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FINAL REPORT

for

Ion Acceleration and Transport in Solar Flares

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Principal Investigator:

James A Miller 18 Aug 97

James A. Miller, Associate Professor
Department of Physics
The University of Alabama in Huntsville
Huntsville, AL 35899
Telephone: (205) 890-6276 Ext. 210
e-mail: miller@mpingo.uah.edu

Research Administrator:

Sue B. Weir

Sue B. Weir
Office of Research Administration
The University of Alabama in Huntsville
Huntsville, AL 35899
Telephone: (205) 890-6000

1. Final Report

The purpose of the work proposed for this grant was to develop a promising model for ion acceleration in impulsive solar flares. Solar flares are among the most energetic and interesting phenomena in the solar system, releasing up to 10^{32} ergs of energy over timescales ranging from a few tens of seconds to a few tens of minutes. Much of this energy appears as energetic electrons and ions, which produce a wide range of observable radiations. These radiations, in turn, are valuable diagnostics of the acceleration mechanism, the identification of which is the fundamental goal of solar flare research.

The specific mechanism we proposed to investigate was based on cascading Alfvén waves, the essence of which was as follows: During the primary flare energy release, it is widely believed that magnetic free energy is made available through the large-scale restructuring of the flare magnetic field. Any perturbation of a magnetic field will lead to the formation of magnetohydrodynamic (MHD) waves of wavelength comparable to the initial scale of the perturbation. Since the scalesize of a flare energy release region will likely be 10^8–10^9 cm, the MHD waves will be of very long wavelength. However, it is well known that wave steepening will lead to a cascade of wave energy to smaller wavelengths. Now, MHD waves consist of two specific modes—the Alfvén wave and the fast mode wave, and it is the Alfvén wave which can interact with the ambient ions and accelerate them via cyclotron resonance. As the Alfvén waves cascade to smaller wavenumbers, they can resonate with ions of progressively lower energy, until they eventually (actually, this is less than ≈ 1 s) can resonate with ions in the thermal distribution. These ions are then energized out of the thermal background and, since lower-fequency waves are already present as a result of the cascading, to relativistic energies. Hence, cascading Alfvén waves naturally accelerate ions from thermal to relativistic energies in one step with one basic mechanism.

In *Miller and Roberts* [1995], we examined this scenario with a quasilinear code which solved simultaneously and self-consistently the Fokker-Planck equation for proton acceleration and the wave diffusion equation for Alfvén wave cascading. We considered two different cascading phenomenologies: Kolmogorov and Kraichnan. We found that the injection of $\approx 400\,\mathrm{ergs\,cm^{-3}}$ of Alfvén waves at any scale and over any time likely to be realized in a flare is sufficient to accelerate $\gtrsim 3\times10^5\,\mathrm{protons\,cm^{-3}}$ to energies > 30 MeV on time scales ~ 1 s. For a volume $\gtrsim 10^{27}\,\mathrm{cm}^3$, the total number of > 30 MeV protons is consistent with that inferred from gamma-ray line emission. This total wave energy density is about the lower limit of what is needed to account for the observed energy content of the protons. Hence, our model can explain the most important features of impulsive flare proton acceleration in a basically parameter independent manner. Some of our specific results were:

1. Spectral energy transfer in the Kolmogorov model is more rapid than dissipation by the energetic protons at high frequencies, leading to the acceleration of a relatively large number of protons out of the thermal distribution to relatively low energies. In contrast, wave energy transfer in the Kraichnan model is much slower than dissipation, and a smaller number of protons are accelerated to much higher energies.

2. At energies where acceleration is faster than escape, the spectrum of trapped protons is approximately a power law with index $(s-5)/2$ in the nonrelativistic regime and with index $(s-3)/2$ in the relativistic regime, where s is the index of the wave spectral density. These spectra are thus harder than those resulting from diffusive shock acceleration, and the spectra of the protons that have escaped from the acceleration region are even harder. In Kolmogorov cascading, these power laws are typically confined to energies below the nuclear line production thresholds, while in the Kraichnan case they can easily extend up to $\approx 1\,\mathrm{GeV}$.

3. The general nature of the spectrum of accelerated protons can be determined analytically over a wide range of turbulence injection scenarios. While the precise spectral shape requires a quasilinear simulation, spectral density normalizations, acceleration time scales, the energy at which the proton spectrum rolls over due to escape, and the proton spectral index below this energy, can be determined analyically without the detailed simulation.

In *Smith and Miller* [1995] we considered the effects of nonlinear Landau damping on proton acceleration. Nonlinear Landau damping is a wave-particle-wave process, wherein two Alfvén waves form a beat wave with a longitudinal electric field which is then able to Landau damp on the ambient ions. This process leads to rapid and efficient ion heating and is able to increase the efficiency of stochastic acceleration by cyclotron resonance by increasing the number the protons at slightly suprathermal energies. We derived quasilinear diffusion coefficients for nonlinear Landau damping and then examined proton acceleration in the presence of both processes with a quasilinear simulation. We found that the efficiency of Alfvén wave acceleration is indeed significantly increased and that low levels ($\delta B/B \ll 1$) of Alfvén waves are able to energize enough protons above $\approx 10\,\mathrm{MeV}$ to account for the gamma-ray line emission in typical impulsive solar flares.

Lastly, in an invited paper [*Miller*, 1995], we considered the controversy commonly referred to as the "solar flare myth," which consists of attributing terrestrially-significant events (e.g., power outages, communication interruptions) to solar flares instead of (correctely) to their cousins the coronal mass ejections.

2. References

Listed below are the papers that were funded by this grant. All three papers are in refereed journals.

Miller, J. A., & D. A. Roberts, Stochastic proton acceleration by cascading Alfvén waves in impulsive solar flares, *Astrophys. J.*, *452*, 912, 1995.

Smith, D. F., & J. A. Miller, Alfvén turbulence dissipation in proton injection and acceleration in solar flares, *Astrophys. J.*, *446*, 390, 1995.

Miller, J. A., Much ado about nothing?, *Eos Trans. AGU*, *76*, 401, 1995.