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RADIO WAVE HEATING OF THE CORONA AND ELECTRON PRECIPITATION DURING FLARES

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ABSTRACT

Electron-cyclotron masers, excited while energy release is occurring in a flaring magnetic loop, are likely to generate extremely intense radiation at decimeter wavelengths. The energy in the radiation can be comparable with that in the electrons associated with hard X-ray bursts, i.e., a significant fraction of the total energy in the flare. Essentially all of the radio energy is likely to be reabsorbed by gyroresonance absorption, either near the emitting region or at some distance away in neighboring loops. Enhanced diffusion of fast electrons caused by the maser can lead to precipitation at the maximum possible rate, and hence account for hard X-ray emission from the footpoints of the magnetic loops.

Subject headings: magnetic fields — masers — radiation mechanisms — stars: radio radiation — Sun: radio radiation

I. INTRODUCTION

It has long been believed that radio radiation, while interesting as a diagnostic of the flaring plasma, is insignificant in the energetics of the flare. Here we suggest that electron-cyclotron masers operate at the local gyrofrequency and generate radiation at decimeter wavelengths that is a significant fraction of the total energy of the flare, in fact (and not coincidentally) comparable with the energy in electrons associated with hard X-ray bursts. Most of the radio energy is trapped in the corona and serves to produce localized heating in a volume large compared with the energy release region. Thus it can transfer energy by radiation from one magnetic loop to another, possibly inducing further instabilities, and spreading the course of the flare. Eventually, the energy probably escapes the corona as soft X-rays. A byproduct of the electron-cyclotron maser is that precipitation of electrons can proceed at the maximum possible rate, and therefore, enhance the hard X-ray, EUV, and Hα radiation from footpoints of loops.

Wu and Lee (1979) recognized that electron-cyclotron masers will be activated under much milder conditions than previously thought. In particular, large growth rates can occur even for relatively mild anisotropies in the electron velocity distribution, e.g., the one-sided loss cones that commonly occur when electrons with small pitch angles precipitate into high-density regions at the footpoints of loops. Hewitt, Melrose, and Rönnmark (1982*a*) have shown that electron-cyclotron masers provide a plausible explanation for Jupiter's decametric bursts. Melrose, Rönnmark, and Hewitt (1982) and Omidi and Gurnett (1982) have shown that electron distributions observed in the Earth's magnetosphere are unstable to amplification of x-mode radiation slightly above the local gyrofrequency (i.e., at $s = 1$) and can explain the terrestrial kilometric radiation. Holman, Eichler, and Kundu (1980) and Melrose and Dulk (1982, hereafter MD), respectively, have suggested that amplification of x-mode radiation slightly above the first and second harmonics ($s = 2$) of the gyrofrequency as the mechanisms for certain very bright ($\gtrsim 10^{10}$ K), short-lived (~ 1 ms), and highly polarized ($\gtrsim 0.8$) radio bursts from the Sun (Dröge 1977; Slottje 1978) and other stars (e.g., Brown and Crane 1978; Gibson and Fisher 1981; Slee *et al.* 1981). MD noted that amplification of radiation at $s = 1$ would proceed faster than at $s = 2$, but the radiation would have almost no chance of escaping the corona because of gyroresonance absorption by the surrounding plasma; even maser radiation at $s = 2$ would not always escape. To our knowledge, the consequences of the maser emission and resonance absorption of the $s = 1$ radiation have not been explored.

In this *Letter* we outline the proposed mechanisms, estimate the energy involved, and relate the effects to the observed properties of hard X-ray and microwave bursts.

II. PROPERTIES OF THE MASER

Solar flares are commonly believed to occur in the corona when magnetic reconnection takes place within

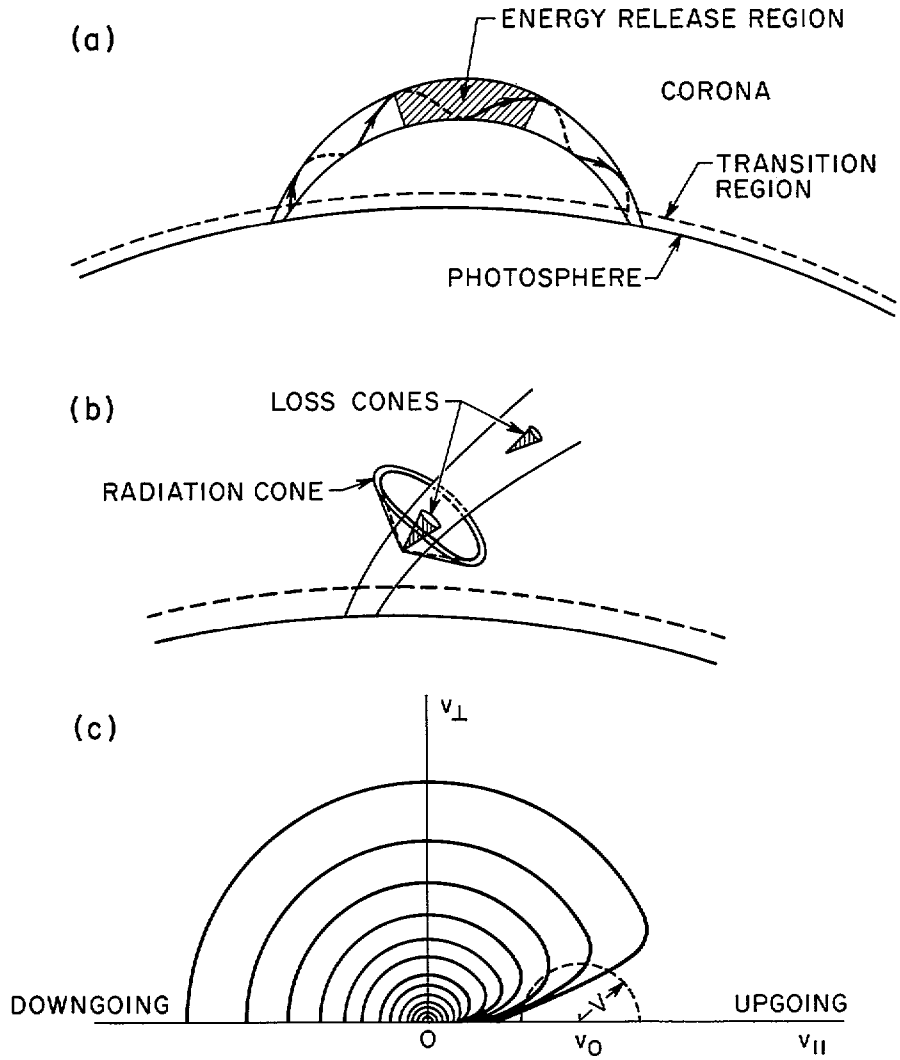

FIG. 1.—(a) Sketch of a flaring loop showing a twisted magnetic field and the energy release region. (b) A portion of the loop showing two one-sided loss cones of the electron distribution and a radiation cone in the direction where the maser growth rate is largest. (c) Contour map of the electron distribution in ($v_\parallel$, $v_\perp$)-space showing the one-sided loss cone, the dense contours of a possible background component near the center, and, by a dashed curve, a resonant ellipse which corresponds to a growing electromagnetic wave mode.

one or more twisted magnetic loops (e.g., the "energy release region" depicted in Fig. 1a). Electrons, heated or accelerated to 10–100 keV energies, proceed down the legs of the loop, some being reflected and trapped, while others precipitate into the dense transition region and chromosphere. As long as the energy release is maintained, the electron distribution in the legs of the loop will be a one-sided loss cone as sketched in Figure 1b. Letting $v_\parallel$ and $v_\perp$ be the components of electron velocity parallel and perpendicular to the magnetic field, the electron distribution in ($v_\parallel$, $v_\perp$)-space is as indicated in Figure 1c.

Consider waves with frequency ω and wave vector $\boldsymbol{k}$, related by a dispersion relation, and electrons with momentum $\boldsymbol{p} = \gamma m \boldsymbol{v}$ and distribution function $f(\boldsymbol{p})$. Gyromagnetic emission or absorption at the sth harmonic occurs when the resonance condition,

$$\omega - s\Omega_e/\gamma - k_\parallel v_\parallel = 0, \qquad (1)$$

is satisfied, where $\Omega_e = eB/m_e c$ is the electron-cyclotron frequency. The growth rate of the waves at the sth harmonic is

$$\Gamma_s(\boldsymbol{k}) = \int d^3\boldsymbol{p}\, A_s(\boldsymbol{p}, \boldsymbol{k})\,\delta(\omega - s\Omega_e/\gamma - k_\parallel v_\parallel) \times \left(\frac{s\Omega_e}{\gamma v_\perp}\frac{\partial}{\partial p_\perp} + k_\parallel \frac{\partial}{\partial p_\parallel}\right) f(\boldsymbol{p}), \qquad (2)$$

where $A_s(\boldsymbol{p}, \boldsymbol{k})$ is a complicated function given by MD and $\omega_p/\Omega_e \ll 1$ is assumed.

In $(v_\parallel, v_\perp)$-space, the resonance condition (1) represents an ellipse (Hewitt, Melrose, and Rönnmark 1982*a*; Melrose, Rönnmark, and Hewitt 1982), so that the triple integrals in equation (2) can be reduced to a single integral around the ellipse. For $\gamma^{-1} \approx 1 - v^2/2c^2$ in equation (1), the ellipse becomes a circle centered on the $v_\parallel$ axis (Wu and Lee 1979) as sketched in Figure 1*c*. In this "semirelativistic case," the resonant circle has radius V centered at $v_\parallel = v_0$, $v_\perp = 0$, where

$$\frac{v_0}{c} := \frac{k_\parallel c}{\omega}, \tag{3a}$$

$$\frac{V}{c} := \left[\frac{k_\parallel^2 c^2}{\omega^2} - \frac{2(\omega - s\Omega_e)}{s\Omega_e}\right]^{1/2}, \tag{3b}$$

where ":= " denotes a definition. This semirelativistic case demonstrates that electron-cyclotron masers should be relatively common as they require no extreme anisotropy; any distribution with $\partial f/\partial v_\perp > 0$ for $v_\perp < V$ can be unstable, and V can take on any value $0 \le V \ll c$. For example, an integral around the semicircle of Figure 1*c* would encounter regions almost exclusively of $\partial f/\partial v_\perp > 0$, so that a wave mode with $k_\parallel = v_0\omega/c^2$ would be amplified. In addition, emission occurs at a frequency ω slightly larger than $s\Omega_e$ so that the radiation need not traverse the sth harmonic layer (where gyroresonance absorption is very strong) and can travel at least to the $(s+1)$th harmonic layer (which may or may not absorb it).

MD, concerned mainly with maser action at $s = 2$ to explain spike bursts observed at 1–3 GHz, noted that maser action at $s = 1$ would proceed fastest and, in almost all circumstances, would dominate in terms of energy emitted; therefore, we will consider only $s = 1$. In circumstances where $\omega_p/\Omega_e \gtrsim 0.2$, amplification of x-mode radiation would be suppressed (Lee, Kan, and Wu 1980; Hewitt, Melrose, and Rönnmark 1982*b*) and o-mode radiation would dominate; for $\omega_p/\Omega_e \gtrsim 0.7$ both modes are suppressed. Neither x-mode nor o-mode radiation at $s = 1$ could escape from the corona because of gyroresonance absorption by, and consequent heating of, the background plasma at the first harmonic (for downward-directed radiation) or second harmonic (for upward-directed radiation). For magnetic fields in the range from 100 to 1000 gauss, the radiation would be at ≈ 300 to ≈ 3000 MHz, i.e., in the decimeter range.

The growth rate of an unsuppressed maser at $s = 1$ of x-mode radiation can be approximated by (MD, eq. [9])

$$\Gamma_1 \approx \eta_1 \frac{n_0}{n_e}\left(\frac{\omega_p}{\omega}\right)^2\left(\frac{c}{v_0}\right)^2 \omega, \tag{4}$$

where n_0 is the number density of electrons with $v > v_0$ and η_1 is a number typically of the order of unity. This growth rate is very large, e.g., with $n_0/n_e \sim 10^{-3}$, $\omega_p/\Omega_e \sim 0.1$, $v_0/c \sim 10^{-1}$, and $\omega \approx \Omega_e \sim 10^{10}$ s^{-1}, we find $\Gamma_1 \sim 10^7$ s^{-1}. With these numbers, the amplification length is ~ 10 m and saturation will occur in a few microseconds, i.e., in less than 100 growth times. For the o-mode, important if the x-mode is suppressed, the growth rate is about 10 times smaller (Hewitt, Melrose, and Rönnmark 1982*b*), but saturation of the maser would still occur very rapidly and over short distances. The growth rate is a sharply peaked function of ω and of the wave angle θ ($\cos\theta := k_\parallel/k$), the maximum growth occurs at an angle θ_0 given by $\cos\theta_0 \approx v_0/c$, the angular width of the emission is $\Delta\theta \approx v_0/c$, and the frequency range is $\Delta\omega/\omega \sim 10^{-2}$ (e.g., MD).

The maser radiation itself causes an enhanced diffusion of electrons into the loss cone through quasi-linear relaxation (Wu *et al.* 1981). The filling of the loss cone, which tends to saturate the maser, is opposed by its emptying at a rate determined by the transit time L/v of an electron along the flux tube. The maser saturates when the effective scattering rate (which is proportional to the intensity of the maser radiation) approaches the loss rate, v/L. The precipitation rate is then near the strong-diffusion limit (Kennel 1969). This corresponds to a rate of precipitation of electrons with a speed in the range from v to $v + dv$,

$$\left.\frac{d}{dt}F(v)\right|_{1,2} = \left(\frac{\alpha_{1,2}}{2}\right)^2 \frac{v}{L} F(v), \tag{5}$$

where $F(v)\,dv$ is the total number of electrons in this range in the trap and where $\alpha_{1,2}$ denotes the angular sizes of the loss cones corresponding to two feet, labeled 1 and 2 respectively.

Alternatively, as discussed by MD, the maser might operate in a pulsed mode in which the pulses are very intense (brightness temperature up to 10^{20} K), the durations of the pulses are small because quasi-linear relaxation rapidly fills the loss cone, and the duty cycles of the pulses are small ($\sim 10^{-6}$) because precipitation more slowly empties the loss cone.

III. EFFECTS OF MASER RADIATION DURING FLARES

Turning our attention to a single flaring loop, we envision that the following process takes place for the seconds or tens of seconds while energy release is occurring. We will describe the energy release as heating the electrons (e.g., Smith 1980), although we do not rule out the possibility that a nonthermal tail could exist and be important for phenomena such as the microwave spike bursts. (Even if a large fraction of the energy goes into directive acceleration of electrons, the basic process should apply, but as we will show, the maser process itself can produce a plethora of precipitating electrons so that directive acceleration may be unnecessary.)

1. Electrons are heated to a few tens of kilo–electron volts, as inferred from impulsive microwave and hard X-ray bursts. Some fraction, $\sim 10\%$, will have small pitch angles so that they immediately precipitate into the transition region or chromosphere. The critical pitch angle is given by $\alpha_{1,2} = \arcsin(B_i/B_{1,2})^{1/2}$, where B_i and $B_{1,2}$ are, respectively, the magnetic field strengths at the top of the loop and at the two feet, labeled 1 and 2, in the transition region. For $0.1 \lesssim B_i/B_{1,2} \lesssim 0.5$, values of $\alpha_{1,2}$ range from 18° to 45°, and the fraction of precipitating electrons ranges from 5% to 29%.

2. In the corona, in one or both legs of the loop, in leg 1 say, a one-sided loss-cone distribution develops as electrons with $\alpha \gtrsim \alpha_1$ are reflected. Amplification of gyromagnetic emission begins and, in $\sim 10\ \mu$s, saturates by rapidly diffusing electrons into the loss cone. We envision many masers operating simultaneously, at many places along the flux tube, and with many $k_\parallel = v_0\omega/c^2$. All produce electrons with small pitch angles in the upward direction.

3. These electrons then travel to the other leg of the loop (leg 2). All with pitch angles $\alpha < \alpha_2$, which may be a few or most depending on the ratio α_2/α_1, precipitate, heating the plasma and emitting hard X-rays. Electrons with $\alpha > \alpha_2$ are reflected above the transition region and add to those coming from the energy release to form a one-sided loss cone. Maser action occurs in leg 2 and electrons are driven back to leg 1 where, again, most or a few precipitate. This cycle occurs in about one transit time, $L/v \lesssim 1$ s, and the process will continue so long as electrons with $\alpha > \alpha_{1,2}$ are present to drive the maser, i.e., so long as energy release continues.

4. The maser action causes electrons to precipitate at an average rate proportional to the number density in the trap; see equation (5). The rate at which particles precipitate tends to adjust to the rate at which fast particles are produced. The number of particles in the trap at any given time is determined by the ratio of the number of electrons accelerated per unit time to the net loss rate, $(\Delta\Omega_L/4\pi)v/L$, where $\Delta\Omega_L = 2\pi(2 - \cos\alpha_1 - \cos\alpha_2)$ is the solid angle subtended by the loss cones. The time profiles of microwave and hard X-ray bursts during their rise phase presumably reflect the increasing number of electrons in the trap and precipitating. During the decay phase, the profiles reflect the decreasing heating rate or, if it is longer, the e-folding time, $[(\Delta\Omega_L/4\pi)v/L]^{-1}$, of the precipitation. For most hard X-ray bursts, the decay is observed to be slower than the rise (B. Dennis, private communication), which may be due to the precipitation time being the longer. However, some bursts are symmetric and a few even decay faster than they rise (e.g., Crannell *et al.* 1978), and these presumably reflect the time profile of the heating or acceleration mechanism. For this to be so, the inequality $(\Delta\Omega_L/4\pi)v/L \gtrsim \tau^{-1}$ must be satisfied, where τ is the characteristic rise or decay time. For example, with $\tau = 1$ s and for ~ 10 keV electrons, this requires $L \lesssim 6 \times 10^9(\Delta\Omega_L/4\pi)$ cm, i.e., a relatively short ($L \approx 10^9$ cm) flux tube and large loss cone ($B_i/B_{1,2} \approx 1/3$).

5. A concentration of electrons builds up near the top of the loop because little or no loss-cone anisotropy develops there, and hence no maser. These electrons emit gyrosynchrotron radiation, thus producing the impulsive microwave bursts which are observed at centimeter wavelengths to come, almost always, from near the tops of magnetic loops (e.g., Marsh and Hurford 1981; Kundu, Schmahl, and Velusamy 1982). Hard X-ray production would be inefficient there because of the presumed low ambient density relative to the footpoints. Regarding the time profiles, the hard X-rays from footpoints would turn off abruptly when energy release and maser action cease, whereas microwaves would continue to be emitted from the electrons remaining in the trap. This accounts for the long-lived tails observed in microwaves but not in hard X-rays.

6. After the initial heating of the loop, the flare energy continues to be dissipated. Steady precipitation involves the electrons with initial $\alpha > (\alpha_1, \alpha_2)$ radiating away perpendicular energy until they enter the larger loss cone and precipitate. Roughly half of the energy (the perpendicular component) goes into amplified decimeter waves, and the other half (the parallel component) goes into precipitating electrons. The former heat the corona while the latter heat the transition region and chromosphere and give rise to EUV, Hα, and hard X-ray bursts.

7. The decimeter waves are emitted on the thin surface of a hollow cone (Fig. 1b) at an angle from the magnetic field $\theta_0 \approx \arccos(v_0/c)$ which, for $0.1 \lesssim v_0/c \lesssim 0.3$, ranges from about 84° to 70°. Depending on the orientation of the field in the legs of the loop, a fraction of the radiation will be emitted downward into a larger field and will be immediately absorbed by gyroresonance absorption at $s = 1$. The remainder will travel upward and outward into a weaker field. If inhomogeneities exist so that $\Delta B/B$ equals roughly a few percent, then some of this radiation will be absorbed locally. Otherwise, it will travel some distance, until it reaches a region where the field strength is halved and gyroresonance absorption at $s = 2$ occurs. For the density ($\sim 10^9$ to $\sim 10^{10}$ cm^{-3}), temperature ($\sim 10^6$ to $\sim 10^7$ K), and field strength ($\sim 10^2$ to $\sim 10^3$ G) expected in nearby loops, the radiation would be absorbed in the very short distance of a few to few hundred meters (e.g., Zheleznyakov 1970). Thus the heating would be very localized and could rapidly raise the temperature, perhaps to the 10^7 K characteristic of the soft X-ray plasma. Eventually the energy leaves the corona by conduction or soft X-ray radiation.

8. The very localized heating in the nearby, nonflaring loops could trigger instabilities therein, for example by changing the conductivity, and thus cause them to flare.

This (radiative) mechanism is an alternative to the local expansion model proposed by Emslie (1981) for interacting loops in flares.

9. Observations indicate that hard X-ray sources are usually near the feet of flux tubes (Hoyng *et al.* 1981; Kane *et al.* 1979, 1982) and not high in the corona, contrary to what is predicted for a trap-plus-precipitation model when only Coulomb scattering is included (Melrose and Brown 1976). The enhanced scattering accompanying maser emission implies a simple relation between the distribution of trap and precipitative electrons; see equation (5). The distribution of precipitating particles should have a distribution harder than that of the trapped particles by one power of v. The two footpoints 1 and 2 of a flaring loop would not, in general, be equally bright because the ratio of precipitation rates is $R = \alpha_1^2/\alpha_2^2 \approx B_2/B_1$ (Melrose and White 1981).

IV. SUMMARY AND CONCLUSIONS

Electron-cyclotron maser emission should occur in flares as down-going energetic electrons are reflected, leading to a one-sided loss-cone distribution. The fastest growing instability is for the x-mode at $s = 1$ providing that $\omega_p/\Omega_e < 0.3$, and for the o-mode at $s = 1$ when the x-mode is suppressed. The maser emission is accompanied by enhanced diffusion of the electrons, and the maser saturates when the diffusion becomes strong in the sense defined by Kennel (1969).

The maser emission has at least three important implications. First, it may involve a significant fraction of the energy of the flare, energy which goes into heating the coronal plasma. Second, the up-going radiation from a flaring loop is absorbed some distance away at the second-harmonic level, leading to a localized heating, which might trigger the flaring process there. Third, the enhanced precipitation implies hard X-ray emission from the feet of the flux tubes, as observed. The distribution function of the precipitating electrons is related in a simple way to that of the trapped electrons; see equation (5). This relation may be combined with hard X-ray and microwave data to derive the physical parameters of the flaring region.

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