Two Alternative Mechanisms for Very Bright Radio Emission from Flare Stars

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Abstract: The bright radio emission from flare stars has three characteristic properties: high brightness temperature, high degree of circular polarisation and rapid temporal variations. Two proposed emission mechanisms, electron cyclotron maser emission (ECME) and plasma emission, are compared and contrasted. It is argued that although the important features of the emission can be explained in terms of either ECME or plasma emission, all three favor ECME. However, the escapes of the radiation through the second harmonic absorption layer remains inadequately understood, and as a consequence doubts about the ECME interpretation remain.

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1. Introduction

The radio emission from flare stars consists of at least two distinct components. (a) Most of the observed emission has brightness temperature $T_B \lesssim 10^{10}$ K and is consistent with gyrosynchrotron emission from mildly relativistic electrons. (b) The very bright emission, $T_B \gg 10^{10}$K, seen sporadically from some stars requires a coherent emission mechanism (e.g., Dulk 1985; Kuijpers 1985, 1989; Bastian 1990; Haisch, Strong and Rondono 1991). The discussion in this paper is concerned entirely with the latter type of emission, which is characterised by high brightness temperature, high degree of circular polarisation, and burstiness involving time-scales as short as milliseconds (e.g., Lang *et al.* 1983, Lang and Willson 1986, Güdel *et al.* 1989, Bastian 1990). Incoherent emission due to any emission process is limited by absorption so that the brightness temperature, T_B, cannot exceed, approximately, the kinetic energy of the emitting particles divided by Boltzmann's constant, k. The rest energy, m_ec^2 of the electron defines a temperature $T_B = m_ec^2/k = 5 \times 10^9$K. Hence, a source with $T_B \gg 10^{10}$ cannot be due to incoherent emission by nonrelativistic electrons. A coherent emission mechanism is required, and electron cyclotron maser emission (ECME) (Melrose and Dulk 1982) and plasma emission (e.g., Kuijpers 1985) are the only two plausible candidates. ECME involves emission at the fundamental of the electron cyclotron frequency, $f_B = 30B$ GHz, where B is in tesla, or perhaps at low harmonics of this frequency. It is the accepted emission mechanism for the auroral kilometric radiation (AKR) from the Earth, the decametric radio emission (DAM) from Jupiter (e.g., Melrose 1976, Wu and Lee 1979, Melrose, Rönnmark and Hewitt 1982, Omidi and Gurnett 1982, Hewitt, Melrose and Rönnmark 1982; Wu 1986) and analogous emissions from the other giant planets (e.g., Leblanc 1990). It is also favored for solar spike bursts (Holman, Eichler and Kundu 1980, Melrose and Dulk 1982, Benz 1986), which are widely assumed to be solar analogs of the stellar bursts. However, there is a difficulty in accounting for the escape of fundamental ECME through the solar corona (Melrose and Dulk 1982), and a similar difficulty applies to ECME from flare stars. Plasma emission, which is the emission mechanism for most meter-wave solar radio bursts, involves emission at the fundamental or second harmonic of the plasma frequency, $f_p = 0.9 \times 10^{-8}\, n_e^{1/2}$ GHz, where n_e is the electron number density per cubic meter.

In this paper, the properties of these two emission mechanisms, as applied to the very bright emission from flare stars, are compared and contrasted. The predicted properties of ECME and plasma emission include the maximum brightness temperature, which is estimated here using an argument based on saturation of maser emission, and the degree of (circular) polarisation. The success (or otherwise) of the predicted properties in explaining solar radio bursts is relevant in assessing the level of confidence to weight give to the predictions for flare stars, and the properties of solar radio bursts are reviewed where appropriate here.

The interpretation of the brightness temperature is discussed in section 2 and the interpretation of the polarisation is discussed in section 3. Possible solar analogs of the radio bursts from flare stars are then considered in section 4, and the conclusions are summarised in section 5.

2. Interpretation of the Brightness Temperature

The actual value of T_B provides a constraint on the emission process. It is argued in this section that high values of T_B at high frequencies tends to favor ECME rather than plasma emission.

(a) Observed brightness temperatures

The emitting areas for the brightest emissions from flare stars are uncertain, leading to uncertainty in estimates of their brightness temperatures. Dulk (1985), assuming source sizes of order the size of the stellar disk, estimated $T_B \sim 10^{12}$–10^{15}K. More recently, Bastian *et al.* (1990) estimated $T_B \sim 10^{16}$ K, and Wentzel and Aschwanden (1991), suggesting that the source size might be as small as 200km, estimated $T_B \sim 10^{17}$–10^{20} K. Mullan (1985) had earlier estimated $T_B \sim 10^{20}$ K for one stellar flare.

The inferred brightness temperatures for solar spike bursts can be estimated from the observed intensity and an area estimated from the rise time of the bursts. Assuming a rise time <1 *ms*, implying a light propagation distance <300 km, one estimates between $T_B \sim 10^{13}$ K (Dulk 1985) and $T_B \sim 10^{15}$ K (Benz 1986). The inferred maximum brightness temperatures for other solar bursts, such as type II and type III, generated by plasma emission is somewhat lower ($T_B \sim 10^{13}$ K); the maximum brightness temperatures increases with decreasing frequency as the type III stream propagates outward into the interplanetary medium (e.g., Melrose 1989a).

The brightness temperatures of the brightest emission from flare stars is brighter than the brightest emission at comparable frequencies from the Sun. That is, the emission is intrinsically brighter, and not simply from a larger emission region.

(b) Expected brightness temperature

The maximum brightness temperature implied by theory may be estimated relatively simply if the maximum is due to saturation of a maser process. Here only the simplest theory is considered for semi-quantitative purposes. More sophisticated theories are available, cf. Wentzel and Aschwanden (1991) on saturation of ECME, but the uncertainty in the value of T_B is such that the simplest semi-quantitative estimate should suffice for present purposes.

Saturation occurs when the source of free energy driving the maser is exhausted. This occurs when the energy density in the radiation is approximately equal to the free energy density, W_f, available in the suprathermal particles that drive the maser. The energy density in the radiation, $\kappa T_B/V_c$, is determined by T_B and the coherence volume of the emission, V_c. Hence, saturation occurs for

$$\kappa T_B = W_f V_c = \eta_f W_p V_c, \tag{1}$$

where η_f is the fraction of the total energy density in suprathermal particles, W_p, that is available as free energy. The coherence volume is the inverse of the volume of **k**-space that the radiation fills:

$$\frac{1}{V_c} = \mu\Delta\Omega\ \frac{\Delta f}{f_B}\left(\frac{f}{c}\right)^3 \tag{2}$$

where $\Delta\Omega$ is the range of solid angle, Δf is the bandwidth of the emission and where the refractive index is assumed to be given by $\mu = (1 - f_p^2/f^2)^{1/2}$.

The relations (1) and (2) lead directly to an estimate for the maximum brightness temperature for ECME. They may also be applied to plasma emission. This is because the generation of the Langmuir waves is due to a maser-like process (the bump-in-tail instability) that saturates when the effective temperature of the Langmuir waves satisfies (1) (e.g., Melrose 1986, p. 48), and the conversion into fundamental or second harmonic emission saturates at the same value to within a factor of order unity (e.g., Melrose 1986, p. 95). This simple saturation theory seems to account reasonably well for the brightness temperatures of type III bursts in the interplanetary medium (Melrose 1989a).

For ECME it is convenient to express the brightness temperature in terms of the ratio $\kappa T_B/m_e c^2$, with $\kappa T_B = m_e c^2$ corresponding to $T_B = 5 \times 10^9$ K. Then (1) and (2), with $\mu = 1$ and (2), give

$$\frac{\kappa T_B}{m_e c^2} = \frac{\eta_f \pi c}{2\Delta\Omega r_0 \Delta f}\ \frac{W_p}{W_m} \tag{3}$$

where $W_m = B^2/2\mu_0$ is the magnetic energy density, and r_0 is the classical radius of the electron.

For plasma emission the refractive index $\mu \neq 1$ needs to be retained in (2). In this case it is convenient to consider the ratio T_B/T_e of the brightness temperature to the ambient electron temperature. The resulting expression, to be compared with (3), is

$$\frac{T_B}{T_e} = \frac{\eta_f \pi c}{\mu\Delta\Omega\, r_0 \Delta f}\ \frac{W_p}{n_e \kappa T_e}, \tag{4}$$

with an additional factor of 4 required in the denominator for second harmonic emission.

Let us compare (3) and (4) for given radiation, that is for given $\Delta\Omega$ and Δf. First, suppose that the right hand sides of (3) and (4) are comparable. Then the brightness temperature for ECME is predicted to be higher than for plasma emission by the factor $m_e c^2/\kappa t_e$, which is $\sim 10^3$ in cases of interest. Now consider the right hand sides of (3) and (4). The factor W_p/w_m in (3) for ECME can be a significant fraction of unity for electrons accelerated due to magnetic reconnection. In comparison, suppose the factor W_p/W_T, with $W_T = n_e \kappa T_e$ the energy density of the thermal electrons, in (4) is due to suprathermal electrons streaming from a region where they are accelerated, as in type III bursts. Then this factor should decrease away from the acceleration region. The factor is relatively small ($\lesssim 10^{-5}$) for type III bursts in the solar corona, and so might also be expected to be small for any stellar counterpart of such plasma emission. It follows that it is plausible that the right hand side of (3) for ECME is larger than the right hand side of (4) for plasma emission. It follows that it is much easier to account for high brightness temperatures in terms of ECME than in terms of plasma emission.

3. The Polarisation of Bright Stellar Radio Emission

The high degree of circular polarisation observed in the brightest emission from flare stars is usually taken as favoring the interpretation in terms of ECME. Although this assumption should not be accepted uncritically, the following discussion suggests that a very high degree of circular polarisation does favor ECME.

(a) Expected polarisation for ECME

Simple theory implies that ECME should be completely polarised in the sense of the x-mode of magnetoionic theory (e.g., Melrose, Hewitt and Dulk 1984). For $f_p << f_B$ this corresponds to elliptical polarisation, with the polarisation ellipse defined by the projection onto the plane transverse to the direction of wave propagation of the electron motion in plane perpendicular to the magnetic field. The observed polarisation of AKR from the Earth (e.g., Shawhan and Gurnett 1982), of Jupiter's DAM (Lecacheux *et al.* 1991; Dulk, Lecacheux and Leblanc 1991) and of the analogous emissions from the other giant planets support the prediction of nearly complete polarisation in the sense of the x-mode. The polarisation of solar spike bursts is sometimes complete in the predicted sense, but the degree of polarisation can be anywhere between zero and unity (Güdel and Zlobec 1991), often with a characteristic intermediate value that is not a strong function of frequency (e.g., Benz 1986). The simplest interpretation of the sense of polarisations is that it corresponds to the x mode (Güudel and Zlobec 1991).

A major ongoing difficulty with the interpretation of solar spike bursts in terms of ECME is that simple theory implies that the emission cannot escape from the solar corona, due to very strong absorption at the second harmonic layer, where the wave frequency is equal to twice the local cyclotron frequency (Melrose and Dulk 1982). There are various suggestions as to how this difficulty might be overcome (e.g., McKean *et al.* 1989, Robinson 1989). The predicted degree of polarisation may be influenced strongly by the way this difficulty is resolved. For example, the suggestion by Robinson (1989) involves escape of o-mode radiation.

(b) Expected polarisation for plasma emission

Simple theory predicts that fundamental plasma emission should be completely polarised in the sense of the o-mode of magnetoionic theory, and that the second harmonic should be weakly polarised in the same sense (e.g., Melrose 1985). Observations of the polarisation of solar radio emission are consistent with the prediction of emission favouring the o-mode. Also some fundamental emission is completely polarised, notably type I emission. However, fundamental emission in type II and type III emission is never completely polarised: the polarisation can vary from

0 to about 70% under different conditions (Suzuki and Dulk 1985). The less than complete polarisation of fundamental type II and type III emission suggests that there is a depolarising mechanism that reduces the polarisation between the source and the observer. Observational support for this suggestion is provided by the observation that the polarisation of type I emission for a given active center decreases systematically as the source moves away from the central meridian (Zlobec 1975). A similar variation occurs for solar spike bursts (Güdel and Zlobec 1991). One interpretation involves three ingredients: (i) the radiation is preferentially emitted in (or refracted into) the radial direction, (ii) radiation that reaches us directly is highly polarised, and (iii) radiation from sources away from the central meridian reaches us only after being reflected off some coronal structure (Wentzel, Zlobec and Messerotti 1986, Melrose 1989b). The reflection produces a mixture of the two modes and so reduces the degree of polarisation.

The expected polarisation for second harmonic plasma emission is low. Moreover, emission at high frequencies favours second harmonic emission versus fundamental emission, which experiences much stronger collisional damping (e.g., Dulk 1985).

4. Solar Plasma Emission Analogs for Stellar Bursts

The third of the characteristic features of stellar radio bursts is that they have time-scales as short as about a millisecond. In discussing possible solar analogs of these bursts, this third property needs to be taken into account. The favoured analog is solar spike bursts, which have appropriately short temporal variations (e.g., Güdel and Benz 1990). However, spike bursts are not always as highly polarised as simple theory implies. Let us therefore consider possible alternative solar analogs due to plasma emission.

There are four possible analogs on which to base a plasma-emission theory for the very bright emission from flare stars: these are types I—IV emission, with type V seemingly a variant on type III (e.g., Suzuki and Dulk 1985). Much of what was previously called type IV emission is now referred to as flare continuum and divided into several classes (e.g., Robinson 1985). Moving type IV bursts are due to gyrosynchrotron emission and is neither sufficiently bright nor sufficiently highly polarised to explain the stellar bursts. The early flare continuum (denoted FCE), and a similar continuum (denoted FCII) that is associated with type II bursts, lasts for about 30 minutes or so, extends to relatively high frequencies and has a polarisation that evolves from low to nearly 100% (Robinson 1985). The late phase of FCE is closely related to type I emission, in the sense that FCE can evolve into a type I storm.

Of these four possibilities, only an analogy with type III bursts seem capable of accounting for the short duration of some stellar bursts. Type II emission involves the passage of a shock wave through the corona and lasts for tens of minutes, and FCE, FCII and type I storms persist for even longer. On the other hand, only the late stages of FCII and FCE, and type I storms seem capable of accounting for the 100% polarisation of stellar bursts. Thus there seems to be an anti-correlation between short duration and high polarisation in solar bursts due to plasma emission. This suggest that plasma emission is not particularly favorable for the bright, highly polarised, short duration, stellar radio bursts.

A theoretical argument that supports the conclusion that plasma emission cannot readily account for the high degree of polarisation of the stellar bursts. The argument is based on the preferential collisional damping of fundamental plasma emission compared to second harmonic plasma emission (e.g., Dulk 1985). The higher frequency of stellar bursts (compared to solar bursts) favors second harmonic emission versus fundamental emission, and hence one would expect low polarisation at high frequencies in any model based on plasma emission.

5. Discussion and Conclusions

The characteristic features of the very bright radio emission from flare stars are high brightness temperatures, high degree of circular polarisation and possible burstiness of short duration. All three features favor ECME versus plasma emission. The arguments may be summarised as follows.

1. Comparison of (3) and (4) shows that, at a given frequency, it is easier to account for a higher brightness temperature in terms of ECME than in terms of plasma emission, and this is consistent with the observed brightness temperatures of solar radio bursts. The high observed brightness temperature for flare stars is more readily explained in terms of saturation of ECME versus saturation of plasma emission.
2. The high degree of circular polarisation favours ECME because, although some solar plasma emission sources (type I emission and the flare continuum) can show very high polarisation, these are not plausible analogs for the stellar emission. Either the solar sources are not particularly bright, they are restricted to lower frequencies, or they show no rapid variability. Moreover, solar observations support the theoretical suggestion that, at the highest frequencies, collisional damping favours second harmonic versus fundamental plasma emission, and second harmonic emission is weakly polarised.
3. The millisecond time-scale favours ECME versus plasma emission because of the assumed analogy between stellar bursts and solar spike burst (which exhibit changes on such a time-scale) coupled with the interpretation of spike bursts in terms of ECME.

Although there are counter-arguments to each of these three arguments, in each case the simplest interpretation favours ECME. Thus, although each of the foregoing three features could be explained in principle in terms of either ECME or plasma emission, taken together, all three are more readily explained in terms of ECME than of plasma emission.

It is concluded the ECME should be the favoured mechanism for the interpretation of the brightest radio emission from flare stars. However, a major problem remains: a convincing explanation as to how the radiation escapes through the second harmonic absorption layer is needed before the ECME interpretation can be fully convincing.

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