FINAL REPORT

for

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"Stochastic Particle Acceleration in Impulsive Solar Flares"

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The acceleration of a huge number of electrons and ions to relativistic energies over timescales ranging from several seconds to several tens of seconds is the fundamental problem in high-energy solar physics. The cascading turbulence model we have developed has been shown previously (e.g., Miller 2000; Miller & Roberts 1995; Miller, LaRosa, & Moore 1996) to account for all the bulk features (such as acceleration timescales, fluxes, total number of energetic particles, and maximum energies) of electron and proton acceleration in impulsive solar flares. While the simulation of this acceleration process is involved, the essential idea of the model is quite simple, and consists of just a few parts:

1. During the primary flare energy release phase, we assume that low-amplitude MHD Alfven and fast mode waves are excited at long wavelengths, say comparable to the size of the event (although the results are actually insensitive to this initial wavelength). While an assumption, this appears reasonable in light of the likely highly turbulent nature of the flare.

2. These waves then cascade in a Kolmogorov-like fashion to smaller wavelengths (e.g., Verma et al. 1996), forming a power-law spectral density in wavenumber space through the inertial range.

3. When the mean wavenumber of the fast mode waves has increased sufficiently, the transit-time acceleration rate (Miller 1997) for superAlfvenic electrons can overcome Coulomb energy losses, and these electrons are accelerated out of the thermal distribution and to relativistic energies (Miller et al. 1996). As the Alfven waves cascade to higher wavenumbers, they can cyclotron resonate with progressively lower energy protons. Eventually, they will resonate with protons in the tail of the thermal distribution, which will then be accelerated to relativistic energies as well (Miller & Roberts 1995). Hence, both ions and electrons are stochastically accelerated, albeit by different mechanisms and different waves.

4. When the protons become superAlfvenic (above about 1 MeV/nucleon), they too can suffer transit-time acceleration by the fast mode waves and will receive an extra acceleration ``kick."

We envisage this acceleration process as occurring in the coronal portion of the flare loop, which is modeled by an ionized homogeneous plasma extending a distance L along a constant magnetic field $\mathbf{B}_0$. An important aspect of stochastic acceleration in general is that it is not directed, as with DC electric fields. This allows cospatial return currents to form, which draw particles up from the denser and cooler chromosphere, ensure charge neutrality, and provide the replenishment for the acceleration region that is necessary to sustain the large fluxes observed in some flares. We modeled this acceleration process with a self-consistent quasilinear simulation, in which stochastic particle acceleration, particle escape from the acceleration region, Coulomb collisions, wave cascading, wave damping by the particles, and acceleration region replenishment are all taken into account. We find that for a broad range of plasma density and magnetic field values, an injection of > 400 ergs/(s-cm^3) of both Alfven and fast mode waves at any wavelength throughout an acceleration region of scale size not exceeding several times 10^8 cm will account for all the major features of the energetic particles from even the largest impulsive solar flares.

The basic overall objective of this 1-year effort was to construct a spatially-dependent version of the above acceleration model. After the first year, this has been completed, along with about 90% of the next stage in the development of the simulation.

Specifically,

- We have developed a spatially-dependent acceleration theory employing the above idea of cascading MHD turbulence. We simulate this spatially-dependent acceleration process by using a novel discretization scheme, in which the coronal region of the loop is divided into a large number N of segments (of equal length L_i, such that $NL_i = L$), so that the particles and waves in each segment can be assumed to be homogeneous (but only throughout that segment). In each segment, the evolution of the protons and electrons is governed by Fokker-Planck equations and the evolution of the waves is determined by wave diffusion equations, which take into account damping by the energetic particles and cascading in wavenumber; these Fokker-Planck and wave diffusion equations are nonlinear and intimately coupled via the wave-particle resonant interactions that lead to stochastic acceleration. The escape of the particles and waves from each segment is taken into account with leaky-box loss terms in the Fokker-Planck and wave diffusion equations for that segment. These losses then form the input for the segments on either side, so that all segments communicate with their neighbors via the exchange of particles and waves. For the segment at the bottom of the coronal portion of the loop, escape out of the side next to the transition region leads to a cospatial return current from the chromosphere, which we model by a drifting Maxwellian and which ensures quasineutrality throughout the loop. This technique leads to a system of 4N coupled nonlinear partial differential equations (where N is typically of order 1000), which we solve using Chang-Cooper finite differencing. The resulting quasilinear simulation conserves energy and particles to within 1 part in 10^8, and is unconditionally stable in time.

Initial results from this work were presented by Miller, Newton, & Mariska 2000 (Lake Tahoe: 2000 AAS SPD Meeting; contributed poster) and Miller 2001 (Washington, DC: April APS Meeting; invited talk); the detailed theory and its application to solar flare particle acceleration observations will be submitted shortly (Miller, J. A., & Mariska, J. T. 2002, ApJ, to be submitted). Briefly, we find that incorporating the spatial transport of waves and particles over the coronal region of the flare loop decreases the efficiency of the acceleration mechanism by a couple tens of percent (depending on the parameters), which is mostly due to not being able to resupply the upper corona with fresh particles fast enough. However, we also find that bump-on-tail electron distributions are a common occurrence, which is an exciting finding in that such distributions are needed for the accepted theory of ^{3}He abundance enhancements in impulsive flares.

- We have also merged this spatially-dependent acceleration code with the NRL Dynamic Solar Flux Tube Model (DSFTM) hydrodynamic code, in order to properly take into account the evolution of the solar atmosphere in response to heating by the energetic particles, as well as the backreaction of this evolution on the acceleration process. During acceleration, huge fluxes of energetic electrons and protons will impinge upon the chromosphere, leading to chromospheric evaporation. This evaporation leads to density and temperature enhancements in the corona where the acceleration occurs, and will therefore affect its efficiency and behavior. A self-consistent treatment of both acceleration and atmospheric response is thus crucial in order to construct the most realistic solar flare acceleration model.

The DSFTM code solves the 1-(spatial)D hydrodynamic equations in computational cells, using a geometry (semicircular loop, constant magnetic field running along the axis of the loop) exactly the same as in the acceleration simulations. Hence, the combination of the spatially-dependent acceleration code discussed above and the hydrodynamic code is quite natural and unforced.

The initial conditions for the DSFTM code are the magnetic field magnitude, the chromospheric temperature, and hydrostatic equilibrium. Given a spatially- and time-dependent heat rate, the hydro equations are then finite differenced to yield the temperature, density, and bulk flow velocity in each cell. We take the cell or segment width in the DSFTM code to be the same as in the acceleration code, and corresponding to about 2000 segments throughout the corona. We have allowed the DSFTM code to be the "driver," and the acceleration code is a large subroutine that is called after each timestep in the driver routine. We first specify the number of cells and the density and temperature (and hence proton N^p_i and electron N^e_i distribution) in each, along with the spatial and time dependence of the wave injection. Initially, the particle distributions are thermal, but will quickly develop nonthermal tails in response to the waves. A single step forward in time then entails the following calculations: The acceleration code first advances the distributions N_i in each cell. Then, in each cell, we determine the thermal and nonthermal components of the distributions by fitting Maxwellians to the low-energy portion of the distributions. We keep track of both components for protons and electrons. The heating rate throughout the loop due to the nonthermal particles is now calculated. This heating rate is then used for the hydrodynamic response, and the hydrodynamic equations are advanced over the same time interval using the DSFTM code to obtain the new temperature, thermal-particle density, and bulk flow velocity in each cell. The thermal components to the particle distributions are then corrected for this new temperature and density. At this point, we will have stepped the particle distributions forward, taking into account both acceleration and hydrodynamic response. The whole process is then repeated for the next timestep.

We are presently in the testing phase of this study, ensuring that the combined simulation is working properly. We point out that this effort is the first of its kind in any field, and is the first time both micro- and macro-scopic processes have been taken into account in a unified treatment of particle acceleration. Preliminary results were shown by Miller & Mariska 2001 (Boston: Spring 2001 AGU Meeting; contributed poster). We hope to continue this research with subsequent grants.

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