifying the emission mechanism unambiguously can be attributed to three aspects of the problem. The first aspect concerns the structure of the magnetosphere. In principle, if one understood the distribution of particles and fields in the magnetosphere well enough, one could hope to predict the radio emission from first principles. However, the uncertainties in our knowledge make this impractical. The second aspect concerns the phenomenological interpretation of the radio data. Some general features clearly constrain the emission mechanism, specifically, the very high brightness temperature, the beaming, and the sweep of linear polarization. However, these features do not suffice to determine the emission mechanism uniquely. Furthermore, other properties of the observed emission (e.g., pulse profiles, microstructure, circular polarization, frequency-to-radius mapping, jumps between orthogonal modes) have not led to well-defined, widely-accepted criteria for selecting between different emission mechanisms. As remarked by Radhakrishnan (1992), "more and more detailed radio observations are NOT what is needed to help with theoretical modeling." Well-defined, observationally-based criteria that allow one to select between different mechanisms are required. The third aspect of the problem concerns the nature of coherent emission processes. It is argued below that coherent emission mechanisms are intrinsically more complicated than incoherent mechanisms, that existing treatments of such mechanisms are oversimplified and that expectations of what a successful theory should explain tend to be unrealistic. All of these three aspects are discussed in this paper, with emphasis on the nature of coherent emission processes. The effects of propagation of the escaping radiation through the pulsar magnetosphere are also discussed.

The very high brightness temperature of pulsar radio emission implies that some coherent emission mechanism is involved. It is clear that the pulsar emission mechanism is not the same as other forms of coherent emission that are known to occur in space and astrophysical plasmas. These are *plasma emission* in solar radio bursts and from planetary bow shocks and *electron cyclotron maser emission* from planetary magnetospheres, probably also in solar radio spike bursts and in the very bright emission from some flare stars (e.g., Melrose 1991). There is much more information on the plasma properties in some of these sources than there is for pulsars, but nevertheless, in no case is the theory better than semiquantitative. In these contexts, there is direct evidence that, at any given time, the coherent emission occurs in a very small fraction of the volume of the source, and it is argued here (section 4) that this is probably an intrinsic feature of every coherent emission process in an astrophysical plasma. This implies that any theory for such coherent emission needs two ingredients: the mechanism for emission from the localized regions and a statistical theory for the distribution of these localized regions within an envelope defined by the effective source. The statistical ingredient is neglected in most existing theories for pulsar radio emission, and needs to be taken into account to treat the emission even semiquantitatively.

The discussion of pulsar radio emission is set out as follows. The structure of the magnetosphere and how it impinges on theories for the radio emission is discussed in section 2. The phenomenological interpretation of the radio emission, and criteria on an acceptable emission mechanism are discussed in section 3. The foregoing general points on coherent emission are discussed in more detail in section 4, where existing models for pulsar radio emission are also reviewed. Propagation effects are discussed in section 5. The conclusions are summarized in section 6.

2. The Particle Populations in the Source Regions

Pulsar magnetospheres are thought to be populated by one-dimensional, relativistic pair plasmas that are created through a pair cascade in 'gaps' where there is a large parallel electric field. In most models, the radio emission is attributed to the pair plasma flowing outward along open magnetic field lines from the polar caps.

2.1 *Gaps and pair production*

Pulsar magnetospheres are assumed to consist of a magnetically closed region and two magnetically open regions. The closed region, or dead zone, is defined by those field lines that close within the light cylinder, of radius $r_{1c} = c/\Omega$, with $\Omega = |\mathbf{\Omega}|$, where $\mathbf{\Omega}$ is the angular velocity of rotation of the star. It is assumed that the dead zone is filled with sufficient plasma to provide the corotation electric field

$$\mathbf{E} = -(\mathbf{\Omega} \times \mathbf{x}) \times \mathbf{B}, \tag{2.1}$$

where x is the position vector relative to the center of the star, and $\mathbf{B}$ is the magnetic induction. The polar caps are the remaining regions where the magnetic field lines are open in the sense that they cross the light cylinder.

An inconsistency arises when one considers whether or not the open region is filled with plasma. On the one hand, if there were no plasma in the magnetosphere, then the electrodynamics implies (a) an electric field with component, $E_{||}$, parallel to the magnetic field, and (b) a large potential difference, Φ_{pc}, between the center and the edge of the polar cap region. For a dipolar field, with $B_P \sim 10^8$ T (10^{12} G) at the poles, the values at the stellar surface (radius $r = R$ with $R = 10$ km) are

$$(E_{||})_{pc} \approx \left(\frac{\Omega R}{c}\right)^{3/2} cB_P, \tag{2.2}$$

$$\begin{aligned}\Phi_{pc} &= \frac{\Omega^2 B_P R^3}{2c} \\ &= 6.6 \times 10^{14} \left(\frac{B_P}{10^8\,\mathrm{T}}\right)\left(\frac{P}{0.1\,\mathrm{s}}\right)^{-2}\ \mathrm{V},\end{aligned} \tag{2.3}$$

where $P = 2\pi/\Omega$ is the period of the pulsar. In the superstrong magnetic field, a stray gamma ray with energy greater than twice the rest energy of the electron decays into a pair, $\gamma + B \rightarrow e^- + e^+ + B$. The components of this pair are accelerated to very high energy ($\lesssim e\Phi_{pc}$) by $E_{||}$. These *primary* particles emit gamma rays, through curvature emission and other processes, triggering a pair cascade (Sturrock 1971). As a result, a secondary pair plasma is created. The secondary pair plasma tends to shield out $E_{||}$, and to set up the corotation electric field (2.1), invalidating the original assumption that vacuum conditions apply.

On the other hand, if one assumes that that the. polar cap regions are filled with plasma, so that the corotation electric field (2.1) is set up everywhere, there is nothing to prevent the plasma from flowing outward along the open field lines and being lost through a pulsar wind. Hence, one requires a source of plasma to maintain the electric field (2.1) in the polar cap regions. The only acceptable source of plasma is a pair plasma generated by the processes outlined above, but this requires $E_{\|} \neq 0$ at least in the source region where the primary pairs are created.

A self-consistent model requires that that there be a source region (or several source regions) with $E_{\|} \neq 0$. Such a region is referred to as a *gap.* Gaps must fil only a fraction of the volume, or be present only a fraction of the time. The pair plasma generated in the gaps populates the remainder of the open-field region, and supplies the particles that form the pulsar wind. There are several specific models for the gaps, including polar-cap, slot-gap and outer-gap models.

The open field lines cross the light cylinder and the magnetic field continues to influence the flow until the Maxwell (magnetic) stress decreases to below the ram pressure (γmnc^2) of the relativistic outflow. Without pair production, the outflow involves only the single-sign Goldreich-Julian density and balancing of the stresses implies Lorentz factors γ large enough for there to be strong gamma-ray emission, so that particles are no longer tied to the field (e.g., Mestel 1981). However, with a dense pair plasma generated through pair creation, more modest γ-values enable the flow to continue to infinity as a wind, dragging the field with it.

2.2 *Location of the source of the pairs*

In polar-gap models, the gap occurs immediately above the stellar surface in the polar cap. In the model of Ruderman & Sutherland (1975) this gap is attributed to the strong binding of nuclei to the stellar surface, preventing ions from being ripped off the surface. This model applies only to neutron stars with $\mathbf{\Omega} \cdot \mathbf{B} < 0$, in which case the sign of $(E_{\|})_{\rm PC}$ is such that ions tend to be accelerate upward. (Neutron stars with $\mathbf{\Omega} \cdot \mathbf{B} > 0$ would not be pulsars in this model.) The binding energy was subsequently shown to be inadequate for this model to apply (e.g., Neuhauser, Koonin & Langanke 1987, Abraham & Shapiro 1991), at least for most pulsars. Despite the absence of a clear alternative physical basis for them, polar-gap models continue to be considered. For example, in the model of Beskin, Gurevich & Istomin (1988, 1993) the pair plasma is postulated to be created in a double layer near the stellar surface. However, why such a double layer should form near the surface is not clear to this author.

In a second class of model, it is assumed that plasma can flow freely from the surface, screening $E_{\|}$ immediately above the stellar surface. This class includes the slot-gap model of Arons and coworkers (e.g., Fawley, Arons & Scharlemann 1977; Scharlemann, Arons & Fawley 1978; Arons 1981, 1983, 1992), and a modified form of the Ruderman & Sutherland model (Cheng & Ruderman 1980). A related "classical" model has been developed by Mestel and coworkers (e.g., Mestel 1981, 1993; Mestel et al 1985; Fitzpatrick & Mestel 1988a, b; Shibata 1991), as discussed elsewhere in these proceedings by L. Mestel. Although these models differ in details, the important feature that they have in common is that somewhere above the surface a large parallel electric field tends to build up. This arises from the incompatibility of two requirements. One is the requirement that the charge density, for $r \ll r_{\rm lc}$, be maintained at the Goldreich-Julian value (Goldreich &

Julian 1969)

$$n_{\rm GJ} = -\frac{2\varepsilon_0 \mathbf{\Omega} \cdot \mathbf{B}}{e}. \tag{2.4}$$

This is necessary for the plasma to shield out the $E_{||}$ that would be present in vacuo. The other requirement is that, in the absence of any other source of charge, the outflowing current be conserved. As the cross-sectional area (α $1/B$) of a magnetic flux tube changes, the current density, $J = en_{\rm GJ}v_{\rm f}$, must change to satisfy J α B. Once the flow speed, $v_{\rm f}$, becomes relativistic, these requirements become, respectively, $n_{\rm GJ}$ α B_z , where the z-axis is along the rotation axis, and $n_{\rm GJ}$ α B, and they are obviously incompatible for any realistic magnetic structure. Hence, an $E_{||}$ builds up, and the two requirements can only be satisfied by this electric field leading to a source of pairs that can provide the required shielding. The upper limit on $E_{||}$ in such space-charge-limited flows is two to four orders of magnitude smaller than $(E_{||})_{\rm pc}$.

The models based on space-charge-limited flows apply to neutron stars with $\mathbf{\Omega} \cdot \mathbf{B} > 0$, when electrons flow away from the stellar surface, and to neutron stars with $\mathbf{\Omega} \cdot \mathbf{B} < 0$, provided that the ions are not too tightly bound. One might expect there to be some qualitative difference between these two cases, that is, one might expect two classes of pulsars determined by the sign of $\mathbf{\Omega} \cdot \mathbf{B}$. However, there is no observational evidence for two such classes. This suggests that the two classes are indistinguishable from an observational viewpoint, or that one class is not observed at all. Assuming that the two classes are indistinguishable, one infers that the binding of the ions to the stellar surface and the inertia of the ions or electrons are unimportant in the processes leading to the production of the secondary pair plasma (cf. Beskin 1982).

A third type of model has outer gaps, associated with the field lines that pass through the surface where the Goldreich-Julian charge density changes sign (e.g., Holloway 1973; Holloway & Pryce 1981). Such outer gaps occur near the last closed field lines at the edge of the dead zone. Outer-gap models are favored for those pulsars that have pulsed gamma-ray emission (e.g., Cheng, Ho & Ruderman 1986a,b).

2.3 *Current closure*

A current flow, with current density $\sim en_{GJ}\,c$, is implied in polar-cap models and the question of how this current closes is an important ingredient in any acceptable model (e.g., Arons 1992). A current circuit that closes near the light cylinder is a feature of most closed-circuit models (e.g., Arons 1979, 1981, 1992; Rylov, 1979; Mestel 1981, 1993; Mestel et al 1985; Beskin et al 1986, 1993). However, the identification of the processes involved in closing the current circuit, so that the star does not charge up, remains one of the weak points of the theory (e.g., Michel 1982, 1991, 1992).

An interesting way of resolving the difficulties with current closure was suggested by Shibata (1991), who proposed a DC circuit with two sources of pair plasma, in an inner gap and in an outer gap. The closure of the current across field lines occurs in the wind zone where the $\mathbf{J} \times \mathbf{B}$ force is related to the acceleration of the wind. An important constraint on the model is that the angular momentum loss is in balance with the energy loss (Holloway 1977). Shibata (1991) found that for fast pulsars there are two possible regimes depending on the dominant component in the angular momentum loss: a wind-dominated regime in which the angular momentum is carried off primarily by the wind, and an outer-gap-dominated regime in which the angular momentum loss is dominated by high-energy photons from the outer gap. The former seems to apply to the Crab pulsar. For slower pulsars these two regimes merge.

An alternative approach to the current closure problem is to assume that the neutron star charges up, so that electrostatic forces cause a closed structure with zero current outflow (e.g., Jackson 1976; Michel 1979, 1982, 1991; Krause-Polstorff & Michel 1985a,b). Such models are not discussed in detail here.

2.4 *The secondary pair plasma*

The production of the secondary plasma is attributed to a pair cascade, which has been treated both numerically and analytically (e.g., Sturrock 1971; Arons & Scharlemann 1979; Daugherty & Harding 1982; Gurevich & Istomin 1985). The primary particles generate gamma rays, with energy $\varepsilon_{\rm Ph}$, through curvature emission, synchrotron emission and possibly other processes. The curvature photons are directed along the magnetic field lines but, due to the curvature of the field lines, the angle, θ, between their direction of propagation and **B** increases systematically. When the threshold

$$\varepsilon_{\rm ph}\sin\theta > 2m_e c^2 \tag{2.5}$$

is exceeded, a photon decays into a pair. (In a detailed calculation the polarization of the photons and the different thresholds for different polarizations need to be taken into account.) If this decay occurs in the gap, then the components of the pair are accelerated in opposite directions by $E_{||}$ and become primary particles. If the decay occurs outside the gap, then the pairs form a secondary pair plasma. The detailed distribution of secondary particles depends on how the value of $E_{||}$ varies through the region where the pairs are created, and the value of $E_{||}$ in turn depends on the distribution of the pairs that tend to shield it out.

Once produced, the pair plasma rapidly becomes one dimensional in the superstrong magnetic field, where superstrong corresponds to B being comparable to the critical magnetic field

$$B_{\rm crit} = m_e^2 c^2/e\hbar = 4.4\times 10^9\,{\rm T}. \tag{2.6}$$

(The ratio $B/B_{\rm crit}$ is equal to the ratio of the cyclotron energy $\hbar\Omega_e$, where $\Omega_e = eB/m_e$ is the cyclotron frequency, to the rest energy, $m_e c^2$.) The perpendicular motion of a particle is simple harmonic motion, and hence is quantized as a simple harmonic oscillator. When the spin is included, the energy eigenvalues are

$$\varepsilon_n(p_{||}) = (m^2c^4 + p_{||}^2c^2 + 2neB\hbar c^2)^{1/2}, \tag{2.7}$$

with the ground state, $n = 0$, nondegenerate, and each excited state, $n = 1, 2, \ldots$, doubly degenerate. The states with different values of n are referred to as the Landau levels. Due to gyromagnetic emission, which is synchrotron emission for

$nB\,/\,B_{\rm crit} \gg 1$, particles jump to lower Landau levels sequentially. For $p_{\parallel} = 0$, the rate of transitions from state n to state $n - 1$ is

$$R_{n\to n-1} = n\alpha\,\frac{4m_e c^2}{3\hbar}\left(\frac{B}{B_{\rm crit}}\right)^2, \tag{2.8}$$

where $\alpha \approx 1/137$ is the fine structure constant. The lifetime for the decay to the ground state is of order the inverse of the transition rate for the slowest transition, which is the transition $1 \rightarrow 0$. This gives a lifetime of order $3/B^2$ s, where B is in tesla. The lifetime is so short, $\sim 2 \times 10^{-17}(B/0{\cdot}1B_{\rm crit})^{-2}$ s in its rest frame (increased by a factor γ in the pulsar frame), that one expects all electrons and positrons to be in their ground state, corresponding to one-dimensional motion.

Another property of the secondary pair plasma concerns the multiplicity factor, which is the ratio of the number of secondaries to the number of primaries, and which is estimated to be in the range 10^3-10^5. The mean Lorentz factor of the secondaries is estimated to be $\gamma \sim 10^2$–10^3.

An effect that should be important in stronger fields, $B \gtrsim 0{\cdot}1B_{\rm crit}$, is the formation of positronium (e.g., Shabad & Usov 1984; Shabad 1992; Meszaros 1992). This effect should impede pair production, and reduce the effectiveness of the shielding of $E_{\parallel}$. However, there is no obvious observational feature in the radio emission that has been associated with the threshold ($B \sim 4 \times 10^8$ T) for this effect to become important.

2.5 *Summary*

One may conclude that some features of pulsar electrodynamics are sufficiently well understood to indicate the general conditions under which pulsar radio emission is generated, but that the finer details are poorly understood.

1. The production of primary and secondary pairs probably occurs in the polar cap regions at some height above the surface of the neutron star.

2. The secondary plasma involves electrons and positrons flowing outward along the field lines in one-dimensional motion.

3. The multiplicity of the secondary pairs is estimated to be 10^3-10^5 and their Lorentz factors to be $\sim 10^2$, but neither number is well determined.

4. The detailed distribution functions of the secondary pairs is poorly determined, e.g., due to the dependence of the distribution of the partial shielding of $E_{\parallel}$ near the edges of gaps.

These arguments suggest that radio emission mechanisms that involve pairs flowing outward along open, curved magnetic field lines in the polar cap regions are consistent with what is known of the electrodynamics. However, important details concerning the distribution functions of the secondary plasma are poorly determined. Clearly, a "bottom-up" approach, in which one attempts to identify the radio emission mechanism from first principles, is not realistic.

3. Criteria for an Acceptable Eumission Mechanism

Several general observational criteria (brightness temperature, beaming and linear polarization, microstructures) are incorporated into nearly all suggested pulsar emission mechanisms. However, other observational features (core or conal emission, frequency to radius mapping, circular polarization) lead to selection criteria that are either controversial or fail to distinguish between different specific emission mechanisms. One criterion that can be used to argue against some emission mechanisms is that the mechanism must apply to both weak-B (millisecond) and strong-B (young, fast) pulsars, that is, the mechanism must apply to a range of four to five orders of magnitude in B.

3.1 *The brightness temperature*

The brightness temperature of pulsar radio emission is very much higher than for any other radioastronomical sources. Its maximum value, estimated to be in the range $T_{\rm b} \sim 10^{25}$–10^{30} K, is at least ten orders of magnitude greater than the next brightest sources, which are some flare stars (e.g., Dulk 1985). The very high $T_{\rm b}$ requires a coherent emission mechanism, and this requirement is built into all the emission mechanisms discussed here. Although it is clear that pulsar emission is due to some coherent emission mechanism, the required high $T_{\rm b}$ does not distinguish between possible coherent emission mechanisms in any obvious way.

3.2 *Beaming*

In all pulsar models, the pulsed nature of the emission is interpreted in terms of beamed radiation from the pulsar sweeping across the line of sight of the observer as the neutron star rotates. In polar cap models, the beaming is explained in terms of the relativistic beaming effect for relativistic particles propagating along the magnetic field lines, which implies that the radiation is confined to a cone with half-angle $\sim 1/\gamma$ about the direction of the magnetic field. This beaming is a feature of emission by relativistic particles and applies to all relevant emission mechanisms. It cannot be used as a criterion to distinguish between emission mechanisms that involve relativistic particles in one-dimensional motion along $\mathbf{B}$.

3.3 *Linear polarization*

The most obvious features of the polarization of pulsars are the high degree of linear polarization, and the systematic sweep of the plane of polarization through a pulse. In young pulsars the polarization is typically 100% linear. Older (slower) pulsars tend to have a more complicated polarization structure, sometimes with a significant circular component.

The linear polarization is well explained in terms of the single-vector model of Radhakrishnan & Cooke (1969). This model applies to any mechanism that produces linear polarization, with the plane of polarization fixed by the direction of the magnetic field at the point of emission. This condition is satisfied by all relevant emission mechanisms, and so cannot be used as a criterion to distinguish between mechanisms.

3.4 *Core and coned emission*

The structure of pulses from different pulsars have been classified in several different ways. Some pulsars, typically younger pulsars, have pulses with a single peak, and others have two or more peaks. Rankin (1983a, b, 1986, 1990) argued for two types of emission: 'core' emission and 'conal' emission, with the former near the center of the pulsar beam and the latter near its edge. The observed pulse profile depends on the relative level of these two components in the beam and on where the line of sight intersects the beam. In its simplest form, this model provides the following interpretation for multiple peaks. The core emission is assumed to dominate in pulsars with single-peak profiles and to give the central component in triple-peak profiles when the line of sight passes, close to the center of the beam. The conal emission is assumed to give the two peaks in double-peak profiles, when the line of sight misses the core component, and the outer peaks in triple-peak profiles. However, when random variation in the intensity is taken into account, more complicated interpretations need to be considered. For example, a double-peak profile at one frequency can be one edge of the conal emission and core emission, with the other edge of the conal emission missing at that frequency (but possibly present at other frequencies); also, the polarization can often allow one to distinguish between such truncated triple and truly double burst profiles.

Lyne & Manchester (1986) argued for a different interpretation in which the observed pulse profiles are interpreted in terms of favored regions for emission within a pulse envelope. Rankin's model could be regarded as a special case of Lyne & Manchester's model, with the favored regions corresponding to a core and a cone.

A controversial point is whether as Rankin argued, the core and conal component are qualitatively different, with different frequency dependencies, and coming from different heights (at a fixed frequency). Rankin's arguments have been interpreted by some authors in terms of intrinsically different core and conal emission mechanisms (e.g., Beskin et al 1993, p. 337). In the alternative model of Lyne & Manchester there is no implication that there is any such difference. In formulating criteria for distinguishing between proposed emission mechanisms, the case for favoring mechanisms that distinguish between core and conal emission is not well established. What is well established is that the beam has an envelope, which in many cases is in the form of a hollow cone, sometimes with a core component and sometimes with a more complicated structure. In the hollow-cone model this envelope is attributed to the magnetic flux tube defined by the set of open field lines, that is, of the field lines that extend beyond the light cylinder.

3.5 *Microstructure*

Another effect that may be related to beaming is the microstructure in pulsar radiation (e.g., Cordes 1975, 1979). Microstructure could be explained in terms of either spatial or temporal structures. An explanation in terms of spatial structures involves subsources with narrow intrinsic beamwidth inside the pulsar beam, which defines an envelope for the narrow beams. As discussed in section 4, small spatial and temporal structures are to be expected in coherent emission mechanisms. Although study of microstructures in the emission may well provide useful information on microstructures in the distribution of particles, once again it does not provide an obvious criterion for distinguishing between different coherent emission mechanisms.

3.6 *Frequency to radius mapping*

There is indirect evidence for a frequency to radius mapping that favors emission from the polar cap regions well inside the light cylinder (e.g., Cordes 1978, 19 9, 1981, 1992; Phillips 1992). In particular, the narrowing of the separation between peaks with increasing frequency is interpreted in terms of emission at higher frequency coming from a lower height where the cone defined by the open field lines is narrower. However, whether this is to be interpreted as broad-band emission from a narrow range of heights, or narrow-band emission from a large range of heights is unclear (e.g., Barnard & Arons 1986). There is some direct evidence from scintillations on the size of the emission region (Wolszczan & Cordes 1987; Kuzmin 1992), which tends to support the suggestion that the emission region is located at $r \lesssim 0{\cdot}1\ r_{\rm lc}$ (Arons 1992).

The frequency to radius mapping suggests that pulsar emission has a characteristic frequency that decreases with increasing height. For all relevant emission mechanisms there is some typical frequency that decreases with height, and it is plausible that all could be made consistent with the data relevant to frequency to radius mapping.

3.7 *Circular polarization*

Some pulsars have significant circular polarization. Radhakrishnan & Rankin (1990) argued that there are two contributions to the circular polarization: an intrinsic contribution, which tends to reverse its sense near the center of the pulse beam, and a circular polarization that arises as a propagation effect. One model that accounts qualitatively for intrinsic circular polarization is based on curvature emission by bunches of particles (e.g., Gil & Snakowski 1990a,b; Gil 1992). However, as argued in section 4, this mechanism is not acceptable for other reasons. There is strong evidence for production of a circularly polarized component as a propagation effect in some pulsars. In particular, changes between orthogonal modes of polarization (e.g., Stinebring et al 1984a, b) may to be due to a propagation effect through a pulsar magnetosphere with elliptically polarized natural modes (e.g., Allen & Melrose 1982; Arons & Barnard 1986; Barnard & Arons 1986).

The arguments that some of the circular polarization is intrinsic to the emission mechanism do not appear strong enough to impose the criterion that the emission mechanism be intrinsically capable of producing partial circular polarization. Until the effects of propagation on the polarization are adequately understood, the possibility of explaining all circular polarization as a propagation effect remains open.

3.8 *High-frequency emission*

Strong high-frequency radiation is observed from five radio pulsars: PSR 0531+21, PSR 0833-45, PSR 1509-58, PSR 1706-44 and PSR 0540-69 in the Large Magellanic Cloud. The main part of the radiation of all these pulsars falls in the X-ray and γ-ray ranges. The γ -ray pulsar Geminga is probably also a radio pulsar which is radio quiet (Harding, Ozernoy & Usov 1993). For the remaining five pulsars, their X-ray and γ -ray luminosities are very high. Assuming that the total energy flux carried by relativistic particles from the polar gaps into the pulsar magnetosphere is proportional to the potential across the polar gaps, the maximum luminosity expected in the modern polar gap models cannot account the observed X-ray and γ -ray luminosities. The high-frequency emission is attributed to an outer gap (Cheng et al 1986a,b). Thus, the study of the high-frequency radiation is unlikely to have direct implications on our understanding of the radio emission, because in the presently favored interpretations, the one is related to the outer gap and the other to the polar gap. A possible exception is in models in which these gaps are related (e.g., Shibata 1991), allowing the possibility of feedback from one to the other.

3.9 *Millisecond pulsars*

The radio emission from millisecond pulsars is remarkably similar to that from most fast, young pulsars. From the pulse profile alone one could not distinguish between a millisecond pulsar and an ordinary pulsar. This suggests a criterion that may be applied to emission mechanisms: the emission mechanism must be capable of accounting for similar emission from slow pulsars and from millsecond pulsars. The parameter that is markedly different for these two classes of pulsars is the magnetic field, *B*. Hence, this criterion would argue against those mechanisms that are sensitive to the value of *B*.

3.10 *Summary*

A “top-down” approach based on criteria deduced from observations has some notable successes, but has failed to provide a unambiguous identification of the emission mechanism.

1. A coherent emission mechanism is required, and a mechanism that involves a one-dimensional distribution of relativistic particles streaming out along polar-cap field lines can account for the basic features of pulsar radio emission.

2. The interpretation of the pulse profile in terms of core and conal emission with different properties is controversial, and the evidence for more than one emission mechanism is not compelling.

3. Other observational properties, such as microstructure, frequency to radius mapping and partial circular polarization, do not lead to criteria that obviously favor one emission mechanism over others.

4. The criterion that the same emission mechanism apply to all pulsars excludes mechanism that are sensitive to the value of B, which varies over more than four orders of magnitude.

Despite the foregoing rather negative discussion, it should be emphasized that progress in understanding pulsar radio emission requires observationally-based selection criteria. The difficulties raised here concern identifying unambiguous, definitive criteria. There is no shortage of detailed data, but the piecemeal interpretation of each specific feature of the observations has not led to a consensus of which of them are crucial to the identification of the emission mechanism, and which may be ignored as minor details.

4. Specific Coherent Emission Mechanism

The bright radio luminosity of pulsars implies that the emission mechanism must be coherent. Three different types of coherent emission are possible in principle. It is argued here that only one of them, maser emission, should be considered in astrophysical applications. Several maser mechanisms remain possible candidates for the pulsar emission mechanism.

4.1 *Three types of coherent emission*

Coherent emission processes can be classified in three ways (e.g., Ginzburg & Zheleznyakov 1975; Melrose 1981, 1986a, 1991), referred to here as antenna mechanisms, reactive instabilities and maser mechanisms.

1. An antenna mechanism involves emission by bunches of particles with negligible velocity dispersion. The coherence is attributed to the particles radiating in phase with each other.

2. A reactive instability involves an intrinsically growing, phase-coherent wave whose growth rate exceeds the intrinsic bandwidth of the growing waves. The intrinsic bandwidth is due to the velocity dispersion of the particles, which is required to be very narrow so that all the particles remain in phase with the growing wave.

3. A maser mechanism involves negative absorption. Maser (or laser) emission is familiar in bound-state systems (atoms or molecules), in which the emission between two levels produces a narrow line. Negative absorption between two levels results from the higher-energy level being overpopulated relative to the lower-energy level, called an inverted population. In a plasma, maser emission can occur under a variety of condition where there is a continuum of states and a continuum of emission frequencies. The allowed transitions are subject to a resonance condition that depends on the specific emission process. The particle distribution needs to have some feature that corresponds

in a meaningful sense to an inverted energy population. In the case of a one-dimensional distribution of relativistic particles, this condition is $\partial f/\partial\gamma > 0$ over some range of γ. Maser emission applies in the random phase approximation, so that (unlike the other two types of coherent emission) the phas of the growing waves is irrelevant.

4.2 *Back-reaction to coherent emission*

In all cases the back reaction to the coherent emission tends to reduce the feature in the distribution of particles that is causing the coherent emission. The radiation reaction to an antenna mechanism tends to disperse the bunch, the back reaction to a reactive instability tends to increase the velocity dispersion, and the back reaction to a maser mechanism is the so-called quasilinear relaxation that tends to reduce the inverted energy population. The time scale on which the back reaction occurs is determined roughly by the time required for the energy density in the radiation to become comparable to the energy density in the radiating particles. This is fastest for an antenna mechanism and slowest for a maser mechanism.

4.3 *Why maser emission mechanisms should be favored*

There is a strong argument for considering only maser mechanisms in astrophysical applications. This argument is presented here in two parts.

On the one hand, in order for coherent emission to occur some process is required to set up the feature in the distribution function that causes the coherent emission. The time scale on which this feature must be set up needs to be at least as short as the time scale on which the back reaction would destroy this feature. For a maser, the process that sets up the effective inverted population is referred to as a pump. It is convenient to use the word ‘pump’ to describe the process that sets up the conditions for the other types of coherent emission, that is, for the creation of a bunch with negligible velocity dispersion required to allow an antenna mechanism to operate, or for the creation of an appropriate distribution with a very narrow velocity dispersion required to allow a reactive instability to develop. The requirements on the pump are most demanding for an antenna mechanism (extreme localization in coordinate space and velocity space) and are very demanding for a reactive instability (extreme localization in velocity space). The requirements on the pump are least demanding for a maser mechanism, and hence the simplest explanation of any coherent emission is in terms of a maser mechanism. In fact, there is no well-established case of a coherent emission in astrophysics that is not due to a maser mechanism.

On the other hand, because of the very rapid transfer of energy from particles to waves, all coherent emission mechanisms have short time and space scales. As a result, a Coherently emitting astrophysical source necessarily consists of a large number of very small, transient subsources. This is observed for coherent emission in cases where appropriate data are available, specifically for plasma emission in the solar wind (e.g., Melrose & Goldman 1987), for electron cyclotron maser emission in planetary magnetospheres (e.g., Melrose 1986b) and for solar spike bursts (e.g., Benz 1986). As a consequence, the overall source must be the envelope of a large number of individual subsources. Thus, a model for coherent emission from an astrophysical source requires not only a specific mechanism but also a statistical theory for the distribution of these individual subsources. One can argue, at least in simple cases, that the only acceptable statistical theory is equivalent to quasilinear theory (e.g., Melrose & Cramer 1989). The localized back reaction to the maser growth tends to maintain the average growth at close to the threshold value, referred to as marginal stability, and the statistical properties can be introduced relatively simply through a stochastic growth theory (e.g., Robinson 1993). Due to the large number of localized, transient subsources the details of the coherent emission in each subsource is partly obscured by the averaging over many subsources. A random collection of coherently emitting sources should act like a single phase-random source, and it is appropriate to use a. maser-type theory to describe it.

4.4 *Emission by lunches*

The antenna mechanism proposed for pulsar radio emission is curvature emission by bunches (e.g., Sturrock 1971; Ruderman and Sutherland 1975; Buschauer & Benford 1976, 1983; Benford 1977; Benford & Buschauer 1977; Kirk 1980). The basic idea is that N particles in a volume less than a cubic wavelength radiate like a ‘macrocharge’ $Q = Ne$, and because the power radiated is proportional to Q^2, the power is N^2 times the power from an individual particle.

There are seemingly insurmountable difficulties with this theory (Melrose 1981, 1992, 1993a). For example, when one takes into account the highly anisotropic nature of curvature emission by relativistic particles, the bunch really needs to be a pancake with its normal within an angle $1/\gamma$ of the direction of the magnetic field. An obvious difficulty is to identify a pump (a bunching mechanism) that allows such an exotic bunch to form; none of the suggested pumps works (Melrose 1978). Moreover, even if such a bunch did form, the coherent emission would quickly be suppressed, both due to the bending of the field lines causing the normal to the bunch to deviate more than $1/\gamma$ away from the direction of the magnetic field (Melrose 1981), and due to the back reaction to the coherent emission dispersing the bunch through the ponderomotive force (Melrose 1978). For these and for the general reasons discussed above, coherent curvature emission by bunches is considered unacceptable by this author. A possible exception is the model of Michel (1992) in which the pair cascade occurs inward due to the electrostatic force, in a model in which the neutron star charges up, which type of emission is somewhat analogous to that suggested for terrestrial cosmic ray showers (e.g., Kahn & Lerche 1965).

4.5 *Relativistic plasma emission*

The currently most widely favored emission mechanism for pulsars is described here as relativistic plasma emission. Plasma emission is the mechanism that operates in solar radio bursts (e.g., Melrose 1986a, 1991). It involves two essential stages: generation of Langmuir waves through a streaming (or other) instability, and a nonlinear process that partially converts energy in Langmuir waves into energy in escaping radiation. Langmuir waves are longitudinal waves with frequency close to the plasma frequency, $\omega \approx \omega_P$. Langmuir waves cannot escape to infinity, and to produce escaping radiation they must be partially converted into one or both of the modes that can escape, which are the o-mode and x-mode of magnetoionic theory. In plasma emission, the maser process is the streaming instability, and the feature in the distribution function that causes the instability is a "bump-in-tail" distribution with $\partial f / \partial v_z > 0$ over a range of velocity, v_Z, along the streaming direction. The pump is the overtaking of slower particles by faster particles tending to increase $\partial f / \partial v_z > 0$.

The overtaking of slower by faster particles may also be the pump in relativistic plasma emission. This may be understood in terms of a simple model. Suppose that all particles leave a source of small spatial extent (small range Δ_{Z0}) over a short time interval (small time interval Δt_0)· The orbit of each particle is $z = z_0 + v_z(t - t_0)$. At a fixed distant point, z , the fastest particles arrive first and the slower particles arrive later, and at any given time the particles present have a range of velocities $\Delta v_z / v_z \sim \Delta_{Z0} / Z_0, \Delta t_0 / t_0$. A fractionation tends to occur in the sense that the range of Δv_z of the particles present (at given z, t) decreases as the beam gets further from the source. This implies a peak in the velocity distribution, with $\partial f / \partial v_z > 0$ below the peak and $\partial f / \partial v_z < 0$ above the peak, and such that these gradients increase with increasing distance from the source The back reaction to the maser emission of Langmuir waves, called quasilinear relaxation, tends to reduce the gradient $\partial f / \partial v_z > 0$. In the relativistic case, the same effects occur due to an initial spread $\Delta\gamma$ in γ.

Relativistic plasma emission is analogous to plasma emission in the sense that it involves two essential stages: an instability that generates waves that cannot escape to infinity, and a nonlinear conversion process (e.g., Istomin 1988) that partially converts the energy in these waves into escaping radiation, that is, into wave modes that are free to propagate to infinity. However, in the application to pulsars all the details are different from the application to the solar corona. In a pulsar magnetosphere the wave properties are assumed to be those of a relativistic, streaming one-dimensional pair plasma (e.g., Melrose & Stoneham 1977; Melrose 1979; Volokitin, Krasnoselskikh & Machabeli 1985; Arons"& Barnard 1986; Beskin, Gurevich & Istomin 1986, 1988, 1993; Lominadze et al 1986; Kazbegi, Machabeli & Melikidze 1991; Asseo 1993; Luo, Machabeli & Melrose 1994). Such a plasma supports a Langmuir-like mode and an Alfvén-type mode at lower frequencies, and two high-frequency modes that are somewhat analogous to the o-mode and x-mode of magnetoionic theory. Thus, relativistic plasma emission involves some instability that generates Langmuir-like or Alfvén-type waves, and these are converted into the escaping waves (in one or both of the two high-frequency modes) through nonlinear processes in the relativistic plasma. There are many specific models that vary in the details of the instability, the waves that it generates and the details of the nonlinear or other conversion mechanism (e.g., Asséo Pellat & Rosado 1980; Asseo, Pelletier & Sol 1983, 1990; Kazbegi, Machabeli & Melikidze 1987).

The streaming instability, in the case of a one-dimensional ultrarelativistic distribution, requires a distribution with $\partial f / \partial\gamma > 0$ in the inertial frame in which the bulk motion of the plasma is zero. This could be due to the high energy beam of positrons moving through the pair plasma, to a relative motion of the electrons and positrons in the pair plasma, or to other less obvious types of relative motion. However, the growth rates for most of these instabilities are too small: the pair plasma leaves the magnetosphere before it has given up significant energy (e.g., Larroche & Pellat 1987). A larger growth rate can result if the generation of the pair plasma fluctuates in time, producing a sequence of beams, with the faster particles in a following beam overtaking the slower particles in a preceding beam (Usov 1987; Ursov & Usov 1988).

The requirement for a pump to maintain $\partial f / \partial \gamma > 0$ has been given relatively little attention. In a pair cascade, one expects there to be few electrons or positrons at low energies, and for their number to rise to a peak at some characteristic energy. One then has $\partial f / \partial \gamma > 0$ below this peak and $\partial f / \partial \gamma < 0$ above it. The back reaction to the streaming instability reduces the gradient $\partial f / \partial \gamma > 0$ through quasilinear relaxation. In the absence of a pump to reestablish the peak, the instability would be confined to the near vicinity of the region where the pairs are produced. Such a model is very restrictive, both on location of the emission region and on the energy available for the maser emission, which is given by the energy in the pairs below the peak multiplied by a presumably small efficiency factor for the relativistic plasma emission. A model is which the production of pairs fluctuates or is appropriately spatially structured (Usov 1987; Ursov & Usov 1988; Lyubarskii 1992) can provide a pump that continues to operate away from the region where the pairs are produced.

Relativistic plasma emission is perhaps the most widely favored pulsar radio emission mechanism, and development of the theory continues. In the past, most treatments have concentrated on the growth rate of the instability, the properties of the waves that grow, and the partial conversion into escaping radiation. As emphasized above, there are other important effects that should be taken into account: the need for a continuous pump, and the implication that the coherent emission occurs in many localized, transient subsources. A continuous pump is present in some models (Usov 1987; Ursov & Usov 1988; Lyubarskii 1992), and microstructures are taken into account in one recent model (Asseo 1993).

4.6 *Maser curvature emission*

Curvature emission is like synchrotron radiation in that, in the simplest case, the absorption coefficient cannot be negative (Blandford 1975; Melrose 1978), so that maser emission cannot occur. However, maser emission is possible when one includes the curvature drift (Zheleznyakov & Shaposhnikov 1979; Chugunov & Shaposhnikov 1988; Luo & Melrose 1992a,b) or field-line distortion (Luo & Melrose 1994).

The curvature drift speed is

$$v_{\mathrm{cd}} = \frac{v^2 \gamma}{\Omega_e R_c}, \tag{4.1}$$

where v is the parallel velocity of the particle and R_c is the radius of curvature of the field line. The direction of the curvature drift (opposite for opposite signs of the charge) is such that the Lorentz force $q\mathbf{v}_{\mathrm{cd}} \times \mathbf{B}$ provides the centripetal acceleration, toward the center of curvature of the field line, needed to make the particle follow the curved path. In the following discussion it is more convenient to introduce a drift angle,

$$\theta_{\rm cd} = v_{\rm cd}/v, \tag{4.2}$$

which is the angle between the momentum of the particle and **B**. The drift angle is proportional to the particle energy, and when the particle energy changes as a result of emission, the drift angle also changes. This dependence is the essential ingredient in curvature-drift induced maser emission in that it allows negative absorption to occur.

The total emissivity (summed over the two polarizations) in the presence of curvature drift is (Luo & Melrose 1992b)

$$\eta(\omega,\theta,\gamma) = \frac{q^2}{4\pi\varepsilon_0}\frac{\omega^2 R_c}{6\pi^3 c^2}\left[(\theta-\theta_{\rm cd})^2\left(\xi^{-1}{\rm K}_{1/3}(y)\right)^2 + \left(\xi^{-2}{\rm K}_{2/3}(y)\right)^2\right]. \tag{4.3}$$

with $\xi = [2(1 - N) + N(\gamma^{-2} + (\theta - \theta_{\rm cd})^2)]^{-1/2}$, $y = \omega/3n^{1/2}\omega_{\rm R}\xi^3$, where N is the refractive index, and with $\omega_{\rm R} = v/R_c$. The absorption coefficients per unit time for a one-dimensional distribution function is

$$\Gamma(\omega,\theta) = -\frac{(2\pi c)^3 n_0}{2\omega^2 mc^2}\int d\gamma\,\frac{df(\gamma)}{d\gamma}\,\eta(\omega,\theta,\gamma), \tag{4.4}$$

where n_0 is the particle number density, and where $f(\gamma)$ is normalized to unity. From (4.4) the conditions for negative absorption are

$$\frac{df(\gamma)}{d\gamma} > 0, \qquad \frac{d\eta}{d\gamma} < 0. \tag{4.5}$$

The original proof that maser action is not possible is based on the inequality $d\bar{\eta}/d\gamma > 0$ (Blandford 1975; Melrose 1978), where n is the emissivity for $\theta_{\rm cd} = 0$. For $\theta_{\rm cd} = 0$ one has

$$\frac{d\eta}{d\gamma} = \frac{\partial\eta}{\partial\gamma} - \frac{\theta_{\rm cd}}{\gamma}\frac{\partial\eta}{\partial\theta}. \tag{4.6}$$

The term involving the θ-derivative allows negative absorption (Zheleznyakov & Shaposhnikov 1979; Luo & Melrose 1992b; Melrose 1993a).

Curvature emission from a single particle has a relatively broad frequency spectrum centered on $\omega \sim (c/R_c)\gamma^3$. Luo & Melrose (1992b) considered the possibility of maser action near, well below and well above this frequency, and found that the optical depth is small except for $\omega \lesssim (c/R_c)\gamma^3$. The maser emission then occurs at an angle $\Delta\theta_0$ to the magnetic field determined by

$$\gamma^2\theta_{\rm cd}\Delta\theta_0 > 1. \tag{4.7}$$

At angles where the curvature drift of electrons tends to cause maser emission, the curvature drift of positrons is opposite and tends to cause absorption, so that a difference in the distribution functions for electrons and positrons is necessary in order for there to be net negative absorption.

Maser curvature emission can also occur due to a twist of the field lines, corresponding to curved field lines that are not confined to a plane (Luo & Melrose 1994). Unlike curvature-drift induced maser emission, this mechanism is not sensitive to the magnitude of the magnetic field B, and electrons and positrons contribute with the same sign. Although this version of curvature maser emission seems more favorable than the curvature-drift induced mechanism, it does require a highly non-dipolar magnetic structure at the surface of the star for the growth rate to be large enough to be of relevance.

Any form of maser curvature emission requires $df / d\gamma > 0$, cf. equation (4.5), and a pump is required to continually regenerate such a distribution. The requirement $df / d\gamma > 0$ is the same as for a relativistic streaming instability, and hence any process that operates as a pump for relativistic plasma emission may also act as a pump for maser curvature emission.

Another (reactive) form of curvature-drift induced instability was proposed by Beskin, Gurevich & Istomin (1993), who considered the limiting case $B \to \infty$. The curvature drift speed (4.1) vanishes in this limit, and the nature of this instability is unclear. It has been claimed that this instability is spurious (Nambu 1989; Machabeli 1991).

4.7 *Cyclotron instability*

A cyclotron instability that involves the anomalous Doppler resonance was proposed by Machabeli & Usov (1979), cf. also Kazbegi, Machabeli & Melikidze (1991). In this anomalous Doppler transition, particles make a transition from the state $n = 0$ to $n = 1$ in (2.7) on emitting a wave quantum. This implies that the perpendicular energy of the electron (or positron) increases on emission. (The parallel energy decreases to provide both the perpendicular energy gained by the particle as well as the energy carried off by the photon.) The emission tends to have an intrinsic circular polarization, and Kazbegi, Machabeli & Melikidze (1991) argued that it is a plausible candidate for “core” emission. The waves that grow in this instability have refractive index greater than unity, and so are in a mode tha cannot escape directly. To produce escaping radiation the energy in these waves needs to be partially converted into energy in the high-frequency modes through a plasma-emission type process.

The source of free energy in this instability is the intrinsic anisotropy of a one-dimensional particle distribution. The effect of the instability, that is the back reaction on the particle distribution, is to tend to make the distribution more isotropic. The emission mechanism in its simplest form is subject to a strict constraint: each particle can make only one transition $n = 0$ to $n = 1$, and so can emit only one cyclotron photon. This implies that the maximum rate at which cyclotron photons are emitted is equal to the rate of particle escape from the magnetosphere. Hence, each particle (energy $\gamma m_e c^2$) loses at most an energy $\hbar\Omega_e / \gamma$, with $\Omega_e / \gamma \approx \omega$, where ω is the observed frequency. It follows that the ratio of the radio power to the total power lost by the pulsar is limited to $< \hbar\omega / \gamma m_e c^2 \sim 10^{-12}$, which is inconsistent with observations. Thus, this mechanism needs a continuous pump, e.g., a mechanism that returns the particles to the state $n = 0$. Otherwise the foregoing energetic argument seems to make the mechanism untenable.

The emission is near the (relativistic) cyclotron frequency, and for this to be in the range of observed radio frequencies requires that the emission occur relatively far from the neutron star ($> 10^7$m for a typical pulsar).

4.8 *Free electron maser emission*

A form of linear acceleration emission was proposed for pulsars by Cocke (1973). The Larmor formula implies that an accelerated charge radiates, and the acceleration of a particle by a parallel electric field is assumed to cause linear acceleration emission. However, emission occurs only if the parallel electric field varies in space or time (Melrose 1978; Kroll & Mullin 1979), and then, for a one-dimensional distribution, maser action is possible only for $df/d\gamma > 0$. The characteristic frequency of the emission is $\omega \sim \omega_0\gamma^2$, where ω_0 is the greater of the typical frequency of the oscillating electric field, or the typical wavenumber times c. The oscillating electric field needs to be identified with a large amplitude wave in the plasma, and there are several possibilities (e.g., Rowe 1992a,b).

A detailed treatment of this mechanism (Rowe 1992a,b) shows that it exists in two regimes. One corresponds to a form of relativistic plasma emission, in which the energy in the emitted waves comes primarily from the energy in the oscillating electric field. The other corresponds to a form of free electron maser emission, in which the oscillating field acts as a wiggler field, and the energy in the emitted waves comes primarily from the energy in the particles. Thus linear acceleration emission may be either an extreme form of relativistic plasma emission, or a form of free electron maser emission. Although there is no strong argument against the mechanism, the case that it might be a realistic pulsar emission mechanism centers on the question as to whether or not the required oscillating $E_{\|}$ is plausibly present.

4.9 *Which is the most plausible mechanism?*

In the opinion of this author, emission by bunches is unacceptable, and should not be considered further. Of the other emission mechanism discussed here, two are sensitive to B: maser curvature emission due to the curvature drift, and the cyclotron instability. For the curvature drift speed, (4.1) implies $v_{cd} \propto 1/B$, and as a consequence the growth rate for this form of maser curvature emission is a sensitive function of the magnetic field. The cyclotron mechanism is clearly strongly dependent on the value of B. Adopting the criterion discussed above that the emission mechanism should apply to millisecond pulsars to young, high-B pulsars and to slow pulsars, this dependence on B makes these mechanism unfavorable. The cyclotron mechanism also seems to be subject to a severe constraint (one radio photon per escaping particle) that would rule it out immediately.

Some form of relativistic plasma emission is perhaps the most plausible emission mechanism. However, free electron maser emission and maser curvature emission due to a twisted magnetic field are not ruled out.

5. Polarization and Propagation Effects

Propagation effects inside the light cylinder may account for jumps between orthogonal modes of polarization and possibly for the partial circular in some pulsars. Another expected propagation effect is induced Compton scattering by the relativistic particles in the wind zone of a pulsar. Besides being of interest in the interpretation of the radio emission, such effects offer the possibility of inferring some properties of the plasma environment through which the radio waves pass.

5.1 *Properties of the natural modes*

The properties of the natural modes in a pulsar magnetosphere (e.g., Melrose & Stoneham 1977; Melrose 1979; Allen & Melrose 1982; Volokitin, Krasnoselskikh & Machabeli 1985; Arons & Barnard 1986; Lominadze et al 1986; Beskin, Gurevich & Istomin 1987) depend strongly on whether one is in the low-frequency or high-frequency regime. The low-frequency regime is $\omega \ll \bar{\Omega} = \Omega_e/\bar{\gamma}$, where $\bar{\gamma}$ is a mean Lorentz factor, and the high-frequency regime is $\omega \gtrsim \bar{\Omega}$. In the low-frequency regime, the two natural modes are somewhat analogous of the hydromagnetic modes, with one being Alfvén-like and the other being magnetosonic-like. The waves are linearly polarized, except for a small range of angles near parallel (to **B**) propagation. At other angles of propagation, a small ellipticity in the polarization is also present if the electron and positron distributions are not identical. In the high-frequency regime, the wave properties are closer to those of the magnetoionic o-mode and x-mode waves. The waves have substantial circular polarization near the cyclotron resonance, which occurs in the high-frequency regime. In models in which the emission occurs well inside the light cylinder, the low-frequency approximation applies near the emission region.

A simple model for the waves properties involves three small parameters, a, b, g (Melrose 1979) and suffices for a description of the wave properties in the low-frequency regime. Let the two modes be labeled ±. The squares of their refractive indices, $1 + \Delta N^2$, and the axial ratios, $T_\pm$, of their polarization ellipses ($T = \infty$ corresponds to transverse polarization orthogonal to **B**) are

$$\Delta N_\pm^2 = \frac{1}{2}(a+b) \pm \frac{1}{2}[(a-b)^2 + g^2]^{1/2}, \tag{5.1}$$

$$T_\pm = \{a - b \mp [(a-b)^2 + g^2]^{1/2}\}/2g. \tag{5.2}$$

The three parameters depend on the number densities n_α and distribution functions $f_\alpha(\gamma)$, with $\int^\infty \gamma f_\alpha \gamma = 1$, where α labels electrons or positrons, through

$$a = -\sum_\alpha \frac{4\omega_{p\alpha}^2}{\omega^2} \int_1^\infty d\gamma\, f_\alpha(\gamma)\, \frac{\gamma\theta^2}{(1+\gamma^2\theta^2)^2} + \sum_\alpha \frac{\omega_{p\alpha}^2}{4\Omega_e^2} \int_1^\infty d\gamma\, f_\alpha(\gamma)\, \frac{(1-\gamma^2\theta^2)^2}{\gamma^3},$$

$$b = -\sum_\alpha \frac{\omega_{p\alpha}^2}{4\Omega_e^2} \int_1^\infty d\gamma\, f_\alpha(\gamma)\, \frac{(1+\gamma^2\theta^2)^2}{\gamma},$$

$$g = -\sum_{\alpha} \eta_\alpha \frac{\omega_{p\alpha}^2}{2\omega\Omega_e} \int_1^\infty d\gamma\, f_\alpha(\gamma)\, \frac{1-\gamma^2\theta^2}{\gamma^2}, \tag{5.4}$$

with $\omega_{p\alpha}^2 = e^2 n_\alpha/\varepsilon_0 m_e$, $\Omega_e = eB/m_e$, and where η_α is the sign of the charge and $\gamma \gg 1$ is assumed.

In the simplest approximation in the low-frequency regime, one has $|g|$, $|b| \ll |a|$, in (5.3) and the wave properties (5.1)–(5.2) simplify to $\Delta N^2 \approx a$, $\Delta N^2 \approx 0$, with $T \approx 0,\infty$, respectively. These are the *O*-mode and *X*-mode, respectively, in the notation of Arons & Barnard (1986). Note that, in this simple approximation, refraction affects the *O*-mode but not the *X*-mode. The counterpart of Langmuir waves occurs where a is of order unity.

5.2 *Circular polarization*

One can imagine four possible causes for circular polarization present in the radio emission from some slower, older pulsars: (a) the emission process has an intrinsically circular component (e.g., Gil & Snakowski 1990a,b; Gil 1992), (b) cyclotron absorption preferentially removes one circular component (e.g., Mikhailovskii et al 1982), (c) the wave mode into which the emission occurs is partially circularly polarized on leaving the source, and (d) linear polarization is partly converted into circular polarization due to generalized Faraday rotation. Apart from (a), all of these involve propagation effects. Explanation (a) invokes curvature emission by bunches, which is not considered acceptable here. One has no reason to expect that maser curvature emission, even if it does occur, has similar polarization properties to curvature emission by a single particle, and one does not expect relativistic plasma emission to have any characteristic circular polarization.

Process (c) requires elliptically polarized wave modes. For (5.2) to lead to significantly elliptical polarization requires that g be nonzero. This requires that the distributions of electrons and positrons be significantly different, with g a function of the difference between these distributions (Kazbegi, Machabeli & Melikidze 1991). However, it appears that the detailed conditions required for this explanation to be effective have yet to be explored thoroughly. Process (d) occurs in a medium with linearly polarized natural modes when incident radiation has linear polarization at an angle to that of the natural modes. (A familiar example is a quarter-wave plate, when the incident polarization is at 45°) In a pulsar magnetosphere this mechanism requires some extreme assumption to allow linear polarization at an angle different from that defined by the natural modes. For example,, it could occur if radiation passed through a vacuum gap: the change in orientation of **B** across the gap causes a change in the polarization of the natural modes between one side and the other, and radiation in one mode as it enters the gap would preserve its polarization across the gap.

All of these suggested explanations for the circular polarization encounter difficulties, and the actual explanation for the circular polarization remains unclear (e.g., Radhakrishnan & Rankin 1990; Radhakrishnan 1992).

5.3 *Jumps between orthogonal modes*

The jumps between orthogonal states of polarization that occur in some older, slower pulsars are probably due to propagation causing rays in the two modes to separate in angle (e.g., Melrose & Stoneham 1977; Melrose 1979; Stinebring et al 1984a,b; Barnard & Arons 1986). Stinebring et al (1984a,b) argued against such an interpretation of orthogonal modes on the grounds that the observed effect does not show an expected strong frequency dependence. However, Barnard & Arons (1986) pointed out that this argument applies only in the high-frequency regime, and that the frequency dependence of the refractive effects in the low-frequency regime is roughly consistent with the observations.

5.4 *Refraction in a striated plasma*

Consider a simple model which would allow a separation between the two modes to occur as a result of refraction. Refraction separates components in the two modes due to any gradients in the difference, ΔN, between their refractive indices. Suppose that the plasma in the inner magnetosphere is striated along the magnetic field lines, so that there are gradients in the plasma density perpendicular to the field lines. Let the z-axis be along the magnetic field and the x-axis along the gradient. Then refraction causes the ray to deviate at a rate $d\theta/dz = \partial\Delta N/\partial x$. The value of U$N$ is probably small ($\lesssim 0{\cdot}1$) in the emission region, but depends on the details of the emission process. Suppose the striations are of thickness Δx. Then a ray initially parallel to the field lines propagates a distance $\delta z \sim (\Delta x R_C)^{1/2}$ before leaving the striation, due to the curvature of the field line. Refraction causes the ray to deviate through an angle $\delta\theta \sim (\delta z/\Delta x)\Delta N \sim (R_c/\delta x)^{1/2}\ \Delta N$. An observationally significant angular change is $\delta\theta \sim 10^{-2}$.

This simple model suggests that a significant deviation of the two rays can occur without appealing to extreme properties of the striations, provided that ΔN is not too small. For example, for $\Delta N \sim 10^{-2}$ one would have $\delta\theta \sim 10^{-2}$ for $\Delta x \sim R_c$. An implication is that if it is accepted that jumps between orthogonal modes are due to refractive effects, then either ΔN is not too small, or there are extremely large local gradients in the plasma density ($\Delta x \ll R_c$). Ignoring the latter possibility, the interpretation of jumps in the orthogonal modes as a refract-tive effect favors some form of relativistic plasma emission, which leads naturally to emission in a regime where ΔN is not very small (a of order unity in (5.1)).

5.5 *Scintillations in a pulsar magnetosphere*

An alternative model for refractive effects. involves random deviations at many plasma inhomogeneities, rather than refraction in a single striation. Such a model corresponds to refractive scintillations.

Scintillations, due to inhomogeneities in an isotropic medium, cause an angular broadening of the source (e.g., Lee & Jokipii 1975). In an anisotropic medium there is an additional effect due to the difference $\Delta N_+ - \Delta N_-$ implying that refraction has a contribution that is opposite for the two modes. Thus, in an anisotropic medium, scintillations cause (a) an increase in the size of the image of a point source, and (b) a separation of the centroids of the images formed in the two modes of the medium (e.g., Melrose 1993b,c). Note that, except for $a \approx b$ in (5.1), one has $|\Delta N_+^2 - \Delta N_-| \sim |\Delta N_+^2 + \Delta N_-^2|$, and this implies that any refraction causes rays in the two modes to separate by about the same angle as their mean deviates from the original ray direction. Let $\delta\theta_\pm$ be the angular deviation of the rays in the two modes. In the special case $\Delta N_-^2 = -\Delta N_-^2$ one has $\delta\theta_- = -\delta\theta_+$, and hence

$$\langle \delta\theta_-^2 \rangle = \langle \delta\theta_+^2 \rangle, \qquad \langle (\delta\theta_+ - \delta\theta_-)^2 \rangle = 4\langle \delta\theta_+^2 \rangle. \tag{5.4}$$

This implies that the images in the two modes separate at the same rate as they broaden.

Applied to a pulsar, (5.4) implies that once the broadening exceeds the intrinsic size of the source, the emission, projected onto the plane of the sky, separates into contiguous regions of opposite polarizations. This provides a natural explanation for the jumps between orthogonal modes, as the line of sight crosses the boundary between such regions. Although (5.4) is strictly valid only for $\Delta N_-^2 \quad -\Delta N_+^2$, which corresponds to $a + b = 0$ in (5.1), the conclusion that the images in the two modes separate at about the same rate as they broaden should be approximately valid for any scintillations in the low-frequency regime, that is, scintillations due to inhomogeneities well inside the light cylinder of a typical pulsar.

According to (5.2), the orthogonal modes are linearly polarized for $(a - b)^2 \gg g_2$, in which case the jump is between orthogonal linear polarizations; the polarizations are significantly elliptical only when the condition $(a - b)^2 \gg g^2$ is not well satisfied.

5.6 *Induced Compton scattering*

Induced Compton scattering can pump photons from higher to lower frequencies, distorting the low-frequency spectrum of any source for which the effect is important. Wilson & Rees (1978) discussed the effect on the escaping radiation of induced Compton scattering by relativistic electrons in a pulsar wind. They found that the effect should be important for parameters thought plausible for the wind from the Crab pulsar. However, the expected signatures of induce Compton scattering are not present, implying that the properties of the wind are different from those anticipated. Wilson & Rees (1978) argued that the absence of the predicted effects places a limit on the Lorentz factors, γ, of the particles in the wind. For the Crab pulsar this limit is $\gamma > 10^4$. This idea was discussed further by Sincell & Krolik (1992) who included the effect of an ambient magnetic field on the Compton scattering. The implications of induced Compton scattering need to be explored in more detail (cf. Coppi, Blandford & Rees 1993).

6. Discussion and Conclusions

The outstanding problem in models for pulsar radio emission is that we simply do not understand how the radio emission is generated. The reasons why we has so far failed to solve the problem include the following.

1. There is no widely accepted, self-consistent model for the magnetosphere, including the location of gaps (the assumed source of pair plasma) and the

details of how the secondary pair plasma is produced. As a result, it is impracticable to attempt to predict the details of the distributions of particles required to identify the relevant coherent emission process.

2. The identification of observationally-based criteria for an acceptable emission mechanism are inadequate to select between several different alternatives. One helpful criterion is that the mechanism not be strongly dependent on $\boldsymbol{B}$, so that it can be applied to old (slow) pulsars, to young (fast) pulsars and to millisecond pulsars.

3. In this author's opinion, there has been a misplaced emphasis on coherent curvature emission by bunches, which is unacceptable for a variety of reasons.

4. There is no obvious simple analog for the pulsar coherent emission process, which presumably involves coherent emission in a relativistic pair plasma. Established coherent emission process, specifically plasma emission and electron cyclotron emission, apply to nonrelativistic plasmas. Some form of relativistic plasma emission, of which there are several in the literature, is perhaps the most plausible mechanism.

5. Possible alternatives to relativistic plasma emission include maser curvature emission and linear acceleration emission, or free-electron maser emission.

6. Relatively little attention has been given to two important features of coherent emission: the need for a pump and the localization of the emission into many small transient subsources. One can expect only an average (over the many subsources) balance between the pump and the back reaction to the coherent emission that opposes it. A coherent emission mechanism needs to be complemented by a statistical theory that describes the ensemble of such subsources, e.g., a stochastic growth theory or a marginal stability theory.

7. A final point that has only been alluded to in the discussion here is that expectations of what a theory for coherent emission in an astrophysical source can explain tend to be unrealistic. For example, even in those cases (the Earth's auroral kilometric radiation and type III solar radio bursts in the solar wind) where spacecraft have probed the source region and measured some properties of the electrons that produce the coherent emission, there remain major uncertainties in treatments of the coherent emission. There is little hope that we will ever understand coherent emission from pulsars in the same sense that we understand incoherent emission in synchrotron and other radioastronomical sources.

In summary, the pulsar radio emission mechanism remains poorly understood, and from the slow progress in our understanding of coherent emission under less exotic conditions) future progress is likely to be slow.

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