PARTICLE ACCELERATION BY MAGNETOSONIC WAVES IN A CORONAL LOOP

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Abstract A model for the acceleration of electrons in a flaring coronal loop is described. The mechanism is stochastic acceleration by resonant interactions with a spectrum of compressive magnetosonic waves. Current results of test particle calculations examining the feasibility of this model are presented.

I. Introduction

The impulsive pha- of solar flares is characterized by strong emission of hard x-rays and of microwaves. The duration of this phase is brief ($\approx$ 1 min) and has a rapid rise time ($\approx$ 5 sec). We are investigating a model for the acceleration of the electrons responsible for the hard x-ray and microwave emissions. The mechanism we are considering is stochastic acceleration by magnetosonic turbulence excited by the flare primary energy release (Kulsrud and Ferrari 1971; Mel- -e 1980; Achterberg 1981; Forman, Ramaty and Zweibel 1986).

Our calculations differ from previous work in two respects: First, we assume that the turbulence is composed of the wave modes of a cylindrical loop. Second, rather than calculating the acceleration rate from quasilinear theory, we integrate particle orbits directly using the guiding center approximation.

II. Magnetosonic Waves in a Coronal Loop

We model a coronal loop by a straight magnetized cylinder of length L and radius a. The cylinder is embedded in an infinite medium of differing density, temperature and magnetic field strength. We require pressure balance as an equilibrium condition. The effects of gravitational stratification are neglected.

A dispersion relation for compressive magnetosonic waves in a magnetic fluxtube can be derived from the equations of ideal magnetohydrodynamics (MHD). The dispersion relation can be solved analytically in the limit of high frequencies, and numerically otherwise.

The character of the waves differs greatly depending on the frequency range under consideration. Certain modes are evanescent, having significant amplitude only near the tube wall at $r = a$. Other modes are oscillatory throughout the tube. The highest-frequency waves can propagate outside the loop, causing wave energy to be lost from the system. This leakage may be related to observations of sequential, spatially-separated flares, because it suggests that a disturbance could propagate from one loop to others nearby.

III. The Equation of Motion

In the absence of waves, particle motion consists of translation parallel to the ambient field combined with gyration perpendicular to the fieldlines at the cyclotron frequency $\Omega \equiv eB/mc$. For processes occurring over timescales and lengthscales long compared to the gyromotion, the particle's magnetic moment $\mu \equiv mv_\perp^2/2B$ is an adiabatic invariant. The particle can be confined in the coronal loop by the magnetic mirror force $-\mu\nabla B$, and can execute repeated bounces from one end of the loop to the other.

The magnetosonic waves considered herein create an a.c. electric field component E_{1z} directed along the loop axis. This electric field can accelerate particles. The physical origin of E_{1z} is as follows: A perturbation B_1 in the magnetic field creates a mirror acceleration $-(\mu/m)\nabla B_1 = -v_\perp^2\nabla B_1/2B$, which is typically larger for electrons (their mean $v_\perp$ being greater). This preferential acceleration causes a charge separation, which creates an electric field.

The equation of motion for an electron in the presence of a single wave is (Barnes 1967)

$$\frac{d^2z}{dt^2} = \left(\frac{\bar{\mu} - \mu}{m}\right)\frac{\partial B_{1z}}{\partial z}, \tag{1}$$

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where $\mu = \kappa T/B_0$ is the mean magnetic moment of the distribution (κ is Boltzmann's constant), and the right hand side is summed over all the wave modes in the system. We integrate this equation of motion numerically using a test particle approach.

IV. The Hamiltonian Formulation

One can derive the equation of motion (1) from a Hamiltonian which, in the rest frame of the wave, is

$$H = \frac{p^2}{2m} + (\mu - \mu) B_0 \left[1 + \frac{1}{2} b \sin(k_z z) \right] + \frac{1}{2} m v_\phi^2,$$

where b is proportional to the wave amplitude and v_ϕ is the parallel phase speed of the wave. Contours of this Hamiltonian are sketched in Figure 1.

The *separatrix* divides the position-momentum phase plane (z, p) into open and closed particle orbits. Particles within the separatrix contour are called *resonant* particles and are trapped in the wave potential. It is these particles which are most important for our acceleration mechanism. The half-height of the separatrix is given by

$$\Delta p_r \equiv (2mB_0|\mu^* b|)^{1/2}. \tag{2}$$

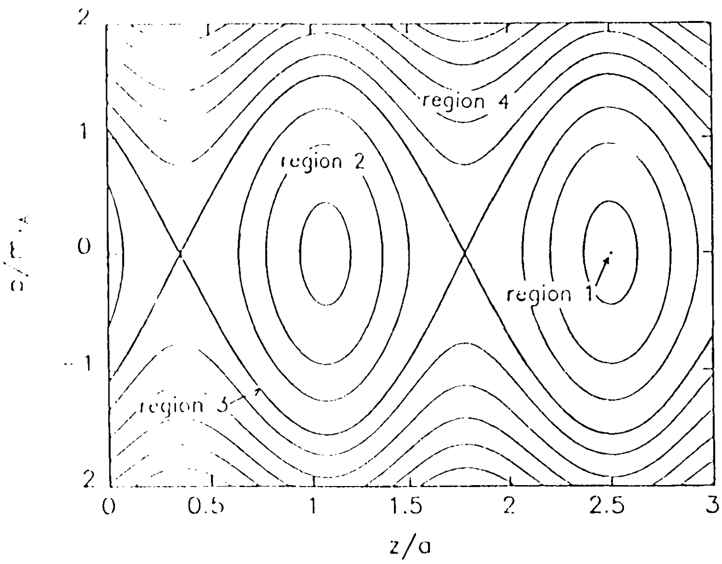

Figure 1 Contours of the Hamiltonian H in the wave rest frame. The scale on the ordinate is arbitrary. Region 1: Minima of the wave potential; particle is stationary in the wave reference frame. Region 2: Trapped region; particle oscillates about the wave speed. Region 3 (thicker contour): The separatrix; particle migrates towards $p = 0$ line. Region 4: Untrapped region; particle moves faster or slower than the wave.

V. Particle Acceleration

If a particle interacts with many waves whose separatrices overlap (in the fashion described below), the particle can move from one wave potential to another, thus diffusing in velocity space. The mechanism for electron acceleration we are investigating relies on this diffusion.

The basic idea is as follows: Electrons in the loop will initially be in resonance with those waves having phase speed v_ϕ near the electron thermal speed. The electrons can be trapped successively by waves of higher phase velocity; the speed of the particles can thus increase up to the maximum v_ϕ in the system. One can visualize this process as a particle "climbing a ladder" of overlapping wave potentials. Note that thermal electrons are accelerated; no injection of energetic particles is required.

Two waves have overlapping potentials when they are close enough in phase speed, and of sufficiently large amplitude, that the areas enclosed in the (z, p) plane by their separatrices intersect. This overlap criterion is not strictly correct, because each separatrix is calculated in its own rest frame and because there exist higher order resonances (due to wave-wave interactions) between the primary ones. However, we have found this criterion to be a useful diagnostic tool in predicting the onset of chaos.

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VI. Chaos

Particle trajectories in overlapping wave potentials are chaotic. This means, for example, that the orbits of particles with nearly identical initial conditions will diverge significantly with time. An example of this phenomenon is depicted in Figure 2, which shows the trajectories of three particles with slightly different initial velocities (the velocity differences are about 10^{-4} and 10^{-3} of the electron thermal speed). The calculated orbits differ significantly despite their initial proximity. This effect occurs regardless of the smallness of the integration timestep.

Because particle trajectories are chaotic, the precise trajectory of a single test particle is not the most physically meaningful quantity one can calculate. More important, for example, is the final state of an ensemble of test particles.

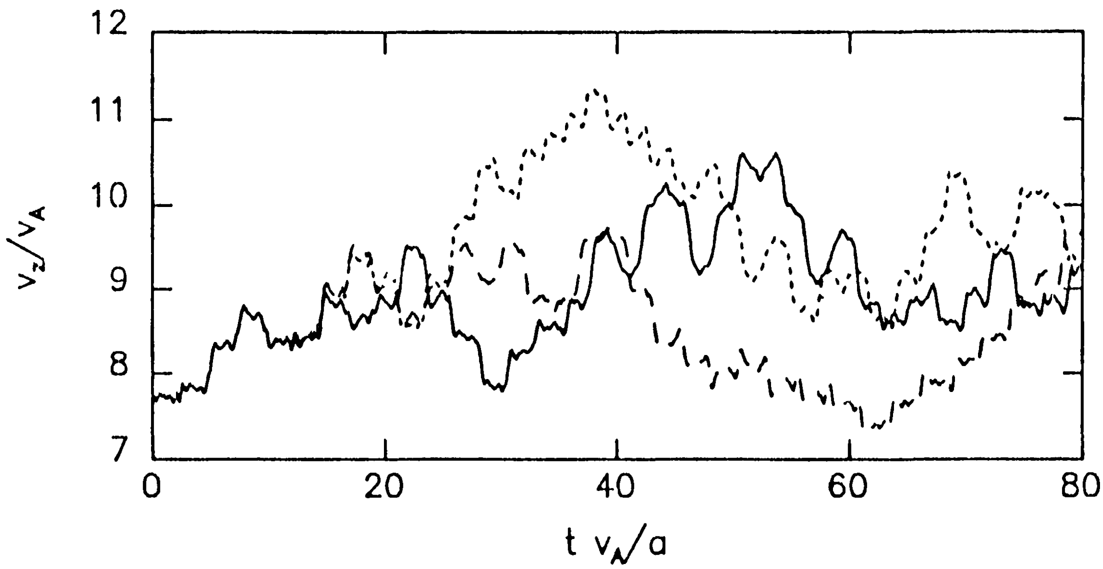

Figure 2 Trajectories of particles with slightly different initial velocities. Solid: $v_{zi} = 7.74500v_A$. Dotted: $v_{zi} = 7.74501v_A$. Dashed: $v_{zi} = 7.74510v_A$.

VII. Preliminary Results

We have begun a series of supercomputer calculations to determine the statistical behavior of electrons in the wave system. In these test-particle simulations we employ the guiding center approximation (in which the gyromotion of the particles is neglected), and we directly integrate the equation of motion (1). The calculations are still in the preliminary stages and program development is not yet complete, but some information has been gleaned from them.

A requirement of this acceleration mechanism is that the waves in the system overlap sufficiently to cover all of the relevant velocity range (from thermal energies to $\sim 10 - 100$ keV). We have found that this requirement imposes certain restrictions on the wave and particle parameters. Wave overlap depends on the separatrix half-height (eq. 2), which is a function of the wave amplitude b and of the particle's magnetic moment μ. Wave amplitudes are limited, however, by our use of linearized MHD to derive the dispersion relation. Consequently, only particles with large enough μ can diffuse throughout the entire velocity range. Pitch-angle scattering is therefore a necessary component of this mechanism.

Some of the waves used in these simulations are damped by leakage out of the tube, as discussed in Section II. The e-folding times range from 0.4 seconds to > 2 seconds. It is necessary, therefore, that waves be introduced into the system over some finite period, rather than instantaneously, to maintain the accelerating spectrum.

We have performed several simulations with the current version of the program. These are characterized by small particle numbers (≈ 100) and short elapsed times (1-2 seconds). Modest particle acceleration has been observed, but not to the energies required for solar flare impulsive phase emission. Figure 3 is a histogram of maximum particle energies reached within 1.5 seconds by a group of particles all initially at the thermal energy; the overall energy of the distribution has clearly increased.

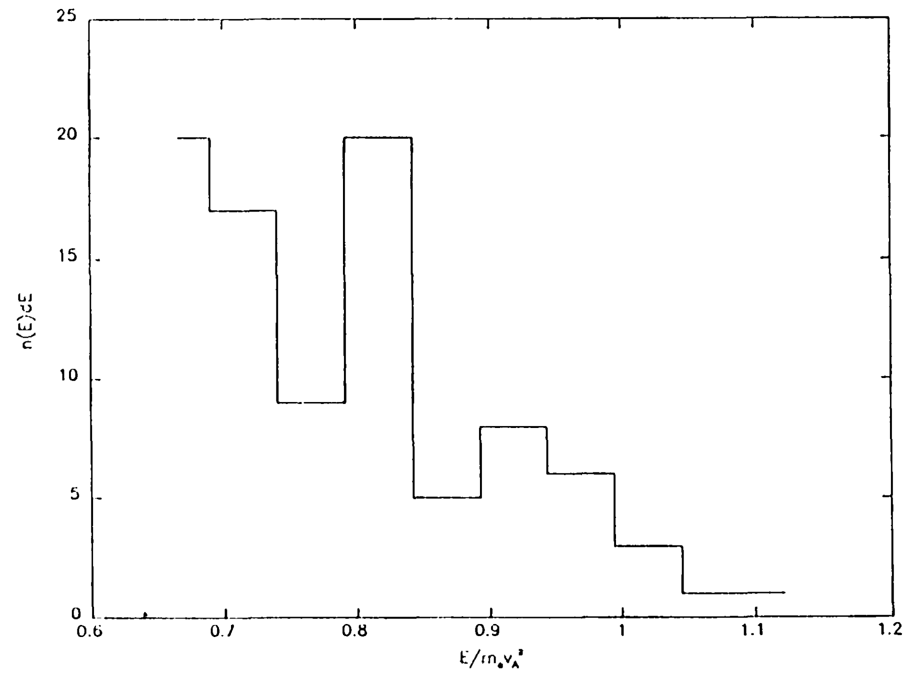

Figure 3 Histogram of maximum particle energies reached within 1.5 seconds. Initial particle energy $E_i = kT = 0.637 m_e v_A^2$. The simulation contained 90 particles, with initial pitch angles between 0 and 89 degrees.

VIII. Conclusion

We have presented preliminary results of a model for electron acceleration in a flaring solar coronal loop. We suggest that a spectrum of compressive magnetosonic waves will be established in the loop by the primary energy release event (*e.g.*, magnetic reconnection), and that particles will be accelerated via resonant interactions with these waves.

In future work this model will be investigated more fully. Simulations with larger particle samples and longer run times, and including effects such as particle scattering by very high frequency waves and prolonged introduction of wave energy, will be considered. It is clear even from the preliminary examples presented here that upwards diffusion in energy does occur. The efficiency and timescale of this acceleration mechanism remain to be determined, but this mechanism is a likely candidate for producing at least some of the hard x-ray and microwave emitting electrons.

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