Final Report

Studies of Particle Acceleration, Transport & Radiation in Impulsive Phase of Solar Flares

NAG5 11918-0002

3/15/02-3/14/05

Vahe Petrosian
Stanford University

1. INTRODUCTION

Solar activity and its most prominent aspect, the solar flares, have considerable influence on terrestrial and space weather. Solar flares also provide a suitable "laboratory" for the investigation of many plasma and high energy processes important in the magnetosphere of the Earth and many other space and astrophysical situations. Hence, progress in understanding of flares will have considerable scientific and societal impact. The primary goal of this grant is the understanding of two of the most important problems of solar flare physics, namely the determination of the energy release mechanism and how this energy accelerates particles. This is done through comparison of the observations with theoretical models, starting from observations and gradually proceeding to theoretically more complex situations as the lower foundations of our understanding are secured. It is generally agreed that the source of the flare energy is the annihilation of magnetic fields by the reconnection process. Exactly how this energy is released or how it is dissipated remains controversial. Moreover, the exact mechanism of the acceleration of the particles is still a matter of debate. Data from many spacecrafts and ground based instruments obtained over the past decades have given us some clues. Theoretical analyses of these data have led to the standard thick target model (**STT**) where most of the released energy goes into an (assumed) power law spectrum of accelerated particles, and where all the observed radiations are the consequence of the interaction of these particles with the flare plasma. However, some theoretical arguments, and more importantly some new observations, have led us to believe that the above picture is not complete. It appears that plasma turbulence plays a more prominent role than suspected previously, and that it is the most likely agent for accelerating particles. The model we have developed is based on production of a high level of plasma waves and turbulence in the reconnection region above a flare loop. This turbulence accelerates particles stochastically which radiate some of their energy in this region but carry most of their energy to the footpoints of the loop, where they lose all their energy and radiate bulk of the observed radiation as in the traditional thick target model. In the past we have worked on various aspects of this model. We have evaluated the interaction rates of the plasma waves with electrons and ions, developed theoretical frameworks for the acceleration, transport and radiative processes, and produced numerical codes for the investigation of these processes. The goal of this grant has been further development and testing of this new paradigm, with emphases on the relative acceleration of electrons and ions and on a comprehensive investigation of the turbulence generation, cascade, and damping processes. In the next section we review several pieces of important evidence that we have uncovered indicating the crucial roles of turbulence, in section 3 we describe accomplishments during the past two years of this grant.

2. Evidence In Support of Turbulence

- **Broad band X-ray and gamma-ray observations** show breaks, cutoffs with power-law or thermal like spectra in between. We have shown that these are reflection of the electron spectrum and must be produced in the acceleration site. The varied shapes arise from competitions between the acceleration, energy loss and spatial diffusion or escape processes while the particles are interacting with the turbulence and background plasma.

- **The presence of distinct looptop (LT) and footpoint (FP) emissions** discovered by *Yohkoh* has been confirmed by *RHESSI*. Moreover, the higher spatial and spectral resolution of *RHESSI* reveals more details, which can be accounted for with the stochastic acceleration of electrons by turbulence. In particular, as shown in Figure 1 (left panel), this process produces a softer spectrum of electrons at the LT and a harder one at the FPs in agreement with observations. In addition, the relative importance of the softer (quasi-thermal) and harder power-law components depends on the level of the turbulence, which can explain observations such as the soft-hard-soft evolution seen during the rise and fall of the impulsive emission. (see also item 1 in the next section).

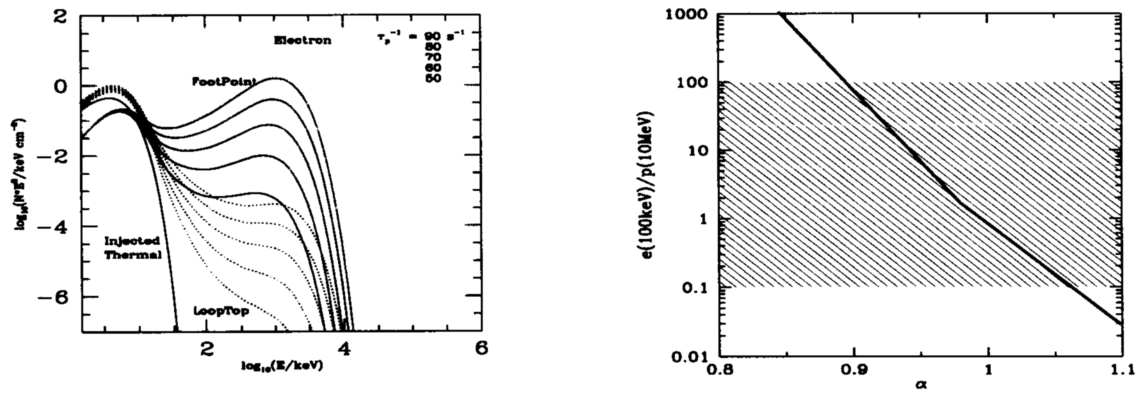

Fig. 1.— **Left panel:** Electron distributions at the LT (dotted) and (the thick target equivalent) FPs (solid). From top to bottom, the turbulence energy density decreases monotonically as indicated in the figure. The black solid line shows the distribution of the injected (background) thermal electron distribution. **Right panel:** The dependence of the number density ratio of the accelerated 100 keV electrons to that of the 10 MeV protons on the plasma parameter $\alpha \propto n^{1/2}/B$. Proton acceleration is more efficient than electrons in weakly magnetized plasmas (with large values of α). The shaded region corresponds to the observed region of this ratio for several big flares with prominent ion nuclear line emissions.

- **Protons as well as electrons** can be accelerated by this model. In fact as shown in Figure 1 (right panel), the ratio of proton to electron acceleration varies with the plasma parameter $\alpha^2 \propto n/B^2$, where n and B are the electron density and magnetic field strength, respectively. This variation can easily accommodate the observed range of this ratio (shaded region).

Some of the details of the above mentioned aspects can be found in Petrosian & Liu (2002, paper 1) and other references cited there.

3. New Accomplishments

During the past three years in addition to continuing our work on comparing the *RHESSI* results with our basic model (see paper 2) we have tackled the difficult problem of the relative acceleration of ^{3}He and ^{4}He observed in SEPs, and coupling of the turbulence with the background plasma and the accelerated electrons and ions.

- **Turbulence During the Decay Phase.** Our analyses of several *RHESSI* flares show that during the decay phase the rate of the energy decay of the emitting plasma confined to the LT region does not agree with the rate expected due to either the (classical-Spitzer) conduction or radiation, or both. We have shown that this discrepancy can be overcome by the combined effects of the suppression of the conductivity and the heating of the background plasma by a level of turbulence lower than that in the impulsive phase, suggesting continued energy release via generation of turbulence by slow reconnection. A paper describing this work is in its final stage for submission to publication (paper 3).

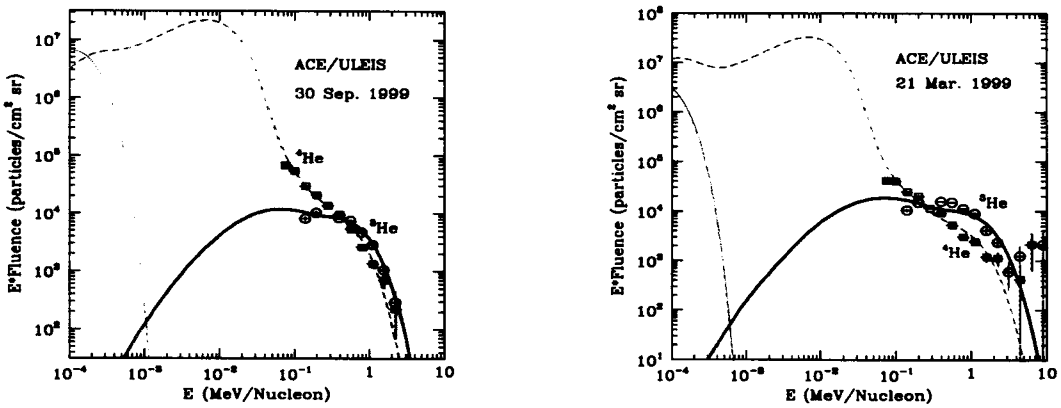

Fig. 2.— Model fit to the spectra of ^{3}He and ^{4}He for two impulsive SEPs. The thin solid line gives the injected ^{4}He distribution. The acceleration of ^{4}He is suppressed by a barrier at $\sim$ 100 keV/nucleon. All of the injection ^{3}He ions, however, are accelerated to hundreds of keV/nucleon energy range.

- **Acceleration of ^{3}He and ^{4}He.** An important achievement of our work has been described in two papers (Liu, Petrosian & Mason 2004, and 2005 in press; papers 5 and 6) where we have shown that the long standing paradox of the extreme enhancement of ^{3}He relative to its photospheric abundance observed in impulsive SEPs can be reproduced by our model. In addition, we can also derive spectra in good agreement with observations. Figure 2 shows two sample spectral fittings from the above works.

- **Damping of Turbulence.** We have carried out a detailed analysis of damping of MHD turbulence (Alfvén, slow and fast modes) by collisional ion viscosity, by collisionless thermal viscosity and due to generation of nonthermal electrons and protons. By comparing the viscous and cascade rates we determine the possible ranges of cutoff scale of the turbulence. In particular we have addressed the angular dependences of these processes and shown that considerable anisotropy is expected, which can have profound influence on the acceleration rate of particles. Figure 3 shows a sample result from this work which is also at its final stage of preparation for publication (paper 7).

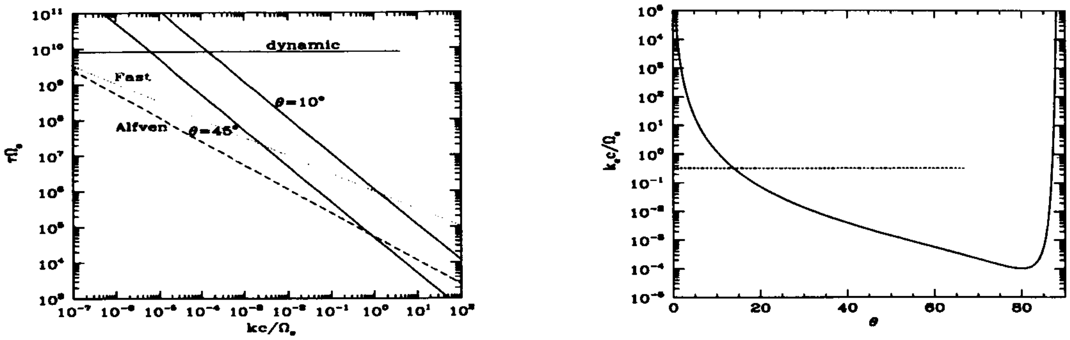

Fig. 3.— **Left panel:** The dependence of the cascade and damping time scales on the wave vector k, where c is the speed of light and Ω_e is the electron gyrogrequency. Above the critical k defined by the intersections the waves are damped. Note that the damping time depends on the wave propagation angle θ with respect to the magnetic field. The physical parameters chosen are typical to solar flares. **Right panel:** The dependence of the critical wave vector k_c on θ. The dotted line indicates the gyroscale of the thermal background protons.

- **Correlation of the ^{3}He enhancement and ^{4}He spectral softness.** According to the SA model proposed above for the ^{3}He enhancement, we expect a correlation between the ^{3}He to ^{4}He ratio and the ^{4}He spectral softness. A preliminary analysis of ACE observations of impulsive SEPs by G. Mason appears to confirm this prediction (private communication). We have begun to investigate this aspect more quantitatively. Figure 4 (left panel) compares with the data some preliminary results from our model fittings.

- **Heavy ion enhancements.** The impulsive flares, which show pronounced ^{3}He enhancement, also show enhancements of heavier ions monotonically increasing with the mass M to charge Q ratio or the mass of the ions. Our study of turbulence damping suggests that high frequency waves propagating nearly parallel to the large scale magnetic field play crucial roles in accelerating ions from a thermal background and producing the observed enhancements. We have initiated this work. There are many uncertainties here. The most important one is that we do not know the ionization states of these elements, which determine the acceleration (via Q/M) and loss ($\propto Q^2/M$) rates. In addition the acceleration rate is very sensitive to the Q/M ratio when this is near 0.5. Figure 4 (right panel) shows a preliminary result, where we have assumed a constant charge $Q = 16$ for elements heavier than iron. The agreement between this model prediction and the data seems encouraging so we intend to continue this line of investigation in particular for intermediate ions.

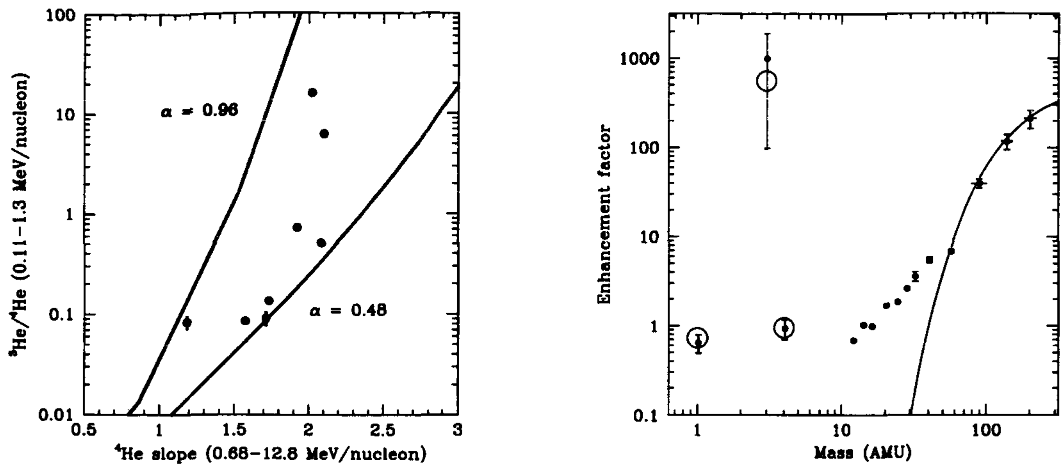

Fig. 4.— **Left panel:** Comparison of model predictions with observations of the correlation between the ^{3}He to ^{4}He ratio and the ^{4}He spectral index. We note that the range of the plasma parameter α is consistent with that for the acceleration of electrons and protons. **Right panel:** Enhancement of ions in impulsive SEPs. The red dots are the observed mean enrichment factor. The open circle and the solid line show the results from a SA model.

4. Published and Other Papers

1. Pertosian, V. & Liu, S., "Stochastic Acceleration of Electrons and Protons. I. Acceleration by Parallel-Propagating Waves", 2002, ApJ, 610, 550

2. Liu, W., Jiang, Y, Liu, S., & Petrosian, V., "RHESSI Observations of a Simple Large X-Ray Flare on 2003 November 3", 2004, ApJLetters, 611, 53L

3. Jiang, Y., Liu, S., Liu, W., & Petrosian, V., "Evolution of the Loop Top Source of Solar Flares — Heating and Cooling Processes", 2005, ApJ (in press)

4. Liu, S., Petrosian, V. & Mason, G., "Stochastic Acceleration of 3He and 4He by Parallel Propagating Plasma Waves" 2003, ApJLetters, 613, 81L

5. Liu, S., Petrosian, V. & Mason, G., 2005, "Stochastic Acceleration of ^{3}He and ^{4}He in Solar Flares by Parallel Propagating Plasma Waves: General Results, ApJ (in press)

6. Petrosian, V., Yau, H. & Lazarian, A.,"Cascade and Damping of Turbulence and Particle Acceleration during Solar Flares" (2005), ApJ (in press)

In addition to the above paper published in refereed journals we have presented many papers (oral and poster) in many scientific meetings and given invited talks at several international conferences.