MICROWAVE EMISSION FROM FLARING MAGNETIC LOOPS

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We discuss the microwave emission from a flaring loop (Spicer 1977). In particular we examine the following question: What will be the characteristics of the radio emission at centimeter wavelengths from a small compact flaring loop (average plasma density $n_e \simeq 10^{10}$ cm^{-3}, average magnetic field at the footpoint of the loop $B_\ell \simeq 500$ gauss and $B_t \simeq 100$ gauss at the top of the loop and length of the loop, $L = 10^9$ cm), when the mechanism which pumps magnetic energy into the plasma in the form of heating and/or electron acceleration satisfies the following conditions. a. The magnetic energy is released in a small volume, (the energy release volume (ERV)), compared to the volume of the loop, and the rate at which magnetic energy is transformed into plasma energy is faster than the energy losses from the same volume. This causes a local enhancement of the temperature by as much as one or two orders of magnitude above the coronal temperature. b). The bulk of the energy released goes into heating the plasma and heats primarily the electrons ($T_e > T_i$). Using these two assumptions one can easily show (Brown, Melrose and Spicer 1979, Vlahos and Papadopoulos 1979) that the high energy electrons in the tail of the velocity distribution in the ERV will instantaneously run away from this volume, and the resulting charge imbalance between the ERV and its surroundings (which still have average coronal temperatures $\sim 10^6$ K), will drive a return current, with velocity V_D. When V_D reaches the value of the local sound speed $C_s \simeq 10^7$ cm/sec low frequency ion acoustic waves will be excited at the interface of the ERV and its surroundings. It has been shown that the heat flow along the magnetic field lines is greatly reduced due to the presence of ion-acoustic turbulence (cf. Manheimer 1977). The bulk of the electrons in the ERV have electron-wave collision times $\tau_w <<$ 10-100 sec, longer than the impulsive phase of the flare. But since $\tau_w \sim v^3$ for those electrons with velocity $v > v_e$ (see Rudakov and Korablev 1966) the electrons in the tail will not "see" the ion sound waves and will stream freely towards the chromosphere.

Vlahos and Papadopoulos (1979) examined the stability of the streaming electrons against the fastest growing waves e.g. Langmuir waves. Their conclusion was that if $(n_s/n) \lesssim 10^{-4}\ (T_e{}^{I}/T_e{}^{II})$, the streaming electrons lose little if any energy to the waves. [Where n_s is the num-

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ber of the streaming electrons, n is the average plasma density in the loop, and $T_e{}^{I}$, $T_e{}^{II}$ are the average temperatures in the impulsive phase at the ERV and its surroundings respectively.] They also estimated the total number of electrons "escaping" during the impulsive phase from the ERV (e.g. for a burst with an impulsive phase of duration $\sim$ 10 sec, $N \sim 10^{33}$ electrons). A part of these electrons will be trapped in the loop (Kundu and Vlahos 1979) and will emit at centimeter wavelengths near the footpoints of the loop by the gyro-synchrotron process. Vlahos and Emslie (1980) performed detailed calculations on the microwave, Hard X-ray and EUV emissions expected from the above model. They showed that the observed emission at all the above wavelengths can be easily reproduced if the velocity distribution in the tail is a power law in energy of the form $f(E) \sim E^{-\gamma}$ for $E > E_{crit}$, with $\gamma \sim 3$-4.

All the above arguments apply for the impulsive phase of the burst. It is natural to expect that the heated plasma in the ERV will expand slowly with velocity $v_E \simeq 10$-100 km/sec (Brown, Melrose and Spicer 1979) in the post burst phase. According to the above model we expect two more stages in the evolution of the microwave burst.

a) For time $t_1 \sim L/v_E \simeq 10\ Lg\ v_8$ sec the hot plasma at the ERV will fill the entire loop, but the bulk of the trapped electrons have not yet thermalized. In this stage the average plasma temperature is $\simeq 10^7$ K, and the microwave emission will have two contributions, (i) a small compact source around the footpoints of the loop (ii) a larger diffuse "halo" due to the contribution of the hot plasma trapped in the rest of the loop.

b) For times $t >> L/v_E$ the energetic electrons will be thermalized and the observed emission will come from a thermal plasma. In this stage the size of the observed source remains constant but its intensity decays slowly. This prediction agrees well with the observational result of Alissandrakis and Kundu (1978) who first observed that a number of microwave bursts have constant source size during the post burst phase.

We finally address the following question: if the energy is released in a closed bipolar magnetic loop, how do the energetic electrons escape into interplanetary space or the upper corona? It is well known (Kundu 1961) that the correlation of hard x-ray and type III bursts is $\lesssim 20\%$. This suggests that only if certain conditions are satisfied the electrons can escape from the loop. We have analyzed a number of possible conditions which are necessary, according to the flaring loop model, for the escape of electrons in the upper corona. We postulate that strong electric fields along the magnetic field lines are present during the impulsive phase. Electrons in the tail of the velocity distribution gain energy freely along the field lines. Depending on the strength of the electric field in the ERV and its time evolution the velocity distribution in the escaping tial may develop a velocity anisotropy $v_\parallel >> v_\perp$, where $v_\parallel$, $v_\perp$ are the components of the electron velocity along and perpendicular to the magnetic field, respectively.

The anomalous doppler resonance instability, which has been widely discussed in the literature (e.g. Kadomdsev and Pogutse 1968, Liu et al. 1977) is driven by the velocity anisotropy in the tail. The basic physical idea is that waves with frequency $\omega = k_\parallel v_\parallel + \omega_{ce}$, where ω_{ce} is the gyrofrequency, are excited by the velocity anisotropy in the tail. These waves subsequently resonate with the electrons in the tail and pitch angles scatter them until $v_\perp \gtrsim v_\parallel$. The growth time for this instability is $\simeq 10^{-3}$ sec for a flaring loop (Vlahos and Emslie 1980). The implications of the sudden increase in $v_\perp$ are twofold: (i) high energy electrons in the tail are trapped since they are scattered by the Anomalous Doppler Resonance Instability into the antiloss cone which is defined by $v_\parallel < v_\perp\ [2\ \delta B/B]^{1/2}$ where $\delta B = (B_\ell - B_t$, and (ii) at the same time the trapped electrons drifr across the magnetic field lines with a velocity

$$v_{D_\perp} \simeq (1/2\ m\ v_\perp^2\ c)/(eB\ R) \simeq 10^5 - 10^6\ \text{cm/sec} \qquad (1)$$

Assuming that the duration of the impulsive phase of the burst is ∿ 10 sec, we can estimate the total number of electrons drifting across the magnetic field lines during the impulsive phase from the formula:

$$N_{ese} \simeq \left(\frac{\delta n}{n}\right) n\ 2\pi R\ (v_{D_\perp}\ \delta t)\ L \simeq 10^{30} \qquad (2)$$

where $(\delta n/n) \simeq 10^{-3}$ is the fraction of trapped electrons, $R \simeq 10^8$ cm is the radius of the loop, $L \sim 10^9$, $\delta t \sim 10$ sec is the duration of the impulsive phase.

In summary, we presented the characteristics of the microwave emission from a flaring loop, where the energy released mechanism satisfies the conditions given above. We discussed qualitatively the time evolution of the energy release, and the characteristic microwave emission associated with it. We also proposed a possible explanation of how mildly relativistic electrons escape from the flaring loop to the upper corona.

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DISCUSSION

Lin: How fast can the electrons travel across field lines for this mechanism? Also, your diagram appears to show the electrons escaping near the footpoints of the loop qhile the lower energy electrons are trapped higher up. Does this mean that only the higher energy electrons escape?

Vlahos: The drift velocity is given by Eq.(1). Since the magnetic field is decreasing across the loop the drift velocity will vary between 10^5 cm/sec and 10^7 cm/sec. Only the electrons with energy ≃ 80-100 KeV interact with the waves excited by the Anomalous Doppler Resonance instability.

Kane: This is very interesting study since not much ahs been done about the escape of energetic electrons. What is the characteristic time for escape of energetic electrons? It might determine possible time differences (if any) in the microwave or x-ray spikes and the type III bursts.

Vlahos: As I discussed above, the drift velocity depends on the geometry and strength of the magnetic field near the surface of the loop. But in any case I expect that if the mechanism described above is the main source of energetic electrons in the upper corona, a time delay between the microwave and the type III bursts of the order of 1-2 sec must be expected.

Gary: You said $v_{\parallel} >> v_{\perp}$ but that energy is taken from the parallel direction and given to the perpendicular direction, which lead to a drift across field lines. Will the particles which escape have enough parallel energy to explain a type III burst?

Vlahos: The Anomalous Doppler Resonance instability which I propose is driven by the velocity anisotropy in the parallel and perpendicular directions ($v_{\parallel} >> v_{\perp}$). Its effect will be to isotropise the velocity distribution in the tail, (e.g. $v_{\parallel} \sim v_{\perp} \sim 1/3$ c) this means that enough energy in the parallel direction is still present to explain the type III bursts.