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ELECTRON-CYCLOTRON MASER EMISSION DURING SOLAR AND STELLAR FLARES

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ABSTRACT. Radio bursts, with high brightness temperature ($\gtrsim 10^{10}$K) and high degree of polarization, and the heating of the solar and stellar coronae during flares have been attributed to emission from the semi-relativistic maser instability. In plasmas where the electron-plasma frequency, ω_p, and the electron-cyclotron frequency, Ω_e, are such that $\omega_p^2/\Omega_e^2 \ll 1$, x-mode growth dominates while z-mode growth dominates if ω_p^2/Ω_e^2 is of order unity. The actual value of ω_p^2/Ω_e^2 at which x-mode growth dominates is shown to be dependent on the plasma temperature with x-mode growth dominating at higher ω_p/Ω_e as the plasma temperature increases. Observations from a set of 20 impulsive flares indicate that the derived conditions for the dominance of x-mode growth are satisfied in about 75 percent of the flares.

1. INTRODUCTION

Emission from the semirelativistic maser instability has been proposed as the source of very bright (brightness temperature greater than about 10^{10}K) and highly polarized radio bursts from the sun and flare stars (Holman et al., 1980; Melrose and Dulk, 1982a). It has also been proposed that absorption of radiation from this instability above the source region produces the heating of solar and stellar coronae during flares (Melrose and Dulk, 1982b, 1984).

The maser instability arises when electrons within the flaring flux tube are accelerated in an energy release region. Energetic electrons with small pitch angles precipitate (producing hard X rays) and are lost from the flux tube whereas electrons of higher pitch angle mirror at some point along the flux tube. The resultant distribution, f, above this mirror point has a loss-cone anisotropy. This distribution in the vicinity of the loss cone has a positive gradient with respect to $v_\perp$, the magnitude of the velocity perpendicular to the magnetic field (i.e. $\partial f/\partial v_\perp > 0$). Waves with frequency close to the electron-cyclotron frequency, Ω_e, and possibly at harmonics of Ω_e, can tap the free energy available from a positive $\partial f/\partial v_\perp$ and grow.

The mode in which the radiation is emitted is dependent on the plasma conditions. For a plasma in which the bulk of the electrons are cold and where the energetic electrons comprise only a small fraction of the total electron density, the maser instability produces x-mode growth if $\omega_p/\Omega_e \lesssim 0.3$ where ω_p is the electron plasma frequency (Hewitt et al., 1983; Wu and Qui, 1983; Melrose et al., 1984). This radiation can escape from the source region and, depending on the plasma conditions, can be reabsorbed at a second harmonic resonance layer thereby heating the corona. For $0.3 \lesssim \omega_p/\Omega_e \lesssim 1.3$, z-mode growth dominates. This radiation, unlike x-mode radiation, cannot escape directly from the source region. Local plasma heating can occur via the absorption of the z-mode radiation but heating of the corona above the flare site must occur via some other process. One such process, suggested by Melrose and Dulk (1984), is that second harmonic x-mode radiation produced by the coalescence of z-mode waves is partially absorbed at a third harmonic resonance layer. The component of the radiation which is absorbed then produces heating of the corona while the remainder escapes to produce the observed radio bursts.

The assumption that the bulk of the electrons are cold is not valid for the source of the maser emission during solar and stellar flares. In this paper, conditions for the suppression of x-mode growth in a hot plasma are derived (Sections 2 and 3) and implications for the heating of the corona are discussed (Section 4). A summary of the results is given in Section 5.

2. CONDITIONS FOR GROWTH AND DAMPING

The semirelativistic maser instability is driven by gyroresonant electrons, i.e. by electrons with velocity, $\mathbf{v}$, such that $\omega - \Omega_e/\gamma - k_z v_z = 0$ where ω is the wave frequency, k_z is the component of the wave-number parallel to the magnetic field and $\gamma = (1 - v^2/c^2)^{-1/2}$ is the Lorentz factor. In the semirelativistic limit i.e. $0 < v^2/c^2 \ll 1$ and $\omega^2 \gg k_z^2c^2$, the resonant electrons lie in velocity space on the semi-circle with centre (Hewitt et al., 1981)

$$v_z/c = k_z c/\omega, \qquad v_\perp/c = 0$$

and radius

$$v_r^2/c^2 = (k_z c/\omega)^2 - 2(\omega - \Omega_e)/\Omega_e.$$

For there to be a finite number of resonant electrons present the radius of the resonance circle must be real i.e.

$$(k_z c/\omega)^2 > 2(\omega - \Omega_e)/\Omega_e.$$

Growth occurs if the resonance circle samples sections of the distribution, f, where $\partial f/\partial v_\perp$ is predominantly positive; damping occurs if it samples regions where $\partial f/\partial v_\perp$ is negative.

The electron distribution in the flaring magnetic flux tube is assumed to be

$$f = ((2\pi)^{1/2} v_T)^{-3} (v_\perp/\sqrt{2} v_T)^2 \exp(-v^2/2v_T^2)$$

where v_T is the thermal speed. This distribution has a similar form as a two sided loss-cone distribution and related types of distributions have been used in discussions of the semirelativistic maser instability (e.g. Wu and Lee, 1979; Hewitt et al., 1981).

For this distribution, (1) - (3) imply that growth occurs if

$$0 < (k_z c/\omega)^2 - 2(\omega - \Omega_e)/\Omega_e \lesssim 2v_T^2/c^2$$

and damping occurs if the reverse of the last inequality in (5) is satisfied.

3. SUPPRESSION OF X-MODE GROWTH

For certain ω_p/Ω_e, x-mode growth cannot occur because the number of electrons which lie on a resonance circle satisfying (3) and (5) is exponentially small. In particular, the x mode has a cutoff which, for $v_T^2/c^2 \lesssim \omega_p^2/\Omega_e^2 \lesssim 1$, is given by (Winglee, 1985)

$$\omega_x = \Omega_e(1 + \omega_p^2/\Omega_e^2 - 9v_T^2/2c^2).$$

This frequency is the minimum frequency obtainable for the x mode and hence, from (3) and (6), there is a finite number of resonant electrons only if

$$(k_z c/\omega)^2 \geq 2(\omega_p^2/\Omega_e^2 - 9v_T^2/2c^2).$$

The number of electrons along a resonance circle which samples regions where $\partial f/\partial v_\perp$ is positive becomes exponentially small when the centre of the resonance circle moves past the root mean square axial velocity of the electrons, i.e. if

$$|k_z c/\omega| \gtrsim \sqrt{2} v_T/c.$$

Hence from (7) and (8), x-mode growth occurs only if

$$\omega_p^2/\Omega_e^2 \lesssim (11/2) v_T^2/c^2.$$

In the theories of Hewitt et al. (1983), Wu and Qui (1983) and Melrose et al. (1984) the bulk of the electrons are cold and x-mode growth is restricted to values of ω_p/Ω_e less than about 0.3. Condition (9) implies that, when the plasma is hot with an average velocity, v_T, greater than about 0.13 c (i.e. $T \gtrsim 10^8$K), x-mode growth can occur at higher values of ω_p/Ω_e. Further, the maximum value of ω_p/Ω_e for which x-mode growth can occur increases with the plasma temperature.

4. OBSERVATIONS

As an indicator of whether plasma conditions during flares actually satisfy the condition (9) for x-mode growth, the inferred values of ω_p^2/Ω_e^2 and v_T^2/c^2 from the 20 impulsive solar flares reported by Batchelor (1984) are shown in the scatter plot in Fig. 1. It is seen in Fig. 1 that about 15 of the flares satisfy condition (9) for x-mode growth. In other words in about 75% of the flares, the plasma at the flare site is sufficiently hot to produce x-mode growth. In these flares, the radio frequency heating of the corona can be produced by absorption of the x-mode radiation at a second harmonic resonance layer.

In the five flares which do not satisfy condition (9), x-mode growth is suppressed and the heating of the corona must be produced by

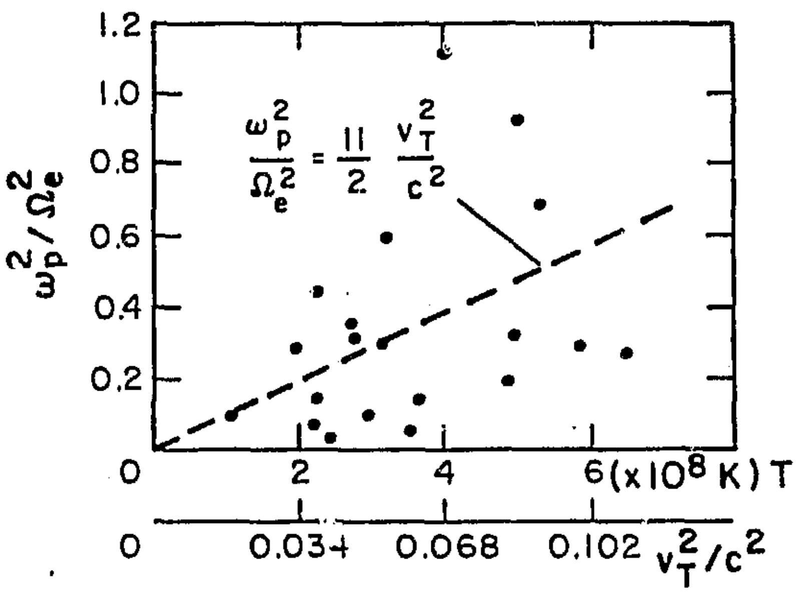

FIGURE 1. Scatter plot of ω_p^2/Ω_e^2 versus v_T^2/c^2 for the twenty impulsive flares reported by Batchelor (1984). Fifteen of the flares satisfy the condition that $\omega_p^2/\Omega_e^2 \lesssim (11/2)\, v_T^2/c^2$ required for x-mode growth while five flares do not.

some mechanism other than the damping of fundamental x-mode radiation. In particular, z-mode growth can dominate when x-mode growth is suppressed (Melrose et al., 1984; Winglee, 1985). Local plasma heating can be produced by the absorption of the z-mode radiation while heating of the corona above the flare site can be produced by the absorption of second harmonic radiation generated by the coalescence of z-mode waves (Melrose and Dulk, 1984).

5. CONCLUSION

In models for the radio frequency heating of the corona during impulsive flares, x-mode radiation emitted from the flaring flux tube is absorbed at a second harmonic resonance layer to produce the heating. It has been shown that a finite plasma temperature allows x-mode growth to occur at higher values of ω_p/Ω_e as the plasma temperature increases. Data from 20 flares indicates that in about 75% of the flares, the plasma conditions are favorable for x-mode growth.

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