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ELECTRON CYCLOTRON WAVE ACCELERATION OUTSIDE A FLARING LOOP

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ABSTRACT

We propose a model for the secondary acceleration of electrons outside a flaring loop. Our results suggest that the narrow bandwidth radiation emitted by the unstable electron distribution inside a flaring loop can become the driver for secondary electron acceleration outside the loop. We show that a system of electrons gyrating about and streaming along an adiabatically spatially varying, static magnetic field can be efficiently accelerated to high energies by an electromagnetic wave propagating along and polarized transverse to the static magnetic field. The predictions from our model appear to be in general agreement with existing observations.

Subject headings: particle acceleration — Sun: flares — Sun: radio radiation

I. INTRODUCTION

In this *Letter*, we propose that electromagnetic (e.m.) radiation excited by an unstable electron velocity distribution inside a flaring loop may escape the loop and accelerate electrons along an open flux tube or along the footpoints of a coronal loop.

A number of observations have shown the nearly simultaneous release of secondary electrons streaming from the surface of the Sun (type III bursts) and the precipitating electrons associated with hard X-ray bursts (see Kane 1981; Kane, Benz, and Treumann 1982). One possible explanation for the accelerated secondary electrons is that they result from the primary precipitating electrons drifting out of the flaring loop and consequently being reflected into the open field lines. However, this mechanism suffers from a number of difficulties; among them is that the drift rate is exceedingly slow (Vlahos 1979), contrary to observations.

A recent parallel development has been the discovery of intense (10^{10}–10^{11} W), narrow-band, highly polarized microwave bursts observed by Slottje (1978, 1979) and Zhao and Jin (1982). These observations have been interpreted as the signatures of the unstable electron distribution, formed inside the flaring loop, by the flare-released precipitating electrons (Holman, Kundu, and Eichler 1980; Melrose and Dulk 1982*a*; Sharma, Vlahos, and Papadopoulos 1982; Vlahos, Sharma, and Papadopoulos 1983).

These observations together with the lack of a viable explanation for the secondary accelerated electrons have motivated us to examine in detail the interaction of a circularly polarized e.m. wave propagating along a spatially varying, static magnetic field as a possible acceleration mechanism responsible for the observed secondary electrons. In this process, the relativistic electron cyclotron frequency and the wave phase change in such a way that the resonance between the particles and wave is maintained in a uniform magnetic field (Kolomenskii and Lebedev 1963; Roberts and Buchsbaum 1964). For such a process, the intense, polarized, narrow-band e.m. waves observed by Slottje (1978, 1979) provide a link between the energetic electrons inside the flaring loop and those observed in the outer corona or interplanetary space (type III bursts). An overall schematic of our proposed acceleration process is shown in Figure 1. Here the precipitating primary electrons are accelerated inside a flaring loop and stream toward the chromosphere. These precipitating electrons can then excite an intense, polarized, narrow-band e.m. wave. This e.m. wave is assumed to escape the flaring loop region and propagate along a open flux tube where it can accelerate the secondary electrons (see Fig. 1). A question can be raised here on the possibility of reabsorption of the e.m. wave before escaping the flaring loop. This is especially important when the excited e.m. wave is near the fundamental electron cyclotron frequency or upper hybrid frequency. Our assumption is that the excited wave approaches the second harmonic inside the flaring loop where the total electron distribution is *not* Maxwellian. It is therefore amplified instead of damped (Sharma, Vlahos, and Papadopoulos 1982; Vlahos, Sharma, and Papadopoulos 1983).

Our main conclusions in this *Letter* are that the e.m. wave can accelerate approximately 10^{-4} of the ambient electrons in the acceleration region to approximately 100 keV. In the following section, we present a brief description of the analytical model for the e.m. wave acceleration mechanism in a spatially varying magnetic field. In the remaining sections, this mechanism is utilized to explain the energetic electrons observed in type III burst.

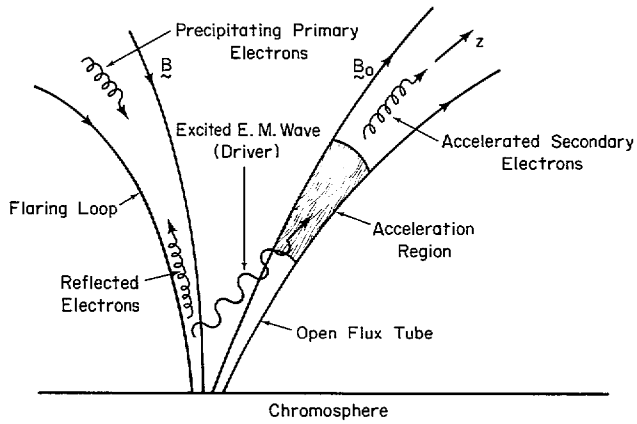

FIG. 1.—An overview of the proposed acceleration model. Precipitating electrons energized within the flaring loop stream toward the chromosphere. These electrons excite narrow-band electromagnetic waves which escape the flaring loop and become the driver for secondary acceleration inside an open flux tube. Energetic secondary electrons with energies of approximately 100 keV stream away from the acceleration region.

II. MODEL OF ACCELERATION MECHANISM

Our model consists of a beam of streaming and gyrating electrons in the presence of an intense e.m. wave together with a static, adiabatically spatially varying magnetic field. The e.m. wave is assumed to propagate in the z-direction and is represented by the vector potential $\boldsymbol{A}(z,t) = A_0[\sin\phi(z,t)\hat{e}_x + \cos\phi(z,t)\hat{e}_y]$, where $\phi = kz - \omega t$ is the phase. The static, spatially varying magnetic field is denoted by $\boldsymbol{B}_0(x,y,z) = -(1/2)\partial B_0(z)/\partial z(x\hat{e}_x + y\hat{e}_y) + B_0(z)\hat{e}_z$. The axial component of $\boldsymbol{B}_0$ is taken to have a characteristic spatial variation given by L, i.e., $B_0^{-1}\partial B_0/\partial z = 1/L$. Furthermore, we have assumed that the spatial variation is adiabatic. To obtain the fully nonlinear, relativistic particle orbits, we denote the transverse position and momentum of a particle by $x = x_g + r\sin\theta$, $y = y_g - r\sin\theta$, $P_x = P_{gx} + P_\perp\cos\theta$, and $P_y = P_{gy} + P_\perp\sin\theta$ respectively. In this representation, (x_g, y_g) and (P_{gx}, P_{gy}) denote the transverse coordinates and momentum of the particle's guiding center, r is the Larmor radius, $P_\perp$ is the transverse momentum, and θ the momentum space angle. We now assume that x_g, y_g, P_{gx}, P_{gy}, r, $P_\perp$, and $\theta + \phi$ are slowly varying functions of z, i.e., change little during a gyro period. This assumption, together with the Lorentz force equation, allows the following set of fully relativistic, nonlinear, normalized orbit equations, describing the acceleration process, to be derived:

$$\frac{\partial u_\perp}{\partial \xi} = \frac{u_\perp}{2}\frac{\partial K/\partial\xi}{K} - \alpha\left(\frac{nK - \gamma\Delta}{\gamma - K}\right)\cos\Psi, \quad (1a)$$

$$\frac{\partial \Psi}{\partial \xi} = \Delta + \alpha\left(\frac{nK - \gamma\Delta}{\gamma - K}\right)\frac{\sin\Psi}{u_\perp}, \quad (1b)$$

$$\frac{\partial \gamma}{\partial \xi} = -\alpha\frac{u_\perp}{u_z}\cos\Psi, \quad (1c)$$

$$\frac{\partial \Delta}{\partial \xi} = \frac{\partial K/\partial\xi}{K}\left[\frac{K}{u_z} - \frac{(n-\Delta)}{2}\frac{u_\perp^2}{u_z^2}\right] + \alpha\left[(1-n^2) + n\Delta\right]\frac{u_\perp}{u_z^2}\cos\Psi, \quad (1d)$$

where $\Psi = \theta + \phi$, $u_z = (\gamma - K)/(n - \Delta) = P_z/m_0c$, P_z is the axial momentum, $\xi = z\omega/c$, $u_\perp = P_\perp/m_0c$, $K = \Omega_0/\omega$, $\Omega_0 = |e|B_0(\xi)/m_0c$, $\gamma = (1 + u_\perp^2 + u_z^2)^{1/2}$, $n = ck/\omega$ is the refractive index of the medium, $\Delta = [K - (\gamma - nu_z)]/u_z$, and $\alpha = |e|A_0/(m_0c^2)$. It is easy to show from equation (1) that, for a uniform static magnetic field, i.e., $\partial K/\partial\xi = 0$, and $n = 1$, the quantity $C \equiv \gamma(1 - u_z/\gamma) - K$ is identically zero. Since $C = 0$ implies that $\omega - v_z(z)k = \Omega_0(z)/\gamma(z)$, where v_z is the axial particle velocity, we note that, if the particle and wave are initially resonant, i.e., $\Delta = 0$, they remain resonant, despite the fact that both γ and v_z are changing (increasing) as a function of z. Thus, in a uniform magnetic field, the resonant particles are continuously accelerated. Those particles not in resonance will periodically exchange energy with the e.m. wave resulting in little or no net acceleration. In a slowly varying magnetic field, those particles which are in resonance, say at $z = 0$, will slowly become "detuned" at a distance z_0 (see Fig. 2). However, if a thermal particle distribution is present, as the magnetic field changes, new particles will become resonant with the wave at different locations in the acceleration region.

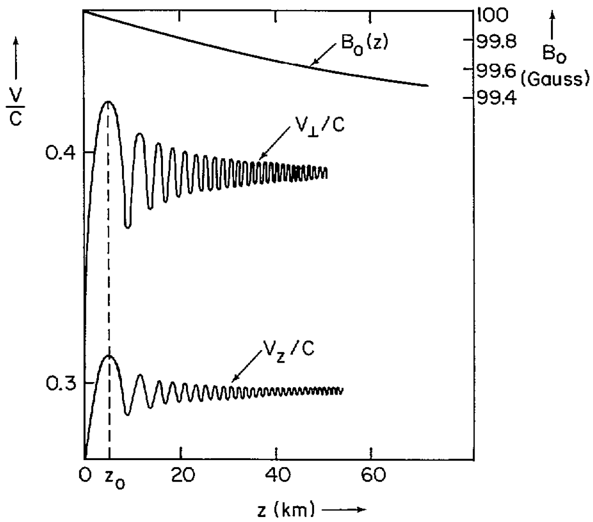

FIG. 2.—The spatial evolution of the normalized velocities, $v_\perp/c$ and v_z/c, and the exponentially varying magnetic field are shown. Parameters used in this figure are $n = 1$ and $\alpha = 10^{-5}$. The particle and wave are detuned at $z = z_0$.

III. ILLUSTRATION

Equations (1a)–(1d) have been numerically integrated for a magnetic field amplitude variation given by $B_0(z) = B_0 \exp(-z/L)$ and $n = 1$. As seen in Figure 2, the test particle and e.m. wave are initially in resonance but slowly become "detuned" in a distance $z_0 = 5$ km; it should also be noted that, at the end of the interaction region, $v_\perp \gg v_z$.

The local cold plasma index of refraction for high-frequency, right circularly polarized waves propagating along z is (Boyd and Sanderson 1969) $n^2 = 1 - \omega_e^2/[\omega(\omega - |\Omega_0|)]$, where ω_e is the plasma frequency and $\omega_e < \omega$. Thus, n is not exactly unity as ω approaches Ω_0. Since it is shown that only the thermal tail of the distribution is resonant with the e.m. wave, the cold plasma approximation appears valid. From equation (1d) we can estimate the necessary magnetic field gradient for the most efficient acceleration ($\Delta = \partial\Delta/\partial\xi = 0$). It can be shown that, as n varies with distance, the resonance can still be maintained by a suitable choice of $B_0(z)$ [e.g., $B_0(z) = B_0 \exp(-z/L)$, where L is dependent on n]. In addition, waves propagating at an angle to the magnetic field can resonate with particles at higher harmonics ($\Delta\omega = l\Omega_e/\gamma - k_z v_z - \omega$). However, the coupling and hence the energy gain are substantially weaker for higher harmonic interaction (Vlahos and Sprangle 1983). Finally, to examine the acceleration process on a distribution of electrons, we employ a nonrelativistic thermal velocity distribution and assume that the monochromatic e.m. wave is initially resonant with electron axial velocities of about $3v_e$, where v_e is the electron thermal velocity (see Figs. 3a and 3b). Following the nonlinear trajectories of 100 resonant particles with initially random phases (the nonresonant particles are neglected since they simply oscillate exchanging energy periodically with the wave), we find that the accelerated electrons form a gyrotropic beam (see Figs. 3a and 3b). The combined velocity distribution for the secondary accelerated electrons shown in Figures 3a and 3b can be approximated by $f_{acc} \sim \exp\{-a_\perp^{-2}(z)[v_\perp - v_{0\perp}(z)]^2\} \exp\{-a_\parallel^{-2}(z)[v_\parallel - v_{\parallel 0}(z)]^2\}$. The characteristic beam velocities in the perpendicular and parallel direction $[v_{\perp 0}(z), v_{\parallel 0}(z)]$ as well as the thermal spread $[a_\perp(z), a_\parallel(z)]$ are functions of z. For a nonmonochromatic wave interacting with the thermal tail, a beam

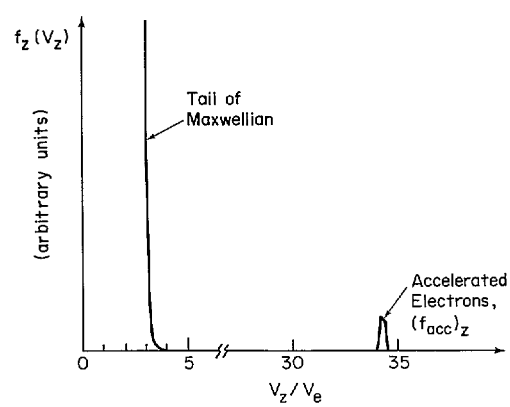

FIG. 3a

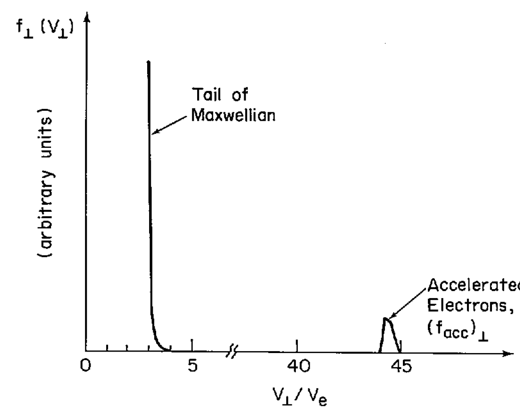

FIG. 3b

FIG. 3.—(a) The electron distribution of axial velocities is shown; here particles with $v_z \approx 3v_e$ are initially resonant. The tail of the initial distribution (Maxwellian), together with the accelerated distribution, f_{acc}, is shown at $z_0 = 5$ km. In this figure, an adiabatically varying magnetic field with $L \sim 10^9$ cm and index $n = 0.7$ is used. (b) Same as (a), except distributions of transverse velocities are shown.

similar in shape to the one shown in Figures $3a$ and $3b$, but with larger thermal spreads, will result (Krasovitskii and Kurilko 1967; Vlahos and Sprangle 1983).

We can now utilize the above information in a composite model to explain the simultaneous production of precipitating electrons and the generation of energetic secondary electrons outside the flaring loop. Since the frequency of the e.m. wave is near the electron cyclotron frequency within the flaring loop, its frequency range is approximately 3×10^8 Hz to 1×10^9 Hz, i.e., the magnetic field is between 100 gauss and 300 gauss. In the intervening region between the flaring loop and the open flux tube, the magnetic field is assumed to be somewhat less then 100 gauss. This implies that (1) in the intervening region, the wave-particle resonance condition cannot be satisfied either because $\Delta\omega = (1 - \beta_z)\omega - \Omega_0/\gamma \neq 0$ or the angle between the wave and magnetic field is too large, and (2) as the e.m. wave approaches the open flux tube, its frequency is greater than the local cyclotron frequency; thus, the e.m. wave approaches the resonance condition from the tail end of the electron distribution function. If the magnetic field variation is different than assumed above, i.e., $\omega \lesssim \Omega_0$, bulk heating and not tail acceleration could result. We have assumed in the acceleration region a slowly varying magnetic field ($L \sim 10^9$ cm), an index of refraction close to unity, i.e., $\omega_e < \Omega_0 \lesssim \omega$, and a wave amplitude consistent with the observed power levels (Slottje 1978). With these assumptions, it can be shown that electrons will be accelerated to energies of approximately 100 keV before becoming "detuned," see Figure 2. Detuning takes place at a distance of a few kilometers from where the point resonance is first established. The wave continues to interact with the tail end of the distribution until it is nearly depleted *or* the magnetic field orientation *or* the index of refraction becomes such that resonance cannot be maintained. Detailed numerical illustrations based on this analysis are beyond the scope of the present *Letter* and will be presented elsewhere.

A rough estimate of the number of accelerated electrons is given by the following arguments. The energy density of the e.m. wave is given by $E_{\mathrm{e.m.}} = \eta_{\mathrm{e.m.}} n_0 R \rho W_{\mathrm{pre}}$, where $\eta_{\mathrm{e.m.}}$ is the efficiency of transforming the reflected electron energy to e.m. wave energy in the flaring loop, n_0 is the ambient density, R is the density ratio of the reflected to ambient electrons, ρ is the density ratio of precipitating to ambient electrons, and W_{pre} is the average energy of the precipitating electrons. The number density of the accelerated electrons is therefore

$$n_{\mathrm{acc}} = \eta_{\mathrm{acc}} \eta_{\mathrm{e.m.}} n_0 R \rho W_{\mathrm{pre}} / W_{\mathrm{acc}}, \qquad (2)$$

where W_{acc} is the final energy gained by each electron and η_{acc} is the acceleration energy conversion efficiency. Approximate numbers for the parameters in equation (2) can be estimated or found in the literature. For example, $R = 10^{-1}$ (see Sharma, Vlahos, and Papadopoulos 1982), $\eta_{\mathrm{e.m.}} \leq 10^{-1}$ (see Melrose and Dulk 1982a; or Sharma, Vlahos, and Papadopoulos 1982), $\rho \approx 10^{-2}$, $W_{\mathrm{pre}} \approx 100$ keV (see Vlahos and Papadopoulos 1979), $W_{\mathrm{acc}} \gtrsim 100$ keV (see Figs. 2 and 3), and our preliminary self-consistent analysis shows that $\eta_{\mathrm{acc}} \approx 0.5$. From equation (2) we find that $n_{\mathrm{acc}}/n_0 \lesssim 10^{-4}$. Clearly, our basic conclusions are not extremely sensitive to the value of η_{acc}.

This illustration is not intended to be quantitatively rigorous. It should be considered as an indication that the mechanism leads to reasonable values for the observables. A fully self-consistent analysis, which includes depletion of the e.m. wave, is necessary for more accurate estimates. This analysis is presently underway.

IV. DISCUSSION AND CONCLUSIONS

The following comments and points can be made concerning our proposed secondary electron acceleration process.

1. The hard X-rays and type III bursts have a common energy source: the precipitating electrons. Thus, the harder the X-ray bursts, the greater the secondary electron energy. This conclusion is consistent with recent observations (Kane, Benz, and Treumann 1982).

2. The thermal tail of the electron distribution absorbs the e.m. wave energy and is accelerated to approximately 100 keV. Equation (2) shows that, if the e.m. wave energy is absorbed by the bulk of the electron distribution as suggested by Melrose and Dulk (1982b), the net acceleration (heating) is approximately 10 eV.

3. The starting frequency (maximum frequency) of the type III burst will be near the resonance $\omega = \Omega_0$ in the open flux tube, i.e., $\omega \approx 3 \times 10^8$ to 1×10^9 Hz. This appears also to be in agreement with observation (Benz, Zlobec, and Jaeggi 1982).

4. The intensity versus time profile of the e.m. driver wave is observed to be "spiky" (Slottje 1978). Thus, based on our acceleration mechanism, we would expect that the type III bursts should also appear in groups.

5. Our mechanism predicts that there should be a time delay between the observed hard X-ray and type III bursts due to the time of flight of the e.m. wave from the flaring loop to the acceleration region (Kane, Benz, and Treumann 1982).

6. The accelerated secondary electrons in the open flux tube may in turn excite through a longitudinal beam-plasma instability radiation at $\omega_e(z)$. Furthermore, since the secondary electrons have a large $v_\perp$, radiation at $\omega = \Omega_0/[\gamma(1 - \beta_z)] \approx \Omega_0$ may also be excited. Our mechanism requires a refractive index close to unity in the acceleration region to ensure reasonable magnetic field gradients of $L \approx 10^9$ cm. This implies

that ω_e should be somewhat less than Ω_0. Radiation well separated in frequency has in fact been observed in the starting frequencies in type III bursts (Benz, Zlobec, and Jaeggi 1982).

Our initial analysis demonstrates for the first time a possible correlation between the generation of precipitating electrons in a flaring loop and energetic electrons in type III bursts. Although we have discussed a specific illustration, our mechanism may be somewhat more general. The general characteristics of this acceleration scheme involve the correlation between magnetically confined energetic electrons and untrapped high-energy electrons via induced radiation. This generic acceleration mechanism may possibly find other applications such as in the correlation between type I and type III storms in the solar atmosphere. Other potential areas of application in astrophysics may include cosmic rays accelerated by pulsar radiation. Clearly, further study and comparison with observations is necessary to completely verify the validity of the proposed acceleration process. This work is presently underway.

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REFERENCES

Benz, A. O., Zlobec, P., and Jaeggi, M. 1982, *Astr. Ap.*, **109**, 305.
Boyd, T. J. M., and Sanderson, J. U. 1969, *Plasma Dynamics* (New York: Barnes and Noble), p. 179.
Holman, G., Kundu, M. R., and Eichler, D. 1980, in *IAU Symposium 86, Radio Physics of the Sun*, ed. M. R. Kundu and T. E. Gergely (Dordrecht: Reidel), p. 457.
Kane, S. R. 1981, *Ap. J.*, **247**, 1113.
Kane, S. R., Benz, A. O., and Treumann, R. A. 1982, *Ap. J.* **263**, 423.
Kolomenskii, A. A., and Lebedev, A. N. 1963, *Soviet Phys. Dokl.*, **7**, 745.
Krasovitski, V. B., and Kurilko, V. I. 1967, *Sov. Phys.—Techn. Phys.*, **11**, 1953.
Melrose, D. B., and Dulk, G. 1982*a*, *Ap. J.*, **259**, 844.
Melrose, D. B., and Dulk, G. 1982*b*, *Ap. J. (Letters)*, **259**, L41.
Roberts, C. S., and Buchsbaum, S. J. 1964, *Phys. Rev. A*, **135**, 381.
Sharma, R. R., Vlahos, L., and Papadopoulos, K. 1982, *Astr. Ap.*, **112**, 377.
Slottje, C. 1978, *Nature*, **275**, 520.
______. 1979, in *IAU Symposium 86, Radio Physics of the Sun*, ed. M. R. Kundu and T. E. Gergely (Dordrecht: Reidel), p. 195.
Vlahos, L. 1979, in *IAU Symposium 86, Radio Physics of the Sun*, ed. M. R. Kundu and T. E. Gergely (Dordrecht: Reidel), p. 173.
Vlahos, L., and Papadopoulos, K. 1979, *Ap. J.*, **233**, 717.
Vlahos, L., Sharma, R. R., and Papadopoulos, K. 1983, *Ap. J.*, **275**, in press.
Vlahos, L., and Sprangle, P. 1983, in preparation.
Zhao, R., and Jin, S. 1982, *Scientia Sinica*, **25**, 422.

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