MASER PULSE EMISSION MECHANISMS

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ABSTRACT

The difficulties with "coherent" curvature emission by bunches of electrons formed through a streaming instability suggest that it cannot account for the observed radio emission for existing polar-cap models of pulsars. Amongst alternative maser mechanisms, that involving acceleration emission due to the electric fields in the waves generated by the bunching instability can account for the gross properties of the observed emission, provided that the relativistic electrons have $\gamma \lesssim 10$ in the wave frame.

1. INTRODUCTION

In polar-cap models for pulsars the most favoured radio emission mechanism is curvature emission by bunches of particles (Radhakrishnan 1969, Komesaroff 1970, Sturrock 1971, Ruderman and Sutherland 1975). The major problem with this proposed mechanism is in accounting for the required bunching. Bunching due to a streaming instability was proposed by Ruderman and Sutherland (1975) and this idea has been explored further by Hinata (1976a,b), Cheng and Ruderman (1977), Benford and Buschauer (1977), Hardee and Rose (1976) and Hardee and Morrison (1979), amongst others. It seems that the instability does not grow fast enough to account for the bunching with parameters currently thought plausible (Benford and Buschauer 1977, Hardee and Morrison 1979).

In the first part of this talk I shall discuss the difficulties encountered with curvature emission due to bunches which are formed through a streaming instability. One point I shall emphasize is the effect of a spread in Lorentz factors of the radiating particles. Next I shall summarize some of the proposed alternative bunching mechanisms and some of the alternative radio emission mechanisms. Then I shall concentrate on possible maser mechanisms. Throughout I restrict my attention to polar-cap models.

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Most of the mechanisms discussed here have been developed on the assumption that the radiating particles are relativistic electrons and/or positrons formed by decay of γ-rays into pairs (Sturrock 1971). (The only exception is Rylov's (1978) klystron mechanism.) In these models one expects the spread $\Delta\gamma$ in Lorentz factors γ to be large. In Ruderman and Sutherland's (1975) model, for example, the initial γ-rays are formed through curvature emission by $\approx 10^{12}$eV positrons, and the secondary electron-positron plasma is formed by the decay of these γ-rays into pairs. One expects $\Delta\gamma \approx \gamma$ in the secondaries because (a) curvature emission is broadband, and (b) in any individual decay $\gamma \to e^+ + e^-$ the energies of the e^+ and e^- can differ by an amount comparable with their mean energy. A large dispersion in velocity favours random phase processes rather than phase-coherent ones. A maser is a random-phase mechanism and emission by bunches is a phase-coherent mechanism.

2. BUNCHING DUE TO A STREAMING INSTABILITY

(a) Bunching Radiation

In the following discussion the bunching radiation is assumed to have the following property (Sturrock, Petrosian and Turk 1975, Melrose 1978). If $P(\underset{\sim}{k})$ is the power radiated per particle per unit volume of $\underset{\sim}{k}$-space, then the power radiated by a bunch is $|n(\underset{\sim}{k})|^2 P(\underset{\sim}{k})$ where $n(\underset{\sim}{k})$ is the spatial Fourier transform of the number density of particles. This theory presupposes that all the particles have the same velocity; we have no theory of bunching radiation which allows for a non-zero velocity dispersion. Note that the foregoing theory applies in the frame in which the spatial distribution of particles is time-independent. For bunches formed through a streaming instability the relevant frame is the wave frame (in which the phase speed of the wave is zero).

Let K' and K be the wave and laboratory frames respectively and let $\beta_\phi c$ be their relative velocity with $\gamma_\phi = (1 - \beta_\phi^2)^{-\frac{1}{2}}$. Let k_L' be the wavenumber of the fastest growing longitudinal wave in K'. In K this corresponds to a wave with $k_L = \gamma_\phi k_L'$ and $\omega_L \approx k_L c$. In K' the bunching radiation results in waves with $k' \lesssim k_L'$, $\omega' \approx k'c$. Under reasonable conditions this emission corresponds to $k \lesssim k_L$ and $\omega \approx kc$ in K.

(b) Velocity Dispersion

For a streaming instability to produce bunching it must be a phase-coherent disturbance which grows. This requires that the growth rate ω_I of the waves exceeds the bandwidth $\Delta\omega$ of the growing waves, i.e.

$$\omega_I \gtrsim k_L c \frac{\Delta\gamma}{\gamma^3} \qquad (1)$$

where $\Delta\omega \approx k_L \Delta v$ is assumed to be determined by the dispersion in velocities.

In K the maximum frequency ω_{max} of the resulting emission by bunches is of order $k_L c$ and hence (1) requires

$$\omega_I \gtrsim \omega_{max} \frac{\Delta\gamma}{\gamma^3} . \tag{2}$$

For most pulsars we have $\omega_{max}/2\pi \approx 1$ GHz. The growth rate ω_I has been estimated by Benford and Buschauer (1977) and Hardee and Morrison (1979) to be $\approx 2 \times 10^4 r^{-3/2}$ s^{-1} where r is radial distance in stellar radii. With some different assumptions Cheng and Ruderman (1980) derived a similar growth rate. With $\Delta\gamma \approx \gamma$, $\gamma^2 \approx 10^5$ and with $\omega_I = 2 \times 10^4 r^{-3/2}$, one finds that (2) cannot be satisfied for $r > 1$. It fails to be satisfied by a large factor for $r \approx 10$ to 100, which is considered plausible for the source region. Only for an extremely narrow velocity spread can (2) be satisfied in existing models.

This difficulty with the velocity spread exacerbates the difficulty that the growth of the instability is not fast enough (Benford and Buschauer 1977, Hardee and Morrison 1979).

(c) Trapping

A streaming instability leads to effective bunching only if the waves trap the particles (Hinata 1976b, Cheng and Ruderman 1977). The results of a more detailed investigation (Hinata 1976b) are reproduced by the following arguments.

To trap the particles the electrostatic potential ϕ' in K' must satisfy

$$e\phi' \approx \gamma' mc^2 . \tag{3}$$

The energy density $E'^2/4\pi = (k'_L \phi')^2/4\pi$ in the waves cannot exceed the total energy density $\gamma' n' mc^2$ in the particles. Using (3) this implies

$$k'_L \lesssim \frac{\omega_p}{c} , \tag{4}$$

where $\omega_p = (4\pi n' e^2/\gamma' m)^{\frac{1}{2}}$ is the invariant plasma frequency. The implied wavenumber $k_L = \gamma_\phi k'_L$ in K is compatible with that derived by Hinata (1976b). In K the emission by bunches is therefore restricted to

$$\omega \lesssim \omega_{max} \approx \gamma_\phi \omega_p . \tag{5}$$

The difficulty which arises with a restriction such as (5) is that given a source region and a model for the number density (more specifically for ω_p) one can compare the predicted and observed dispersion delays (Cordes 1978, Matese and Whitmere 1980). The predictions and observations are incompatible for models currently thought plausible.

(d) Coulomb Interactions

Cheng and Ruderman (1977) have pointed out that ϕ' must be large enough to overcome the tendency of Coulomb forces to disperse a bunch. Glossing over relativistic effects in the electric forces, this condition, together with (3), leads to a limit on the number N of particles per bunch,

$$N \lesssim \frac{\gamma' mc^2}{e^2 k'} \approx \frac{\gamma mc^2}{e^2 k} , \qquad (6)$$

where the final approximate equality involves $\gamma \approx \gamma_\phi \gamma'$ consistent with the neglect of relativistic effects in K' (in effect we assume $\gamma' \approx 1$).

The difficulty which arises with (6) is that the observed brightness temperature T_b just satisfies (Melrose 1978)

$$\kappa T_b \lesssim N\gamma mc^2 , \qquad (7)$$

where κ is Boltzmann's constant. With $T_b \approx 10^{31}$K and with the numbers chosen above (7) fails to be satisfied by about three orders of magnitude. However, Cheng and Ruderman (1980) estimated a similar limit on T_b and suggested that observations of micropulses imply only $T_b \approx 10^{26}$K, consistent with the limit.

3. ALTERNATIVE MECHANISMS

These various difficulties suggest that we should explore alternative bunching mechanisms and alternative emission mechanisms. Two alternative bunching mechanisms have been considered. Self-bunching due to radiation reaction has been suggested (e.g. Benford and Buschauer 1977) based on the work of Goldreich and Keeley (1971). However, the effect invoked seems intrinsically one-dimensional (Melrose 1978). Another bunching mechanism has been suggested by Cox (1979); the number of particles in a dilute stream injected into a dense plasma is self-limited by electromagnetic forces. The characteristic size of the resulting bunches is of order a skin depth, and the difficulty mentioned in connection with (5) arises.

Alternative (non-maser) emission mechanisms mostly fall into the general class of "plasma-emission", i.e. a two-stage process in which particle energy is converted into microturbulent energy which then produces escaping radiation due to nonlinear or mode-coupling processes. In a sense emission by bunches formed through a streaming instability falls into this class. A specific such mechanism has been developed by Kaplan and Tsytovich (1973, p. 267) and more recently Kawamura and Suzuki (1977) and Hardee and Morrison (1979) have made suggestions along these lines.

Rylov (1978) has proposed a klystron mechanism in which an instability bunches the electrons which radiate as a phased array. This mechanism could be regarded as a phase-coherent version of Melrose's (1978) maser mechanism. The klystron mechanism requires a negligible velocity dispersion, which is consistent with Rylov's (1976, 1977) and Jackson's (1976) models of pulsar magnetospheres.

4. MASER MECHANISMS

(a) Possible Masers

If the velocity dispersion is large then the relevant form of "coherent" emission is a maser mechanism. Curvature emission cannot lead to maser action (Blandford 1975, Melrose 1978). A cyclotron maser is possible but it would radiate at too high a frequency to be compatible with polar-cap models. The only remaining possibilities involve emission due to acceleration by electric fields. Maser action due to a parallel uniform electric field as proposed by Cocke (1973) is ineffective (Kroll and McMullin 1979). The electric fields must be either microscopic or varying.

(b) Chiu and Canuto's Mechanism

Chiu and Canuto (1971) and Virtamo and Jauho (1973) have invoked maser action due to bremsstrahlung (electron-ion collisions) in a strong magnetic field. The collision frequency must be significant, placing any possible source region in the surface regions of the neutron star. The "inverted population" is a relative drift of electrons and ions. The maser has the attractive feature of being broadband. Possible difficulties with the mechanism are (a) that there is no obvious preference for the frequencies $\approx$ 1 GHz observed, and (b) that it has not been demonstrated that the conditions required (on the relative drifts) should obtain in the inferred source region.

(c) Oscillating Electric Field

If a streaming instability does develop then maser action is possible due to the perturbed motion of particles in the oscillating (parallel) electric field (Melrose 1978). This mechanism operates irrespective of whether the waves are phase-coherent or phase-random. The "inverted population" required is that the distribution of particles be an increasing function of γ over some range. The maser is broadband operating at $\omega \lesssim \omega_0\gamma^2$ where ω_0 is a characteristic frequency of the electric field. Melrose (1978) assumed the electric field to be time-varying. The analysis is unaltered for a space-varying electric field with ω_0 reinterpreted as k_0c with k_0 a characteristic wavenumber. The optical depth τ for amplification for $E^2/4\pi \approx \gamma nmc^2$, $k_0c \approx \omega_p$ and for a path length limited by the curvature ρ of the field lines, is

$$\tau \approx \frac{\rho\,\omega_{max}}{c\gamma^7}, \tag{8}$$

with $\omega_{max} \approx \omega_p \gamma^2$. For reasonable parameters ($\omega_{max} \approx 2\pi \times 10^9$ s^{-1}, $\rho \approx 10^9$cm), $\tau >> 1$ requires $\gamma \lesssim 10$.

The major difficulty with this mechanism is the low values of γ required. It is worth emphasizing that the relevant value of γ in (8) is in the wave frame, i.e. γ in (8) should be γ'. If in fact γ is of order 10^2 to 10^3 in the laboratory frame, then we require (a) that we have $\gamma_\phi \approx 10$ to 10^2, and (b) that we have $\Delta\gamma' \lesssim 10$ in the wave frame. It is not clear whether these conditions are compatible with existing models, but it might be remarked that there is a desire to predict $\gamma \approx 10^2$ to 10^3 in existing models in order for the frequency $(c/\rho)\gamma^3$ of curvature emission to fall in the observed range. The plausibility of $\gamma' \lesssim 10$ requires further investigation.

This maser mechanism seems capable of accounting for the observed emission under conditions which are considered plausible in other models, with the exception of the condition $\gamma' \lesssim 10$. In addition due to the smaller value of ω_p required, the mechanism does not encounter the difficulty discussed in connection with (5) above.

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DISCUSSION

MICHEL: It seems to me that there may be a semantic point to be made. On one side you have density inhomogeneities radiating by oscillations instead of by curvature radiation. For "masering" one starts with velocity inhomogeneities but ends up with coherent radiation from density inhomogeneities. In a sense, then, one has radiation from "bunches" in either case.

MELROSE: I agree. Fixed phase and random phase instabilities are related, and bunching radiation and "plasma" emission are related, too. I am arguing against bunching radiation only in the specific sense used in connection with pulsars, specially a bunch radiating as a macro-charge.

SCHEUER: Can you get broad-band microstructure from your maser mechanism?

MELROSE: The maser mechanism itself is broad band and hence can produce broad-band microstructure. However, the maser output depends on the initial radiation being amplified, except when the maser is saturated.

ROSADO: Do you have an idea about the strength of the oscillating field needed to obtain the highest observed brightness temperatures of about 10^{31} K?

MELROSE: The electric field strength appears squared in the growth rate and consequently there is no simple relation between the electric field strength and the resulting brightness temperature.

MANCHESTER: What are the polarization characteristics of the oscillating electric field maser?

MELROSE: There is a specific direction in the mechanism, namely that of the electric field which is by assumption that of the background magnetic field. The radiation (at a given angle of propagation) is linearly polarized in this direction. The resulting linear polarization is orthogonal to that predicted for curvature radiation but there is no simple observational test which would obviously distinguish between them.