

## Combining Hydrodynamics Modeling with Test Particle Tracking to Improve Flare Simulations

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**Abstract.** Accurate simulations of solar flares require accurately modeling of both the thermal and non-thermal particle distributions. Most current flare models concentrate on the evolution of the non-thermal particle distributions while treating the thermal plasma as static. In order to improve flare simulations Montana State University has developed simulation codes that couple the evolution of the non-thermal particle distribution and the thermal plasma of a flare in a self-consistent manner.

### 1. Introduction

We have combined thermal plasma and non-thermal particle numerical models in order to more accurately model solar flare behavior. The Particle Transport Code (PaTC) uses test particle tracking to simulate non-thermal electrons' or ions' interactions with background plasma as they move along magnetic field lines. The second code, called MSUloop, is a hydrodynamic equation solver that simulates the evolution of the temperature and density distribution along a magnetic field line, or loop, under the influence of gravity with a parameterized heating function. The non-thermal particle collision models provide heating and momentum deposition for the thermal plasma. The thermal plasma models in turn provide an evolving temperature and density structure for the non-thermal particles' target plasma. This allows us to simulate thermal and non-thermal flare emission under a variety of increasingly realistic solar conditions and provides a means to verify the predictions of multiple flare models with observed flare behavior.

### 2. Method

In this simulation, a loop was generated using a magnetic field model that exponentially decreases with height ( $B(h) = B_0 \exp\left(\frac{-h}{H_0}\right)$ ). This geometry does not represent a realistic solar loop, however, it makes for a test case that can be easily compared to analytical results. The loop was then given a temperature and density distribution according to the RTV scaling laws (Rosner et al. 1978) and allowed to come to hydrostatic equilibrium. Beams of non-thermal electrons, with an anisotropic pitch angle profile, were then injected into the loop apex. PaTC tracked the non-thermal test particles as they propagated through the model plasma. Energy losses and changes in the velocity component parallel to

the magnetic field due to collisions and magnetic effects were modeled for each test particle. The per collision changes to the energy and the parallel velocity are given by

$$\Delta E = \frac{-KE}{2} \left[ 1 - \cos \left( 2 \cdot \arctan \left( \frac{e^2}{b KE} \right) \right) \right] \quad (1)$$

$$\Delta v_{\parallel} = - \left( \frac{KE}{m_e} \right)^{\frac{1}{2}} \left[ 1 - \cos \left( 2 \cdot \arctan \left( \frac{e^2}{b KE} \right) \right) \right], \quad (2)$$

where  $KE$  is the kinetic energy of the test particle,  $e$  is the charge of an electron in e.s.u. units,  $m_e$  is the electron mass,  $b$  is the impact parameter which is derived from a random distribution where the minimum and maximum values of  $b$  are  $3\sigma$  from the distribution mean, and  $v_{\parallel}$  is the velocity of the test particle parallel to the magnetic field. The change in parallel velocity due to spatial changes in the magnetic field strength is given by

$$\delta v_{\parallel} = \frac{KE}{m_e} (1 - \cos^2 \alpha_p) \frac{d \ln B}{ds} \delta t, \quad (3)$$

where  $s$  is the loop coordinate and  $\alpha_p$  is the pitch angle of the particle. For more detailed explanations and derivations of the above equations see Tandberg-Hanssen & Emslie (1988) and Benz (1993).

The changes in energy and momentum of each test particle were multiplied by a scaling factor in order to represent the total non-thermal electron distribution. The losses of energy and momentum from the non-thermal electrons were then used as source terms for the thermal plasma. MSUloop then calculated the plasma's response to this input of energy and momentum and provided the temperature and density structure of the plasma, which were used as inputs for the next iteration of PaTC.

The calculation of the time-scale for the two codes to exchange information is still undergoing testing and revision. For the current simulation, this exchange time scale was defined to be the minimum time needed for information to propagate across a cell in the grid used in the MSUloop code,  $t_e = \min \left( \frac{\Delta x}{v_A} \right)$ , where  $v_A$  is the Alfvén speed in a cell and  $\Delta x$  is the length of the cell. The integration time step  $dt$  for the MSUloop code was determined by the Courant Condition of stability for each cell. For PaTC,  $dt$  was arbitrarily chosen to be a factor of  $10^{-2}$  shorter than the exchange time scale. These time scales provided stable results while allowing for a reasonable computational time.

Table 1.

A listing of the non-thermal particle properties

Total Energy Deposited into Loop	$10^{28}$ ergs
Non-Thermal Power Spectrum	$F(E) = F_0 E^{-3}$
Non-Thermal Particle Energy Range	25 – 50 keV
Time Profile	Heaviside Step
Beam Duration	3 seconds

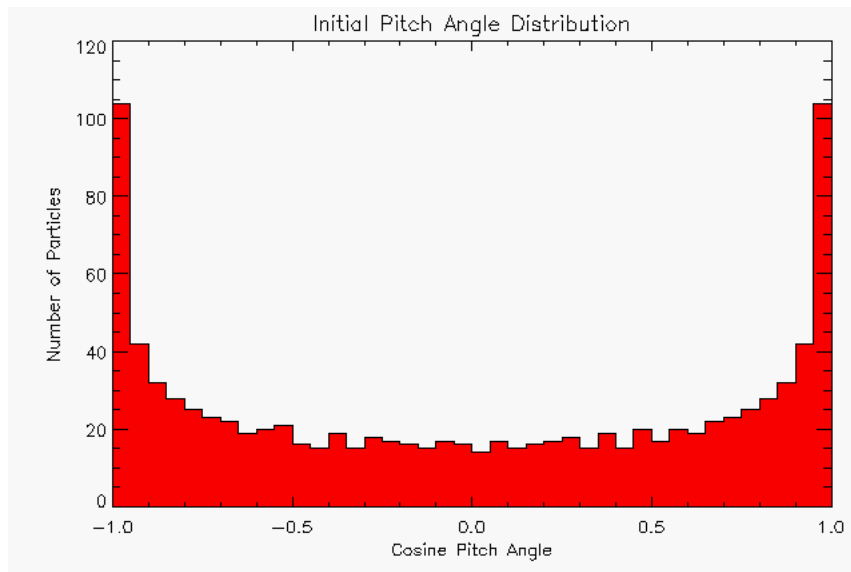


Figure 1. Initial pitch angle distribution of the non-thermal electrons.

### 3. Results

An electron beam as described by table 1 was injected into the loop apex and allowed to evolve in the loop described in section 2. There was an initial deposition of energy at the foot points followed by a long period of energy deposition at the loop top. The first effect was a result of non-thermal electrons in the loss cone precipitating quickly to the denser chromosphere where they are immediately thermalized. The longer period of energy deposition at the loop top at first seems counter-intuitive since the plasma density is much lower. Magnetic mirroring causes the non-thermal particles to spend a significant fraction of their time at the loop top causing more collisions per unit coronal loop length than would be expected in the non-mirroring case. The effects of magnetic mirroring in this simplified case are far more exaggerated than in a realistic solar loop, but it has been shown that mirroring is a factor in the generation of loop top hard X-ray sources observed in some flares (Fletcher & Martens 1998).

### 4. Future Work

This paper describes the early development of a suite of software designed to more accurately model solar flares. Codes have been developed to take the density and temperature profiles from the simulated loop and generate spectra that are then folded through various instrument response functions, such as XRT on Solar-B. This software will allow for direct comparison between theoretical models and observations. Hard X-ray emission is currently being modeled in order to compare with instruments such as HXT and RHESSI.

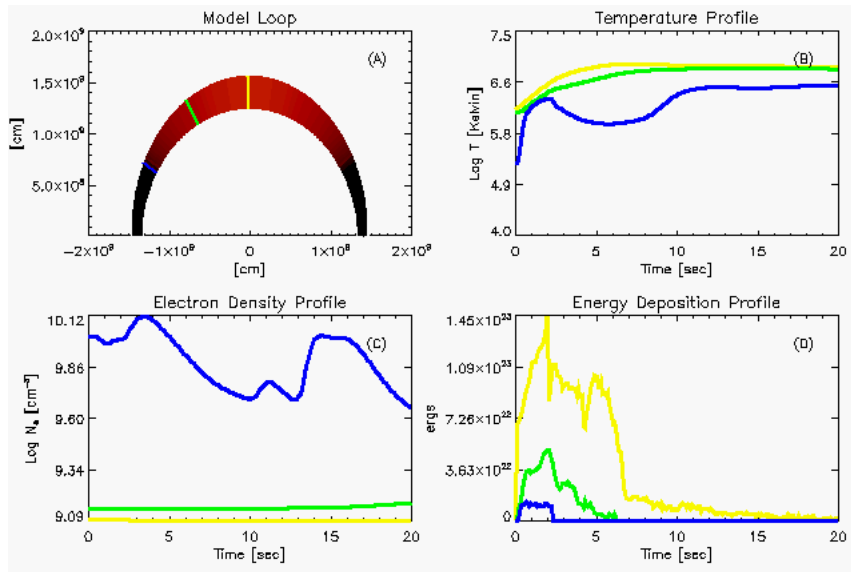


Figure 2. Time profiles of three positions on the modeled loop. Plot A shows the location of the three slices of the loop. Plot B shows the temperature variation in the three slices as a function of time. Plot C shows the time variation in the slices and plot D shows the total energy deposition in each slice by the non-thermal particles as a function of time.

Once the numerical models have completed testing against analytical solutions and the stability of solutions have been characterized as a function of grid cell spacing and test particle number, more realistic magnetic field models will be used in simulations. Initially, a Syrovatskii current sheet model will be used (Syrovatskii 1971). This will allow for comparison with works that model solar flares by other means (Fletcher & Martens 1998). Eventually, magnetic field extrapolations from data will be used to define the loop geometry in order to provide simulations that are primarily data driven.

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