THEORETICAL PROBLEMS RELATED TO STELLAR RADIO EMISSION

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ABSTRACT. Some outstanding research problems relating to stellar radio flares are discussed. Emphasis is placed on "coherent" emission mechanisms for the very brightest bursts and on magnetic coupling between stars in a binary system.

1. INTRODUCTION

Formulating a theory for radio stars or for any other radioastronomical objects involves three stages: (i) the identification of the emission mechanism or mechanisms, (ii) the construction of a mathematical model for the source, and (iii) the use of the model to infer information about the source from the radio data. In identifying the emission mechanism, the brightness temperature T_B is particularly important; it allows us to estimate whether the source is thermal ($T_B \lesssim 10^6$ K for stellar coronae and winds), nonthermal and incoherent ($\kappa T_B \lesssim \varepsilon$, κ = Boltzmann's constant, ε = energy of radiating particles), and "coherent" ($\kappa T_B \gg \varepsilon$). Thermal emission from radio stars is attributed to stellar winds; in this case we are at stage (iii) in our theoretical interpretation. The emission from most flare stars has $T_B \lesssim 10^{10}$ K and so can be interpreted as incoherent gyrosynchrotron emission from electrons with energy < 1 MeV. Accepting the gyrosynchrotron interpretation we are at stage (ii) in this case. However it is not certain that emission with $T_B \cong 10^{10}$ K is incoherent rather than coherent. This point may be decided from the polarization; a source with $T_B \cong 10^{10}$ K would be optically thick if it were a gyrosynchrotron source and then it should be weakly polarized whereas a cyclotron maser source should be highly polarized. The very brightest emission ($T_B \gg 10^{10}$ K) from some flare stars, notably the M dwarfs, certainly requires a coherent emission mechanism. Although cyclotron maser emission seems the most plausible mechanism, there is one serious difficulty with it.

My brief for this paper is to point out some outstanding research problems in the theoretical interpretation of radio stars. The problems concerning stellar winds involve details of the models, specifically the

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matching of the predicted and observed frequency spectra. I do not propose to discuss these problems further. The standard problem connected with the gyrosynchrotron sources is the modelling of the magnetic structure and the particle spectra to account for the observed radio spectra. A particularly challenging problem with the radio stars in binary systems involves the magnetic coupling between the stars; this coupling is likely to provide the free energy for the acceleration of the gyrosynchrotron emitting electrons. I comment further on this problem in Section 4. My main interest is in the coherent emission mechanism: cyclotron maser emission is discussed in Section 2 and some qualitative comments on possible alternative plasma emission mechanisms are made in Section 3.

2. ELECTRON CYCLOTRON MASER EMISSION

Electron cyclotron maser emission has had a long history as a possible solar radio emission mechanism, e.g. the discussion by Hewitt et al. (1982), but it has become accepted as a plausible mechanism only over the past few years. The first major success was a theory by Wu and Lee (1979) for the auroral kilometric radiation (AKR). In discussing the theory here, I start by comparing and contrasting Wu and Lee's theory with an earlier one of my own (Melrose 1976) which had many but not all the attractive features of the later theory. I then discuss problems with the application of this theory to solar and stellar sources.

(a) The Parallel Driven Cyclotron Maser

A spiralling electron and a wave are said to resonate at the sth harmonic when the resonance condition

$$\omega - s\Omega - k_\parallel v_\parallel = 0 \qquad (1)$$

is satisfied. Here $\Omega = \Omega_e(1-\beta^2)^{\frac{1}{2}}$ is the electron's gyrofrequency, with Ω_e the nonrelativistic electron gyrofrequency, $v_\parallel = \beta_\parallel c$ and $v_\perp = \beta_\perp c$ are the velocity components and $k_\parallel = (N\omega/c)\cos\theta$ and $k_\perp = (N\omega/c)\sin\theta$ are the wavenumber components parallel and perpendicular to the magnetic field respectively, and N is the refractive index. For waves in a mode M(= x, o or z for the x-mode, o-mode or z-mode) the dispersion relation $N = N_M(\omega,\theta)$ is assumed to be satisfied. Let $f(\mathbf{p})$ be a distribution of electrons. Cyclotron maser emission at the sth harmonic occurs when the absorption coefficient $\gamma(\mathbf{k})$ is negative. The contribution from resonance at the sth harmonic to $\gamma_s(\mathbf{k})$ is of the form

$$\gamma_s(\mathbf{k}) = \int d^3\mathbf{p}\; A_s(\mathbf{k},\mathbf{p}) \left\{\frac{s\Omega}{v_\perp}\frac{\partial f(\mathbf{p})}{\partial p_\perp} + k_\parallel \frac{\partial f(\mathbf{p})}{\partial p_\parallel}\right\} \delta(\omega - s\Omega - k_\parallel v_\parallel), \qquad (2)$$

where $A_s(\mathbf{k},\mathbf{p})$ involves Bessel functions of order s and argument $k_\perp v_\perp/\Omega$. We may classify cyclotron masers as parallel-driven or perpendicular-driven depending on whether the dominant negative contribution comes from the terms $k_\| \, \partial f/\partial p_\|$ or $(s\Omega/v_\perp)\, \partial f/\partial p_\perp$ respectively.

If one makes the nonrelativistic approximation $p_\perp = m_e v_\perp$, $p_\| = m_e v_\|$, $\Omega = \Omega_e$, then the resonance condition (1) does not depend on $v_\perp$, the integral in (2) may be written in terms of $dv_\perp v_\perp dv_\|$ and the $v_\|$- integral performed over the 6-function. In this case there is no restriction on the $v_\perp$-integral, and one may perform a partial integration over the $\partial f/\partial p_\perp$ term

$$-\int_0^\infty dv_\perp v_\perp \, A_s(\underset{\sim}{k},\underset{\sim}{p}) \, \frac{s\Omega_e}{v_\perp} \frac{\partial f}{\partial v_\perp} = s\Omega_e \int_0^\infty dv_\perp f \, \frac{\partial A_s(\underset{\sim}{k},\underset{\sim}{p})}{\partial v_\perp} .$$

For waves with refractive index $N \lesssim 1$, only $s > 0$ is allowed and only $k_\perp v_\perp/\Omega \ll 1$ is relevant, then $\partial A_s/\partial v_\perp$ is positive and one concludes that the $p_\perp$-derivative cannot lead to maser emission. Thus in the nonrelativistic approximation the only possibility is a parallel-driven maser.

This nonrelativistic case was analysed by Melrose (1973,1976) using a bi-Maxwellian streaming distribution, which is a special case (j = 0) of the distribution

$$f(\underset{\sim}{p}) \propto \left(\frac{v_\perp^2}{V_\perp^2}\right)^j \exp\left[-\frac{v_\perp^2}{2V_\perp^2} - \frac{(v_\| - U)^2}{2V_\|^2}\right] . \tag{3}$$

In (3), U is a streaming speed, $V_\perp^2/V_\|^2 \neq 1$ describes a temperature anisotropy, and j = 1,2,3,... simulate loss-cone anisotropies. It was found that growth in the x-mode at s = 1 can occur when the following conditions are satisfied. (i) Negative absorption is restricted to frequencies below the center of the line at $\omega - \Omega_e - k_\| U = 0$, and $k_\| U$ must be large enough so that the center of the line is above the cutoff frequency for the x-mode. This requires $\omega_p^2/\Omega_e^2 \ll 1$, where ω_p is the plasma frequency, and

$$N_x \frac{U}{c} \cos\theta > \frac{\omega_p^2}{\Omega_e^2} . \tag{4}$$

(ii) For the driving term ($p_\|$-derivative) to overcome the stabilizing contribution from the $p_\perp$-derivative, one requires

$$\frac{V_\perp^2}{V_\|^2} > \frac{c}{\sqrt{2} N V_\| \left|\cos\theta\right|} \tag{5}$$

It is the condition (5) which is difficult to satisfy under plausible astrophysical conditions. Inclusion of a loss cone anisotropy leads to the left-hand side of (5) being replaced by $(j+1)\, V_\perp^2/V_\|^2$. Thus inclusion of a loss-cone anisotrophy ($j > 0$) is effectively equivalent to increasing $V_\perp^2/V_\|^2$ by the factor $(j+1)$. (Revision is required to the existing discussion of the nonrelativistic loss-cone instability given by

Goldstein and Eviatar (1979). These authors started from a formula for the absorption coefficient in which the sign of the $p_\perp$-derivative was erroneously taken to be opposite that in (2).)

(b) The Perpendicular-Driven Cyclotron Maser

The major advance made by Wi and Lee (1979) was recognizing that when Ω in (1) is approximated by $\Omega_e(1-\beta^2/2)$ the resonance condition (1) becomes a quadratic rather than-a linear equation for $v_\parallel$. The resonance condition may be interpreted in terms of a resonance ellipse in velocity space (Hewitt et al. 1981, 1982, Omidi and Gurnett 1982, Melrose et al. 1982). The integral in (2) is then around a semicircle $(v_\parallel-v_0)^2 + v_\perp^2 = v_R^2$ with $v_0 = k_\parallel c^2/s\Omega_e$ and $v_R^2 = v_0^2 - 2(\omega-s\Omega_e)\, c^2/sR_e$. The important qualitative points are: (i) the $v_\perp$-integration is then limited and for a loss-cone distribution (which has $\partial f/\partial v_\perp > 0$ at small $v_\perp$) the $p_\perp$-derivative in (2) can be destabilizing at every point around the contour of integration, (ii) $|k_\parallel c/\omega|$ is necessarily small for the semicircle to be in the region of velocity space populated by electrons, and this implies (a) emission at large angles to the magnetic field, and (b) that the term $k_\parallel \partial f/\partial p_\parallel$ in (2) is intrinsically small and relatively unimportant. This instability is driven by the p_+-derivative and so may be called <u>perpendicular-driven</u>.

In the application to **AKR** the instability is attributed to precipitating electrons which reflect as B increases, leading to a one-sided loss-cone distribution. Upward emission ($k_\parallel v_\parallel > 0$) is implied for these upward propagating electrons. It is this version of the cyclotron maser theory which has been applied to solar (Holman et al. 1980) and stellar (Melrose and Dulk 1982, Dulk et al. 1983) sources.

(c) Difficulties with the Cyclotron Maser Mechanism

A difficulty with the cyclotron maser theory for solar and stellar applications is that in order to escape radiation generated at $s = 1$ must pass through layers where ω is equal to $2\Omega_e$, $3\Omega_e$ etc. Three ways of overcoming this difficulty have been suggested: (i) the radiation may escape through the "window" at small sine (Holman et al. 1980) (the optical depth is proportional to $\sin^2\theta$ and so is necessarily < 1 for sufficiently small sine), (ii) the escaping radiation is generated by the maser at $s = 2$ (Melrose and Dulk 1982), (iii) the maser generates z-mode waves at $\omega > \Omega_e$ and the escaping radiation results from the coalescence of two z-mode waves into o-mode or x-mode radiation at $\omega \gtrsim 2R_e$ (Melrose et al. 1984).

Suggestion (i) encounters the difficulty that it would require a very special source structure for radiation emitted at $\theta \cong \pi/2$ at $\omega \cong \Omega_e$ to arrive at the layer $\omega \cong 2\Omega_e$ at sine $\cong 0$. It might appear that this difficulty can be overcome by appealing to the parallel-driven maser which does generate radiation at small sine. However, if the requirement (5) can ever be satisfied it is likely to be for downgoing (into increasing B) electrons and then the maser emission is initially directed downwards; thus a change in θ by " 180°, rather than s 90° for the perpendicular-driven maser, would seem to be required. No plausible source model based on either maser mechanism has been developed.

The difficulty with suggestion (ii) is twofold. The maximum growth rate at the sth harmonic for either the parallel-driven or the perpendicular-driven maser is of the form

$$|\gamma_{\max}| \cong \xi_s(\theta)\,\frac{n_1}{n_e}\,\frac{\omega_p^2}{\Omega_e}\,\langle\beta_\perp^2\rangle^{s-2} \quad , \tag{6}$$

where $\xi_s(\theta)$ is a factor of order unity, n_1/n_e is the ratio of the precipitating to the thermal electrons and $\langle\beta_\perp^2\rangle$ is the average of $\beta_\perp^2$ over the distribution function. Effective growth at $s = 2$ requires (a) that the much faster growth at $s = 1$ be suppressed, and (b) that $|\gamma_{\max}|$ at $s = 2$ be sufficiently large for growth at $s = 2$ to be optically thick. Requirement (a) can be satisfied for $\omega_p/\Omega_e \gtrsim 0.3$ (Hewitt et al. 1982) and there is then a range of ω_p/Ω_e where growth of either the z-mode or the o-mode at $s = 1$ or the x-mode at $s = 2$ is favored. Although this leads to hope that either suggestions (ii) or (iii) might overcome the difficulty, to date there is no plausible model which clearly demonstrates that this is the case.

Besides this difficulty with thermal absorption, there are other basic problems in formulating a model based on the cyclotron maser mechanism. One concerns the relation between the large and the small scales. Maser emission saturates quickly and so is restricted to localized regions (Melrose and Dulk 1984). In view of this it is by no means clear how one incorporates the basic physics (calculations of growth rates etc.) into a large scale model for an astrophysical maser. A related problem is that maser emission must be driven continuously; it requires a "pump" just as does a laboratory maser or laser. The relatively long duration of stellar flares requires that this deriving mechanism operate continuously over the observed timescale. For the perpendicular-driven maser one requires a continuous supply of precipitating electrons. Moreover these electrons must be forced to precipitate, as in AKR; a dribble of precipitating particles from a trapped electron distribution is inadequate. This leads to a third problem in the formulation of a model: an acceleration mechanism and a source of free energy is required. The coherent radio emission is not restricted to stars in binary systems and so the source of free energy is not necessarily associated with magnetic coupling between stars. Flaring correlates with rapid rotation in convective stars (e.g. Bopp 1980), and presumably the driving mechanism for the maser emission is similar to that in solar spike bursts and is associated with a solar-type flare.

One may conclude that the formulation of an acceptable model based on the cyclotron maser mechanism involves some formidable problems.

3. PLASMA EMISSION AND STELLAR FLARES

The dominant radio emission mechanisms for solar radio bursts are gyrosynchrotron emission in the microwave range and plasma emission at decimeter, meter and longer wavelengths. I define "plasma emission" to include any mechanism which involves conversion of plasma microturbulence into escaping radiation. In solar decimeter-wave bursts the effect of the magnetic field on the microturbulence seems to be important and upper-hybrid and Bernstein modes are probably involved, e.g. the reviews by Kuijpers (1980) and elsewhere in these Proceedings. At meter and longer wavelengths the magnetic field is weak, in the sense $\Omega_e \ll \omega_p$, and the microturbulence involves Langmuir waves.

Consideration of possible analogs for solar bursts leads to two alternatives to the cyclotron maser mechanisms for stellar flares. First, the emission could be due to many unresolved type III-like bursts. The solar bursts would need to be scaled up to higher frequencies. This scaling in itself presents a difficulty because collisional damping becomes stronger at higher plasma frequencies. Also the brightness temperature T_B would need to be scaled up: the maximum T_B observed for type III bursts in the solar corona is $\cong 10^{13}$ K compared with $\cong 10^{15}$ K for some stellar flares. Also type III bursts are only weakly polarized and one would need to invoke some additional mechanisms, such as thermal absorption at $s = 3$ which eliminates the x-mode component to produce the observed high polarization of some stellar flares. A final difficulty is energetic: it is estimated that only $\cong 10^{-3}$ of the solar energetic electrons escape to produce type III bursts with the net conversion efficiency $< 10^{-10}$ for the radio power compared to the power going into electron acceleration. These difficulties seem formidable, but in view of the difficulties with the cyclotron maser theory, it would be worthwhile exploring such an alternative model.

Another variant on plasma emission involves Langmuir (or other) waves generated by a loss-cone anisotropy, as has been proposed for decimeter-wave bursts (e.g. Kuijpers 1980), type I bursts (Melrose 1980, Benz and Wentzel 1981) and microwave flare kernels (Zaitsev and Stepanov 1983). A detailed discussion of the growth of the Langmuir waves has been presented recently by Hewitt and Melrose (1984). A further alternative model could be based on this mechanism. The difficulties are similar to those with the type III model mentioned above. However the energetic requirements are less severe.

4. MAGNETIC COUPLING AND ELECTRON ACCELERATION

It seems that the radio emission from most flare stars can be explained in terms of gyrosynchrotron radiation. For the RS CVn stars, for example, the radio brightness temperature may not exceed about 10^{10} K, and if this is the case then it is probably unnecessary to invoke a coherent emission mechanism. If we accept the gyrosynchrotron hypothesis, the question arises as to how the electrons are accelerated, and this leads to the underlying question of the source of free energy. At least for the RS CVn stars and the AM Her stars it is plausible that the ultimate source of the free energy is from magnetic coupling between the two stars in a binary system.

The magnetic coupling between stars is not understood. Three types of model have been envisaged. The central problem is that in the ideal MHD approximation, as the stars rotate and move around their orbits, the magnetic field lines would be wound up indefinitely. One way of overcoming this is to invoke dissipation or magnetic reconnection (Bahcall et al. 1973, Treves 1978, Joss et al. 1979, Lamb et al. 1983). The build up of magnetic stresses is minimized, but not eliminated, for stars in synchronous rotation. The idea is that the system finds a magnetic configuration in which dissipation in a localized region or regions allows the build up in magnetic stresses to be continuously relaxed. The details are ill-defined. The second type of model is based on an assumed analogy with the 10-Jupiter system (Dulk et al. 1983, Chanmugam and Dulk 1983) in that one star is regarded as a conductor moving through the magnetic field of the other. However, again the details are somewhat uncertain, especially in view of recent changes in ideas concerning the 10-Jupiter system (e.g. Neubauer 1980, Goertz 1983). In the third approach (Uchida and Sakurai 1983) the distribution of field lines threading between the two stars is calculated under specified boundary conditions.

A much more systematic and thorough investigation of the magnetic coupling is required. One interesting point arising from the existing literature is that the rate of energy dissipation may be only weakly dependent on the model. Typically it seems that when a conducting object (one star) of area A moves with speed v through an ambient field B (due to the other star) free energy becomes available at a rate of order $(B^2/2\mu_0)$ Av. It would be desirable to confirm this and determine the condition under which it applies.

Finally there is the problem of electron acceleration. Again this is poorly understood. Magnetic dissipation, double layers and small-amplitude Fermi acceleration are all possible mechanisms. Realistically the best one can hope to achieve at our present level of understanding is to modify proposed models for acceleration in the solar corona (e.g. Chapter 4 of Sturrock 1980) to the stellar sources. I know of two such models currently in press (Kuijpers and van der Hulst 1984, Bogdan and Schlickeiser 1984).

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