Part VIII

Coherence phenomena

Friday morning. Session Chair: Misha Popov

- How is the coherent radio-frequency emission produced and why is it depolarized?
  - ⋆ Coherence phenomena
    - ∗ Physical considerations pertaining to modes of plasma flow, instabilities, particle bunching and coherence mechanisms as they affect radiation processes.
    - ∗ Physical and observational characteristics of microstructure as they pertain to emission mechanisms.
    - ∗ Theoretical models of pulsar radio-frequency spectral characteristics.
    - ∗ Theoretical and observational discussions of the absorption phenomenon.

Don Melrose started this session with an excellent review entitled, Coherent radio emission mechanisms for pulsars. *Dr. Melrose submitted a more extensive version of his paper, which we are very pleased to include here in the* Proceedings.

COHERENT RADIO-EMISSION MECHANISMS FOR PULSARS

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Abstract

Coherent emission mechanisms may be classified as (i) maser mechanisms, attributed to negative absorption by resonant particles in a resistive instability, (ii) a reactive or hydrodynamic instability, or (iii) to emission by bunches. Known coherent emission mechanisms in radio astronomy are plasma emission in solar radio bursts, maser emission in OH and other molecular line sources, electron-cyclotron maser emission from the planets, and pulsar emission. Pulsar radio emission is the brightest of all known coherent emission, and its brightness temperature is close to the maximum conceivable in terms of energy efficiency. Three possible pulsar radio emission mechanisms warrant serious consideration in polar cap models; here these are called coherent curvature emission, relativistic plasma emission, and free electron maser emission, respectively.

1. Coherent curvature emission is attributed to emission by bunches. There is a fundamental weakness in existing theoretical treatments which do not allow for any velocity dispersion of the particles. There is no satisfactory mechanism for the formation of the required bunches, and were such bunches to form they would quickly lose their ability to emit coherently due to the curvature of the field lines.
2. Relativistic plasma emission is a multistage emission process involving the generation of plasma turbulence and the partial conversion of this turbulence into escaping radiation. In pulsars the dispersion characteristics of the relativistic electron-positron plasma determines the form of the turbulence, which may be in either longitudinal waves or Alfvén-like waves. Various instabilities have been suggested to produce turbulence, and a streaming instability is one possibility. Alternatively, in a detailed model proposed by Beskin *et al.* (1988) the instability depends intrinsically on the curvature of the field lines, and in a theory discussed by Kazbegi *et al.* (1988), a cyclotron instability generates the turbulence relatively far from the neutron star.
3. Free electron maser emission or linear acceleration emission requires an oscillating electric field, postulated to be due to a large amplitude electrostatic wave. A recent analysis of this mechanism (Rowe 1992) shows that it allows emission in two different regimes that provide a possible basis for the interpretation of core and conal emission in pulsars. Effective maser emission seems to require Lorentz factors smaller than other constraints allow.

Other suggested theories for the emission mechanism include one that arises from a loophole in the proof that curvature absorption cannot be negative, and another that involves a closed "electrosphere" in which the radio emission is attributed to emission by bunches formed as a result of pair production due to a primary charge accelerated towards the star by its Coulomb field.

1. Introduction

Despite about two decades of theoretical effort, there is still no consensus of the specific nature of the radio-emission mechanism for pulsars. Two reasons may be identified for this unsatisfactory situation. First, the emission mechanism itself appears not to be closely related to any of the more familiar radio emission mechanisms in astrophysics. Pulsar radio emission is very bright and the emission mechanism must be *coherent* in the sense defined below. There are three other well established coherent mechanisms in astrophysics: *maser line emission* in OH and other molecular lines from circumstellar and interstellar clouds, *plasma emission* from the solar corona, and *electron cyclotron maser emission* from the Earth's auroral zones and from the giant planets. Theories for these coherent emission processes are not as well developed as theories for incoherent emission processes, and they are not particularly familiar to most astrophysicists. Moreover, it is clear that the pulsar radio emission mechanism is not related in a simple way to any of these mechanisms; a possible exception is optical emission from pulsars for which a cyclotron maser theory has been suggested (Stoneham 1981). Second, the plasma parameters in the emission region, that is, the region where the pulsar radio emission is generated, are poorly known. Moreover the plasma has exotic and hence unfamiliar properties. Specifically, 1) the magnetic field is superstrong, $B \gtrsim 10^8\,\mathrm{T}$, 2) there are likely to be very strong and variable electric fields associated with the enormous potential drop available ($V \approx 10^{12}$–$10^{16}\,\mathrm{V}$), and 3) the particles are probably relativistic electrons and positrons in one-dimensional orbits along curved magnetic field lines. A working definition of a *coherent* emission mechanism is simply that it a mechanism which cannot be explained in terms of incoherent processes. This definition is deliberately vague because the coherence may be produced in several different ways. To identify a specific coherent mechanism one needs to specify a particular coherent emission process. Also, a coherent emission mechanism involves a source of free energy which needs to be identified. There are three types of emission mechanism that warrant serious consideration:

1. *Coherent curvature radiation*: Bunches of highly relativistic electrons or positrons produce the emission through perpendicular acceleration due to the curvature of the field lines along which they propagate. The coherence is postulated to be produced by N particles in a bunch smaller than a wavelength emitting N^2 times the power per individual particle so that all N particles radiate in phase with each other.
2. *Relativistic plasma emission*: Plasma emission is the dominant emission process in solar radio bursts and various forms of 'relativistic plasma emission' have been suggested for pulsars. Plasma emission is a multistage emission process. The stages involve:
    (a) the generation of 'plasma turbulence', which involves an instability generating waves in a natural wave mode of the plasma (Langmuir waves in the solar corona) such that these waves cannot escape directly from the plasma to infinity, and
    (b) a partial conversion of energy in this plasma turbulence into escaping radiation.

    Possible conversion processes are nonlinear wave-wave interactions, mode coupling due to inhomogeneity and scattering by particles. The 'coherence' is produced in the first stage, and may be attributed to a very high effective temperature of the turbulence. In the conversion to escaping radiation the plasma acts as a passive converter.
3. *Free electron maser emission*: A parallel (to the magnetic field) electric field is postulated to accelerate the relativistic particles which, as a consequence, produce acceleration emission. If the electric field is periodic in space then the modulation of the motion of the relativistic particles causes them to radiate as in a free electron maser. The coherence is produced by maser action: the absorption is negative when the distribution function of the relativistic particles is an increasing function of energy.

Other radio emission processes have been suggested (*e.g.*, Chiu and Canuto 1971, Chiu 1972, Virtamo and Jauho 1973, Mertz 1974, Kovalev 1979, Rylov 1978), but only the three foregoing types of emission process are discussed here.

These radio emission mechanisms are formulated within the framework of the polar cap model for the pulsar in which the magnetosphere is populated by relativistic electron-positron pairs (*e.g.*, Sturrock 1971, Ruderman and Sutherland 1975). A large potential drop along field lines in the polar cap zone causes acceleration of primary particles to high energies, and these particles emit γ rays. The pairs are generated as secondaries due to the decay of the γ rays into pairs as they propagate across the magnetic field lines. Radio emission mechanisms for other models of the pulsar magnetosphere have not been explored in as much detail. One alternative is the 'slot gap model' (*e.g.*, Arons 1979, 1981, 1983, Arons and Scharlemann 1979), which differs from the polar cap model in important structural details rather than in fundamental principles. An entirely different model for the pulsar results if the neutron star is allowed to have a net charge which, it is argued, tends to build up as a direct result of the electrodynamics of a rotating magnetized star (Rylov 1976, Jackson 1976, 1980, Michel 1981, 1982, 1983). In such models charged particles can be trapped inside the magnetosphere by the Coulomb field of the charged star. How the pulsar radio emission might be produced in such a model has been discussed by Rylov (1981, 1982, 1984), and Krause-Polstorff and Michel (1985a,b) and Michel (1987, 1990). Although this type of model is given a secondary place in the present review, it should be emphasized that it remains a viable and markedly different alternative to the more conventional polar cap models. The main emphasis is this review is on the physical ideas underlying theories of coherent emission in general and for these pulsar radio emission processes in particular. In Section 2 the concept of 'coherent emission' is discussed and its favored forms for the interpretation of other (than pulsar) situations in radio astronomy are reviewed briefly. Coherent curvature emission is discussed in Section 3, relativistic plasma emission in Section 4, and free electron maser emission in Section 5.

2. Coherent emission

It is traditional to classify emission mechanisms radioastronomical sources as 'thermal', 'incoherent', or 'coherent'. Thermal emission is well defined: it is due to a Maxwellian distribution of emitting particles at a specific temperature, T, say. Thermodynamic arguments, expressed in terms of Kirchoff's law, require that the brightness temperature T_B not exceed T. Incoherent emission is also clearly defined: it is due to spontaneous emission when the corresponding absorption process is unimportant. Incoherent emission is attributed to energetic particles, with energy, ε, say, and absorption is unimportant only for $k_B T_B \ll \varepsilon$, where k_B is Boltzmann's constant. Absorption by the inverse of the emission process, often called *self-absorption*, limits the brightness temperature to $k_B T_B \lesssim \varepsilon$ under most circumstances.

Three classes of coherent emission

Coherent emission is not well defined. A working definition is that coherent emission is any nonthermal emission that cannot be explained in terms of incoherent emission. Ginzburg and Zheleznyakov (1975), in a review on pulsar emission mechanisms, classified coherent emission mechanisms as "maser" mechanisms and "antenna" mechanisms. However, a clearer distinction between processes is achieved by introducing three classes. These are:

1. *Maser mechanisms*: A maser mechanism corresponds to negative absorption or, equivalently, to a resistivity instability driven by resonant particles. The growth of the waves is treated in the random phase approximation, which implies that the phase of the amplified waves is irrelevant. The growth rate for the instability must be much less than the bandwidth of the growing waves; phase mixing then causes memory of the initial phase to be lost before the waves grow significantly. Also, because the interaction is a resonant one, the growth rate of a maser may be determined by relating absorption to emission using the Einstein coefficients. Any maser instability may be interpreted in terms of the familiar idea (for laboratory lasers) of an inverted energy population. In a classical context this requires that the particle distribution function have an appropriate gradient in momentum space.
2. *Reactive instabilities*: Plasma instabilities can be either *resistive* or *reactive*. A reactive instability, called a 'hydrodynamic' instability in the Russian literature, has a growth rate greater than the intrinsic bandwidth of the growing waves, so that the initial phase is remembered and a phase-coherent wave grows. In a reactive instability the particles are not resonant, and the instability may be attributed to the particles becoming bunched in space causing a current with a specific phase relation to the wave (*e.g.*, Melrose 1986, p. 66).
3. *Emission by bunches*: On dimensional grounds, the power radiated spontaneously by a charge q due to any emission process is proportional to q^2/ε_0. If there are N identical charges moving in identical orbits in a bunch that fills a spatial region small compared with the coherence volume of the emitted radiation, then the bunch acts like a single macrocharge, and the power radiated is proportional to N^2q^2/ε_0. The coherence in this case is due to the particle radiating in phase because of their initial arrangement in bunches. The theory of bunching generalizes in a simple way to an arbitrarily shaped bunch of identically moving particles, but it is restricted to the case where there is no dispersion in the velocity of the particles.

It might be remarked that in specific cases there is a relation between reactive and resistive instabilities—they pass over into each other when the growth rate is approximately equal to the bandwidth of the growing waves. However, the relation between emission by bunches and the other two types of instability is not well established.

Direct and indirect emission

An important point is that radiation can escape directly from an astrophysical source only if it is in a natural mode of the plasma that joins on continuously to the vacuum wave modes as the plasma parameters B and ω_p tend to zero. It is convenient to refer to the two high frequency branches of the natural wave modes of the plasma as the *escaping wave*, and to refer to a mechanism that produces radiation in the escaping waves as a *direct* emission process. In all plasmas of relevance the escaping waves have refractive index less than unity, and this precludes their direct generation through a streaming instability (specifically through Cerenkov emission). A direct emission process requires an acceleration of the particles. Curvature emission and free electron maser emission, (as well as synchrotron emission, bremsstrahlung and electron-cyclotron maser emission in other contexts) are direct emission processes. From a formal point of view, the simplest type of coherent emission mechanism to treat quantitatively is a direct maser emission process. Saturation of the maser gives direct information on the level of the escaping radiation. Maser emission is not possible for curvature emission, and the free electron maser emission is the simplest relevant direct maser emission process.

Indirect emission is synonymous here with plasma emission: plasma turbulence that cannot itself escape is generated by a streaming or other instability and must subsequently be converted into escaping radiation. In the first stage of plasma emission, saturation of the maser may determine the level of the plasma turbulence, described by its effective temperature, say, provided that the turbulence is generated through a resistive instability. There are thermodynamic-like restrictions on nonlinear conversion processes, and under appropriate conditions these lead to the conclusion that the brightness temperature of the escaping radiation cannot exceed about the effective temperature of the plasma turbulence.

Properties of coherent sources in radioastronomy

There are four classes of radioastronomical sources that require coherent emission mechanisms. These are, in order of their discovery, (i) solar radio bursts, the most widely studied of which are type III bursts, (ii) the decametric radio emission from Jupiter and related emission from other planets, notably the auroral kilometric radiation (AKR) from the Earth, (iii) maser emission in OH and other molecular lines from interstellar and circumstellar clouds, and (iv) pulsar radio emission. A distinguishing feature of coherent emission is its high brightness temperature. For type III bursts the brightness temperature varies from the minimum detectable to a characteristic maximum between 10^{14} and 10^{15} K. The brightness temperature of Jupiter's decametric radio emission, for the Earth's AKR, for solar spike bursts and for very bright radio emission from some flare stars can be somewhat higher than for type III. There is observational evidence for brightness temperatures up to about 10^{18} K. The maximum brightness temperatures for molecular line sources are around 10^{15} K. Pulsar radio emission can be much brighter than for these other sources. The highest values estimated are about 10^{31} K for the Crab pulsar, *e.g.*, Cordes (1979, 1981), although this estimate is subject to considerable uncertainty and it has been argued that the maximum value implied by the data does not exceed 10^{26} K (Cheng and Ruderman 1980).

Coherence and brightness temperature

The significance of the brightness temperature from a theoretical viewpoint is twofold. On the one hand, a sufficiently high brightness temperature precludes interpretation other than through a coherent emission mechanism. On the other hand, the actual value of the brightness temperature should reflect a saturation level for the coherent emission process. The idea of a saturation level is relatively familiar in the context of a maser line-emission mechanism. There is a pump for the maser, and the pump excites atoms or molecules to the upper state of the maser transition at a certain rate that can be estimated. The saturation level of the maser corresponds to the rate of downward transitions due to maser emission balancing the pump rate. Saturation of OH line masers accounts satisfactorily for the observed brightness temperatures, *e.g.*, Elitzur (1982). An analogous type of saturation may occur in plasma emission and in electron-cyclotron maser emission. The implied level for electron-cyclotron maser sources is in reasonable agreement with the observed brightness temperatures (Melrose and Dulk 1982). Interestingly, for type III bursts the saturation level of the streaming instability is also in reasonable agreement with the observational data on brightness temperatures (Melrose 1989), which implies that both the instability and the conversion process both tend to saturate.

Saturation of a maser is an attractive possible way of explaining the observed brightness temperatures. More generally, it is relevant to ask how high the brightness temperature might be in principle. The maximum brightness temperature may be estimated as follows. Suppose that the emitting particles have a mean number density n and an energy $\varepsilon = \gamma mc^2$. Further, suppose that a fraction α of the energy density $(\gamma - 1)nmc^2$ in the particles is converted into escaping radiation. Provided that this occurs on a short enough timescale, the maximum brightness temperature follows by equating the energy density in the radiation to the energy $\alpha(\gamma - 1)nmc^2$. The energy density in the radiation may be written as $k_B T_B / V_c$, where T_B is its brightness temperature and V_c is its coherence volume. The *coherence volume* of the radiation depends on its frequency ω, its relative bandwidth $\Delta\omega/\omega$ and the range of solid angle $\Delta\Omega$ to which it is confined:

$$V_c = \lambda^3 / \Delta\Omega(\Delta\omega/\omega), \qquad \lambda = 2\pi c/\omega. \qquad (1)$$

The maximum conceivable brightness temperature is then given by

$$(T_B)_{\max} \approx \alpha V_c (\gamma - 1) nmc^2 / k_B . \qquad (2)$$

For electrons one has $m_ec^2/k_B = 0.5 \times 10^{10}$ K. For $\gamma \gg 1$ the emission is confined to a forward cone with half angle $\approx 1/\gamma$ implying $\Delta\Omega \approx \pi/\gamma^2$. Then for the relatively broad band ($\Delta\omega/\omega \approx 1$) emission observed, eq.(2) requires

$$(T_B)_{\max} \approx \alpha n \lambda^3 \gamma^3 \times 10^9 \, \mathrm{K}. \qquad (3)$$

The number density n and the Lorentz factor γ are model dependent. A plausible estimate follows from the Goldreich-Julian (1969) value, say $10^{16}\,\mathrm{m}^{-3}$, and the most widely favored estimate of γ is of order 10^2. Then at a frequency of 1 GHz ($\lambda \approx 0.3$ m) the limit eq.(3) implies $T_B \lesssim 3\alpha \times 10^{30}$ K. Estimates of the radiation efficiency factor α as high as 10^{-4} exist in the literature (*e.g.*, Beskin, Gurevich and Istomin 1986, 1988), and it is clear that with these rough estimates such a relatively high efficiency is required to account for the high observed brightness temperatures.

The fact that the observed brightness temperatures appear to be close to the limiting brightness temperature eq.(3) has general implications that are independent of the specific coherent emission mechanism. One implication is that the efficiency for conversion of particle energy into radio emission, described by the parameter α, must be relatively high, *e.g.*, of the order 10^{-4} as estimated by Beskin, Gurevich and Istomin (1986). Another implication is that the Lorentz factor of the particles cannot be too small, *e.g.*, $\gamma \ll 10^2$ in (3) would make it difficult to reconcile with the large brightness temperatures estimated from observation.

3. Curvature emission by bunches

Coherent curvature emission was the first emission mechanism considered for pulsar radio emission (*e.g.*, Gunn and Ostriker 1971, Sturrock 1971, Éidman 1971, Ruderman and Sutherland 1975, Elsässer and Kirk 1976, Ochelkov and Usov 1980). Early data on the rotation of the plane of polarization through a pulse supported curvature emission by ultrarelativistic particles streaming from the magnetic polar regions of a rotating neutron star (Radhakrishnan and Cooke 1969, Komesaroff 1970). From a formal point of view, curvature emission is essentially identical to synchrotron emission by a particle with pitch angle equal to $\pi/2$; both are attributed to emission by an ultrarelativistic particle moving along an arc of a circle. Any acceptable model for pulsar radio emission should explain the sweep of the linear polarization in essentially the same way as in this simple model. Note that this requirement does not necessarily imply that the emission be due to curvature emission, but rather that the emission mechanism leads to radiation polarized along either the projection of the magnetic field on the plane of the sky or the direction orthogonal to it. All three of the mechanisms discussed here satisfy this requirement in principle.

Seemingly the most plausible pulsar emission mechanisms would be a maser version of curvature emission. However, curvature absorption cannot be negative (Blandford 1975, Melrose 1978), for essentially the same reason as synchrotron absorption cannot be negative (Twiss 1958, Wild, Smerd, and Weiss 1963). This leaves three possibilities: (i) the emission mechanism is curvature emission and the coherence is produced by a non-maser process such as emission by bunches, (ii) there is a loophole in the proof that maser emission is not possible, as there is for synchrotron emission (*e.g.*, McCray 1966, Zheleznyakov 1967, Kaplan 1968), or (iii) the emission mechanism is not curvature emission. A loophole in the proof that curvature absorption cannot be negative was pointed out by Zheleznyakov and Shaposhnikov (1979) and discussed further by Shaposhnikov (1981) and Chugunov and Shaposhnikov (1988). Maser emission is possible in principle when the effect of a drift across the magnetic field lines is taken into account.

Curvature emission by bunches has been proposed and explored in considerable detail, *e.g.*, the review by Ginzburg and Zheleznyakov (1975), and also Buschauer and Benford (1976, 1983), Benford and Buschauer (1977), and Kirk (1980). In astrophysics there is no known emission process that is due to coherent emission by bunches in the way assumed in coherent curvature emission. The framework on which the theory is built is less well established than for plasma emission processes and maser mechanisms.

There are at least three problems with coherent curvature emission. A fundamental difficulty is that no detailed theory for a bunching instability exists for the case where the velocity dispersion is nonzero. It should be emphasized that this is a severe deficiency in the theory, as one suspects that the inclusion of velocity dispersion would modify the theory substantially. The other two difficulties concern the mechanism for the formation of the bunches, and the effect of the curvature of the bunches.

The bunching mechanism

It is usually assumed that the bunches form as the result of an instability leading to self-bunching. One specific mechanism for this was proposed by Goldreich and Keeley (1971), Cheng and Ruderman (1977), and Buschauer and Benford (1978), but this mechanism seems to rely on a specific artificial geometry (Melrose 1978, Asséo, Pellat, and Sol

1981). A variety of other instabilities have been invoked as possible ways in which the bunches might form, (*e.g.*, Ruderman and Sutherland 1975, Hinata 1976a, Cheng and Ruderman 1977). The idea is that a reactive instability involves some self bunching of the particles, and the supposition is that the bunches formed in a streaming instability can then lead to coherent curvature emission. However, while it is true that reactive instabilities produce self bunching of the particles, in practice this self bunching is quite weak. Furthermore, the bunching instability requires that the bunches be localized in both coordinate space and in velocity space (any velocity dispersion must destroy the coherence on the time for the bunch to increase in dimensions by a wavelength due to the relative motion of the particles), and *a reactive instability increases the velocity dispersion.* Apart from the Goldreich-Keeley instability, which appears to be inapplicable, it has not been shown that any instability would produce the type of bunching required for effective coherent curvature emission by bunches. As discussed below, a very specific self-bunching mechanism is required. Moreover, besides being questionable as bunching mechanisms, proposed instabilities appear to grow too slowly (*e.g.*, Benford and Buschauer 1977, Hardee and Morrison 1979, Asséo, Pellat and Rosado 1980). In the absence of an acceptable bunching mechanism, coherent curvature emission continues to be viewed more favorably than is justified.

As remarked above, there is an entirely different model for a pulsar magnetosphere based on the neutron star becoming charged. Within the framework of such an "electrosphere" model, (*e.g.*, Rylov 1981, 1982, 1984, Krause-Polstorff and Michel 1985a, b and Michel 1988, 1990), the following mechanism for the formation of bunches has been proposed. The Coulomb field of the star accelerates a test charge of the appropriate sign from large distances towards the star. A cascade or avalanche of pair production results, analogous to the cascade that occurs in a cosmic-ray shower. The electric field tends to separate the positrons and electrons, resulting in sheet-like bunches of charges of the one sign. It is argued that these bunches can radiate coherently due to curvature emission, with the radiation directed towards the neutron star rather than away from it (as in the polar cap models). However, possible radio emission mechanisms in this type of model have yet to be explored in as much detail as for the polar cap models.

Emission by bunches

The existing theory for emission by bunches with no velocity dispersion may be summarized as follows (*e.g.*, Éidman 1971, Sturrock, Petrosian and Turk 1975, Melrose 1978, 1981). Let $P(\boldsymbol{k})d^3\boldsymbol{k}/(2\pi)^3$ be the power radiated by a single particle in the range $d^3\boldsymbol{k}/(2\pi)^3$. Let $n(\boldsymbol{k})$ be the spatial Fourier transform of the number density of the radiating particles. Then the power radiated $P_{\text{bunch}}(\boldsymbol{k})d^3\boldsymbol{k}/(2\pi)^3$ due to the bunching emission is

$$P_{\text{bunch}}(\boldsymbol{k}) = |n(\boldsymbol{k})|^2 P(\boldsymbol{k}) . \tag{4}$$

The simple case where N particles radiate N^2 times the power per particle corresponds to the limit of an arbitrarily small bunch,

$$\lim_{\boldsymbol{k}\to 0} n(\boldsymbol{k}) = N , \tag{5}$$

where N is the total number of particles in the bunch. In practice, one may interpret $n(\boldsymbol{k})$ as being equal to the number of particles per coherence volume, that is, $n(\boldsymbol{k}) = nV_c$.

A difficulty with coherent curvature emission that concerns the effect of the curvature on the bunches is as follows. The value of $\boldsymbol{k}$ associated with the coherent emission is very specific: the bunch must be shaped such that its spatial Fourier transform has its maximum value at the $\boldsymbol{k}$ of the emitted radiation. The emission from ultrarelativistic particles is confined to a forward cone with half angle $\approx 1/\gamma$. For curvature emission this cone is nearly along the magnetic field $\boldsymbol{B}$. Thus, in Fourier space bunching emission corresponds to the component $k_\perp$ perpendicular to the field lines being smaller than the component $k_\parallel$ along the field line by a factor of order $1/\gamma$, that is,

$$k_\perp \lesssim k_\parallel/\gamma, \quad k_\parallel \approx \omega/c , \tag{6}$$

where ω is the frequency of the emission. This corresponds to a very flat pancake shaped bunch with the normal within an angle $\approx 1/\gamma$ of $\boldsymbol{B}$. As the bunch propagates along the field line this direction of emission changes as the orientation of $\boldsymbol{B}$ changes. The normal to the pancake needs to rotate to follow the local direction of $\boldsymbol{B}$ for it to remain within $\approx 1/\gamma$ of $\boldsymbol{B}$. There is no proposed mechanism that would cause a bunch to rotate in this way. Hence, even if a bunch were initially effective in radiating coherently it would cease to be effective after propagating a distance R_c/γ, where R_c is the radius of curvature of the field line.

4. Relativistic plasma emission

Relativistic plasma emission in pulsars is analogous to plasma emission from the solar corona in that it is a multistage process. However, the details of the stages must be quite different. Aspects of the theoretical investigations concern the dispersive properties of a relativistic electron-positron plasma, the relevant wave modes for plasma turbulence leading to relativistic plasma emission, instabilities that generate the turbulence, the conversion of the turbulence into escaping radiation, and possible modification of the radiation as it propagates through the plasma.

The generation of plasma turbulence

The first stage of plasma emission in the solar corona involves Langmuir waves, which are longitudinal waves near the plasma frequency, generated by a streaming instability. In generalizing to a pulsar magnetosphere, one first needs to determine the wave properties. There is an extensive literature on the dispersive properties of the relativistic electron-positron plasma in a pulsar magnetosphere and on the nature of the wave natural modes, (*e.g.*, Canuto and Ventura 1972, Hardee and Rose 1976, 1978, Melrose and Stoneham 1977, Onischenko 1981, Gedalin and Machabeli 1983, Volokitin, Krasnovsel'skikh and Machabeli 1985, Arons and Barnard 1986, Beskin, Gurevich and Istomin 1986, 1988, Lominadze *et al.* 1986). Generation of two distinct types of turbulence in the pulsar magnetosphere have been considered:

1. Generation of *longitudinal waves* is one possibility (*e.g.*, Hinata 1976b,c, Hardee and Morrison 1979, Cox 1979, Lominadze, Mikhailovskii and Sagdeev 1979, Pellat 1979, Asséo, Pellat and Rosado 1980, Jones 1980, Suvorov and Chugunov 1980, Shaposhnikov 1981, Egorenko, Lominadze and Mamradze 1983, Verga and Fontan 1985, Usov 1987, Kazbegi, Machabeli and Melikidze 1987a,b).

2. Generation of ***Alfvén-like waves*** is an alternative, as pointed out by Tsytovich and Kaplan (1973), Suvorov and Chugunov (1975), Kawamura and Suzuki (1977), Lominadze *et al.* (1982), and as is now favored, *e.g.*, Beskin, Gurevich and Istomin (1986, 1988).

Although the details of various possible instabilities in such a relativistic electron-positron plasma have been discussed extensively in the literature, it seems fair to say that no clearly acceptable source of plasma turbulence suitable for relativistic plasma emission has been identified. An important physical aspect to any proposed instability concerns the source of the free energy. Three classes of instability have been considered: (i) streaming instabilities, (ii) curvature-driven instabilities, and (iii) cyclotron instabilities. However, each proposed mechanism seems to be subject to one criticism or another, with a general criticism being that specific mechanisms are not efficient enough in the sense that the instability does not grow fast enough to produce the required turbulence effectively (*e.g.*, Asséo, Pellat and Sol 1983, Kazbegi, Machabeli and Melikidze 1987b).

Production of escaping radiation

The specific mechanisms involved in the conversion of the plasma turbulence into escaping radiation have been given relatively cursory attention, *cf.* Istomin (1988), however. It might be remarked that attempts to treat the analogous processes in plasma emission from the solar corona have proved problematical, but the observations suggest a simple result: the conversion processes seem to saturate at a brightness temperature of the escaping radiation equal to the effective temperature of the plasma turbulence, *e.g.*, Melrose (1989). As a consequence, it is probably reasonable to assume that the conversion processes occur with similar efficiency in a pulsar magnetosphere.

Even after the escaping radiation is generated, it may be absorbed due to a gyromagnetic resonance, *e.g.*, Mikhailovskii *et al.* (1982). A similar problem occurs for escape of radiation in strongly magnetized regions of the solar corona, *e.g.*, Melrose and Dulk (1982). The properties of the escaping radiation may also be modified due to a generalized form of Faraday rotation (*e.g.*, Melrose 1979, Mikhailovskii *et al.* 1982, Barnard and Arons 1986, Barnard 1986).

The model of Beskin, Gurevich and Istomin

The most detailed model so far formulated for pulsar radio emission is that by Beskin, Gurevich and Istomin (1986, 1988). Important ingredients in this model include: (i) a plasma response function that incorporates the inhomogeneity associated with the curved magnetic field (Beskin, Gurevich, and Istomin 1987), (ii) a curvature-driven reactive instability in an Alfvén-type drift mode whose existence depends on this inhomogeneity, and (iii) the conversion to escaping radiation due to one of several possible conversion mechanisms including relevant nonlinear processes in the relativistic plasma (*e.g.*, Istomin 1988). Beskin, Gurevich and Istomin (1986, 1988) pointed out that the inclusion of the curvature of the field lines splits the Alfvénic type mode into several modes. The appearance of new wave modes when intrinsically new physical effects are included is a characteristic feature of plasma-dispersion theory. Let us refer to these modes as 'curvature modes' to emphasize this point. The curvature modes are intrinsically growing, which corresponds to a reactive instability associated with the curvature inhomogeneity. A notable feature of the theory of Beskin *et al.* is that it allows the escaping radiation to be in either of the two natural high frequency modes of the plasma. This feature provides the possibility of explaining some observational details relating to the difference in polarization characteristics of 'core' and 'conal' emission and of the flipping between orthogonally elliptically polarized modes in some pulsars (*e.g.*, Radhakrishnan and Rankin 1990). This attractive feature does not depend strongly on the specific details of Beskin *et al.*'s model and applies to any emission mechanism that produces a variable mixture of the two high-frequency natural modes.

The model of the Georgian group

The Georgian group (*e.g.*, Lominadze *et al.* 1987, Kazbegi, Machabeli and Melikidze 1987a, b, 1988) has presented some alternative ideas on the generation mechanism for the plasma turbulence in a pulsar magnetosphere. They explored three different instabilities: a streaming instability, a cyclotron instability, and a streaming-like instability due to the drift of the relativistic particles across the curved field lines. The cyclotron instability is due to the anomalous Doppler effect, in which emission of waves occurs due to a transition from a lower to a higher Landau orbital, with a decrease in parallel energy supplying both the energy of the emitted photon and the energy for the increase in perpendicular energy. The relevant resonance condition has harmonic number $s = -1$ in

$$\omega - s\Omega_e/\gamma - k_\parallel v_\parallel = 0, \qquad (7)$$

where $\Omega_e = eB/m$ is the nonrelativistic cyclotron frequency. Such an instability, which is possible for waves with refractive index greater than unity (allowing $\omega - k_\parallel v_\parallel < 0$ and hence $s < 0$), is driven by the anisotropy of the particle distribution when all the particles are in their lowest Landau orbital, and this anisotropy is reduced by excitation of some particles to higher orbitals. For the wave frequency determined by eq.(7) to be in the observed range for pulsars, the instability must occur far from the neutron star where the value of B is sufficiently small. Thus the source region in a model based on this cyclotron mechanism is located much further from the star than is favored in most semi-empirical models. The other instabilities discussed by these authors may produce appropriate turbulence closer to the neutron star.

More generally, relativistic plasma emission is a plausible emission process that involves a natural extension of known physics from solar radio physics to the more exotic environment of pulsar magnetospheres. It should be regarded as the most favored mechanism for pulsar radio emission. The specific model of Beskin, Gurevich and Istomin (1986, 1988) is the most detailed available, and its authors claim that their model can account for all the important features of the observed pulsar radio emission. However, the instability mechanism of Beskin *et al.* has been criticized by Larroche and Pellat (1987). Wider acceptance or otherwise of this mechanism must await further discussion in the literature. It is desirable to develop alternative models, such as those suggested by the Georgian group and that discussed below, to the same level of sophistication as Beskin *et al.*'s model so that meaningful comparisons between the predictions of different theories can be made.

5. Free electron maser emission

The third coherent pulsar radio emission mechanism discussed here may be called either 'linear acceleration emission' (Cocke 1973, Melrose 1978, Kroll and McMullin 1979) or 'free electron maser emission'. The emission is attributed to the acceleration of the relativistic particles in the magnetosphere by a parallel electric field. If the electric field varies in space or time, the resulting emission can result in maser action. This is a direct maser mechanism, and as such has two attractive features. First, like curvature emission and unlike plasma emission, the particles emit the escaping radiation directly. Second, like electron-cyclotron maser emission and other maser processes, the source of free energy and the saturation level of the maser may be discussed using well established and relatively simple ideas. A major disadvantage of the mechanism is that there is no well established theory for the generation of the required parallel electric field. There is another difficulty in that the growth rate decreases strongly with increasing Lorentz factor of the particles (Melrose 1978), and this is difficult to reconcile with the known brightness temperature, *cf.* the discussion above following eq.(3). Malov and Malofeev (1981) and Gil (1983) have presented an independent argument that makes the required relatively small Lorentz factors difficult to reconcile with the observational evidence on pulsar radio emission.

Linear acceleration emission has been analyzed in detail by Rowe (1992). Rowe considered relativistic electrons in a superstrong magnetic field whose motion is modified by a large amplitude static longitudinal wave with the wave vector along the magnetic field. A Lorentz transformation allows one to treat the effect of any superluminal longitudinal wave. There is a resonance condition that determines ω and $k_\parallel$ of the emitted wave in terms of ω' and $k'_\parallel$ of the longitudinal wave. This is

$$\omega - k_\parallel v_{\rm D} = s(\omega' - k'_\parallel v_{\rm D}), \tag{8}$$

where s is an harmonic number and $v_{\rm D}$ is the *drift velocity*, which is a constant of the motion and is a complicated function of other parameters. To lowest second order in an expansion in the amplitude of the longitudinal wave, the drift velocity is equal to the initial velocity of the particle. The resonance process eq.(8) for $s = 1$ may be interpreted in terms of a scattering of small amplitude waves ω', $k'_\parallel$ into the waves ω, $k_\parallel$. Contributions from $s \neq 1$ appear when the amplitude of the longitudinal wave is not small, specifically when the parameter $eE/m\omega'$ is not a small number, where E is the maximum electric field in the wave.

Rowe evaluated the absorption coefficient and argued that it is negative in two separate regimes. Writing

$$\cos\theta_{\rm c} = \omega/kv_\phi, \quad v_\phi = \omega'/k'_\parallel, \tag{9}$$

where v_ϕ is the phase speed of the longitudinal wave, the absorption coefficient is of the form

$$\gamma(\omega) \propto (s\omega' - \omega)\partial f/\partial p_{\rm D}\,. \tag{10}$$

Using the resonance condition eq.(8) one finds that negative absorption is possible in the two cases ($k_\parallel = k\cos\theta$)

$$\omega < s\omega', \quad \theta > \theta_{\rm c}, \quad \partial f/\partial p_{\rm D} < 0, \tag{11a}$$

$$\omega > s\omega', \quad \theta < \theta_{\rm c}, \quad \partial f/\partial p_{\rm D} > 0. \tag{11b}$$

For $s = 1$ eq.(11a) may be interpreted as a form of induced or stimulated scattering; it is analogous to stimulated Raman scattering in which the energy in a laser line is pumped over into the Stokes line. Similarly, eq.(11b) corresponds to a maser-like process that is analogous to a form of stimulated Raman scattering in which energy is pumped over into the anti-Stokes line due to an inverted population of the scattering particles. In the former case the energy in the escaping radiation comes from the large amplitude wave which is damped as a consequence. This may be regarded as a form of nonlinear Landau damping. In the latter case the energy in the escaping radiation comes from the scattering particles. The latter case may be regarded as a form of *free electron maser emission.*

An attractive feature of this mechanism is that it involves two different regimes for the emission that depend on angle. It is tempting to identify the core and conal emissions in pulsars as corresponding to the regimes of eqs.(11b) and (11a), respectively. In this way one could hope to account for core and conal emissions as two parts of a single emission process. This idea has yet to be explored in detail.

6. Discussion and conclusions

To conclude this review it is appropriate to summarize the progress made over the past decade since IAU Symposium No. 95 *Pulsars*. The status of the three pulsar radio emission mechanisms discussed above are as follows:

1. *Coherent curvature emission* remains a conceivable emission mechanism for pulsars, but little progress has been made in overcoming the difficulties with it.
    (a) A fundamental difficulty is that the theory of bunching instabilities does not allow for any velocity dispersion of the emitting particles; no realistic treatment of emission by bunches can be formulated until this deficiency in theoretical development is rectified.
    (b) No adequate bunching mechanism has been identified, at least for polar cap models. An extreme form of bunching is required; specifically, the relativistic particles of a single sign need to form well separated bunches with a pancake shape with normal almost exactly along the field lines. Perhaps the most plausible bunching mechanism is that proposed in the context of an 'electrosphere' model for the pulsar electrodynamics by Rylov (1982), and Michel (1987, 1990).

    In view of the difficulties coherent curvature emission should not be regarded as the favored mechanism for pulsar radio emission, at least for polar cap models.

2. Considerable progress has been made in the formulation of *relativistic plasma emission.* A detailed model that treats the important stages of plasma emission has been presented by Beskin, Gurevich and Istomin (1986, 1988). This model contains some new ideas that require further critical discussion before they (or modifications of them) are accepted or rejected, *cf.* Larroche and Pellat (1987), for example.
    (a) The natural wave modes include Alfvén-like drift modes, referred to here as a

'curvature modes', whose existence depends intrinsically on the curvature inhomogeneity of the plasma.

(b) There is a reactive instability that causes turbulence in a curvature mode to grow; this instability is controversial however.

(c) Nonlinear wave-wave interactions in the plasma limit the growth of the instability and cause partial conversion of the turbulent wave energy into escaping radiation.

This model, or a revision of it, is likely to be a favored pulsar radio emission mechanism in polar cap models of pulsars for the foreseeable future. However, experience with the interpretation of plasma emission from the solar corona, where the data is much more detailed and the plasma properties are much simpler and more familiar, suggest that considerable caution is required is assuming that the important theoretical problems are close to being solved. In particular, it is relevant to note that streaming instabilities have fallen into disfavor for relativistic plasma emission in pulsars because the calculated growth rate is too small; but a similar situation applies for the generation of Langmuir waves in type III bursts in the interplanetary medium where the waves are known to grow despite the fact that the estimated growth rate seems too small, *e.g.*, Melrose and Goldman (1987). In view of this, a reasonable speculation is that a future model that invokes a more strongly growing but as yet unidentified streaming instability may be more favorable than present models.

3. Linear acceleration emission, described here as *free electron maser emission*, is attractive primarily because it is a direct maser emission mechanism. The weaknesses with the mechanism are that no viable mechanism has been proposed for the required large amplitude electrostatic waves, and that for the growth rate to be large enough the free energy must be in electrons with relatively small Lorentz factors and this is not readily reconciled with other requirements (Melrose 1978, Malov and Malofeev 1981). A particularly attractive feature of a more detailed analysis of the mechanism (Rowe 1990) is that it implies two distinct regimes of emission by a single distribution of particles. There is a natural cone $\theta = \theta_c$, and the two distinct regions [*cf.* eqs.(11a,b)] correspond to lower frequency emission at $\theta < \theta_c$ and higher frequency emission at $\theta > \theta_c$. These two regimes might account for core and conal emission, respectively.

Finally, while most authors adopt the polar cap model as the basis for discussion of pulsar radio emission, there are strong arguments for considering the alternative model based on the neutron star being charged. Radio emission within the framework of such a model has been discussed by Rylov (1982) and Michel (1987, 1990). It is desirable to explore the implications of such an electrosphere model on the observed properties of the radio emission in more detail.

In conclusion, among possible mechanisms for coherent pulsar emission at least four (or seven, if one distinguishes between possible forms of relativistic plasma emission) distinct mechanisms may be identified. In approximate order of plausibility in my opinion (pointedly, curvature emission by bunches does not rate a mention), these are:

1. Relativistic plasma emission, *e.g.*, in the general form discussed by Beskin, Gurevich and Istomin (1986, 1988). However, the possible instabilities need to be explored further, with four distinct candidates currently under consideration:
   (a) a streaming instability,
   (b) a curvature-driven instability,
   (c) an anomalous Doppler cyclotron instability, and
   (d) a drift-driven instability.
2. Free electron maser emission, *e.g.*, in the form proposed by Rowe (1990).
3. Maser curvature emission, as proposed by Chugunov and Shaposhnikov (1988).
4. Emission by sheets of charge due to a pair cascade in an electrosphere model, perhaps with an alternative emission mechanism, *e.g.*, modified versions of the mechanisms explored by Kahn and Lerche (1965).

Of these the model of Beskin, Gurevich and Istomin (1986, 1988) is the most detailed, and it is desirable that models based on the other possible mechanisms be developed to a corresponding level of detail to allow meaningful comparison with observations.