Energetic Particles Accelerated by a Parallel Collisionless Shock Wave

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July, 1991

Abstract

Presented here are recent results from computer simulations of the energetic charged particle environment near "nominally" parallel shocks. The Fermi mechanism is the dominant accelerating process at such shocks. The most serious problem associated with the theory of this mechanism is that until recently, it has been largely unknown how particles get extracted out of the thermal population into the "seed" energies which are assumed in analytical models. To address this question, we present the results of a self-consistent numerical calculation in which the protons of the plasma are treated discretely (by solving their Lorentz force equation) and the electrons are treated as a massless fluid. In this calculation, Maxwell's equations are solved to obtain the variation of the electric and magnetic fields. With such a tool at our disposal, not only is it possible to see how protons are accelerated from thermal energies to seed energies, but we are also able to investigate the effect that the energetic particles (which have been injected into the Fermi process) have on the fields which provide their scattering centers. A comparison of the results obtained from the computer simulation with actual spacecraft observations in the region near the Earth's bow shock will also be given.

1 Introduction

Collisionless plasma shock waves for a long time have been known to accelerate protons to high energies both in the "scatter-free" limit, where the particle gains energy by drifting along the shock front [Armstrong, *et al.*, 1985], and via a statistical process whereby the particle is scattered across the shock by converging scattering centers (imbedded in the flow on either side of the shock) [Forman and Webb, 1985]. In both of these theories, it is assumed that the "seed" particles already have an energy that is large enough that the interaction time with the shock is very long (note that low energy particles are convected through very rapidly since they move with the bulk of the plasma) and the efficiency of the mechanism will be the greatest. Note that even when a considerable amount of wave activity exists near the shock, the energy gain resulting from the drift along the shock front cannot be neglected [Decker and Vlahos, 1986]. The main concern then is by what process do thermal particles get injected into seed energies? This question has long concerned observationalists and theorists since the discovery of energetic particles coincident with observed shock waves in space. Only recently has some progress been made [Burgess, 1987; Scholer, 1990].

The description of the plasma and fields near a parallel shock (one in which the propagation direction of the shock is anti-aligned with the incident magnetic field) is considerably more complicated than that of a perpendicular shock [Quest, 1988] The following scenario is currently accepted: large amplitude magnetic waves exist upstream of the shock front, which are created by particles that have been reflected by the shock; these waves have phase velocities, in a frame co-moving with the plasma, directed away from the shock, however, they get convected into the shock since their phase speed is smaller than that of the incoming plasma; the waves are thus steepened as they make the transition into the downstream where they eventually decay. The three regions of a parallel shock are (1) upstream, characterized by long wavelength, small amplitude wave structures, (2) shock transition region, characterized by smaller wavelength, larger amplitude waves and finally (3) the downstream region, characterized by longer wavelength, smaller amplitude, decaying waves. Note that because of the large amount of wave activity near the shock, the local angle between the shock normal and incident magnetic field may significantly depart from zero.

2 The Model

The numerical model that has been employed is known as the hybrid simulation program [Winske and Leroy, 1984], which models the plasma as consisting of two charged particle species; protons and electrons. Observations of collisionless shocks suggest that the electron kinetics does not play a major role in the structure of the shock, hence, the hybrid model treats the electrons as a massless fluid while the protons are treated kinetically by solving their Lorentz force equation. The model described here sets up a Maxwellian plasma which flows from left to right in a simulation "box". The plasma is then turned around by a rigid wall at the right hand boundary. A shock wave results from the interaction of the reflected stream of protons with the incident stream. The shock wave then propagates from right to left in the simulation box. Since a reflected particle may exit the region of upstream waves (to the left), and therefore exist the system without ever having a chance to scatter back towards the shock, we inject a background spectrum of waves, with a spectral index consistent with observations, into the system at the start. We maintain the injection of the waves at the left boundary as time proceeds in the simulation. This allows particles to be scattered back to the shock after initially reflecting and helps initialize of the Fermi process.

Since it is expected that only a small number of particles will ever reach the energies that we wish to investigate (typically there are 150,000 simulation particles, while there are usually only one or two with energies of over 50 keV) we improve the high energy particle statistics by "splitting" simulation particles, as they cross various energy levels, into two particles which each contribute 1/2 to the density and fields. This allows for a greater number of particles with large energies while maintaining the self-consistency of the simulation. In the simulations performed here, we use 20 energy levels starting with 2.5 times the ramming energy of the plasma ($\sim 0.5keV$) and ending with 200 times this value (the particles that have crossed the 20^{th} energy level each contribute 2^{-20} to the fields and density, and similarly for the other levels). At the end of the simulation there are typically 80,000 particles that have been split and more than half of these have energies larger than 50 keV.

3 Numerical Simulation Results

In Figure 1, we display the x *vs. time* trajectory of a typical, strongly energized particle superimposed on a stack plot of the transverse magnetic field component B_y (upper panel). The stack plot is produced by off-setting 1-D snap-shots of B_y at increasing times, thereby giving the temporal evolution of the component. In the lower panel, we display the particle's kinetic energy, in a frame that is moving with the shock, as a function of it's position. In this panel, the shock is located at 600 c/ω_i ($1\ c/\omega_i \simeq 100\ km$ for typical solar wind conditions at 1 A. U.). This particle is a good example of the initial energization from thermal energy into an energy in which Fermi acceleration is clearly taking place. The initial energization is accomplished by drifting along the shock front due to the ∇B force. In this case the particle drifted along the shock at a time when the local angle between the incident magnetic field and shock propagation direction was near perpendicular. After which, it scattered in the upstream and downstream waves, which move with different velocities. All of the energetic particles that we have looked at display similar tendencies, i.e., the initial acceleration takes place near the shock (shock drift acceleration), however, the amount of energy that they gain in this initial burst varies (from $\sim 1 - -20keV$).

In Figure 2, we display upstream and downstream energy spectrum of protons based on the computer simulation model described above (lower panels) and actual spacecraft observations (upper panels) [Ellison, *et al.*, 1990]. Two distinct populations of particles are clearly seen in the upstream distributions: the solar wind population with $E \sim 1\ keV$ and the diffuse population with

$E \sim 10\ keV$. The energy falls off drastically as a power law for $E > 20\ keV$ as seen in both observations and simulations. There is also a noticeable lack of particles between the two populations indicating that the process which extracts particles from the thermal population into diffuse particles occurs very near the shock front (see above). The downstream distribution, in contrast, is very broad. However, there is a noticeable "shoulder" about $E \sim 10\ keV$, which leads to a power law decline at higher energies.

4 Conclusion

We have displayed results from recent numerical simulations (hybrid model) of proton acceleration from thermal energy to suprathermal energies by a parallel (on average) shock. We conclude that particles are accelerated from thermal energies to "seed" energies via shock drift acceleration, i.e., the initial acceleration process occurs very near the shock front for several ion gyro–periods. Once accelerated to a high enough energy, Fermi acceleration becomes the dominate process, energizing protons from a few keV to more than 100 keV. The proton energy spectra obtained from the computer simulations are in very good agreement with differential fluxes of protons observed in the Earth's foreshock.

Acknowledgments

I wish to thank David Burgess, Steve Schwartz and Don Ellison for their contributions to this work in which a more detailed manuscript will soon be submitted.

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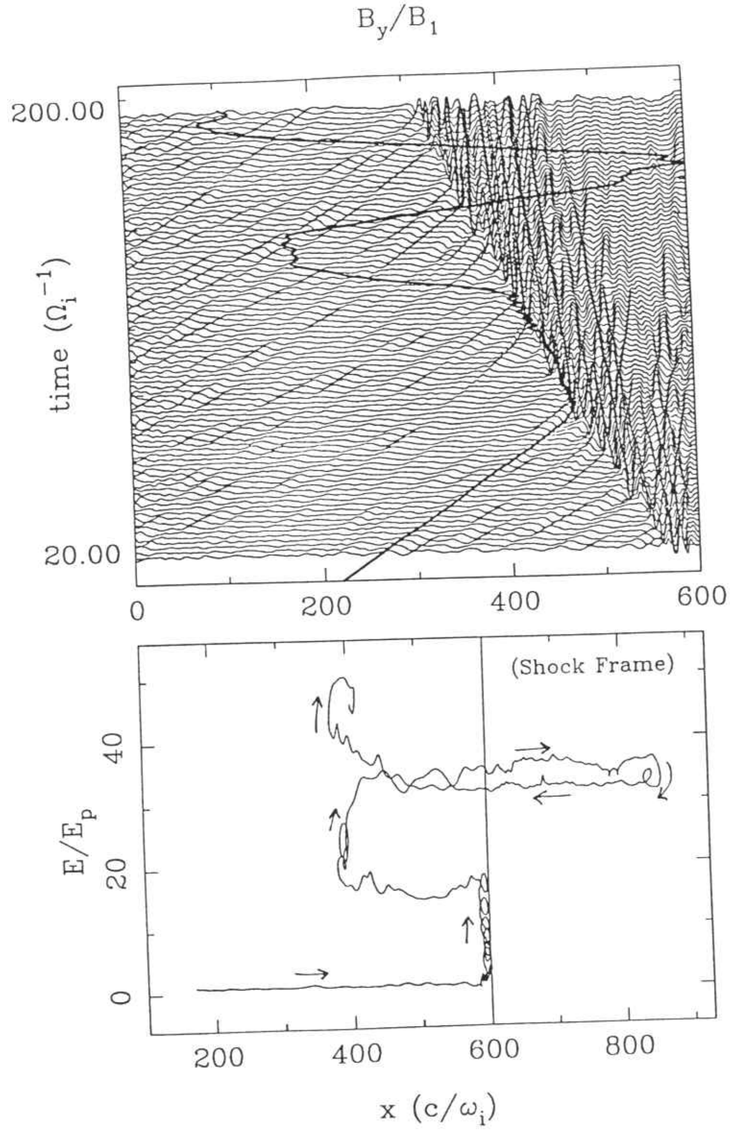

Figure 1. Upper panel: A typical particle trajectory in x *vs. time* space superimposed on a stack plot of the transverse magnetic field component (see text). Lower panel: The kinetic energy (normalized to the plasma ramming energy $\frac{1}{2}mU_1^2$) of the particle whose trajectory is displayed in the upper panel, as viewed in the shock frame of reference (note that the trajectory in the upper panel is displayed in the simulation frame of reference).

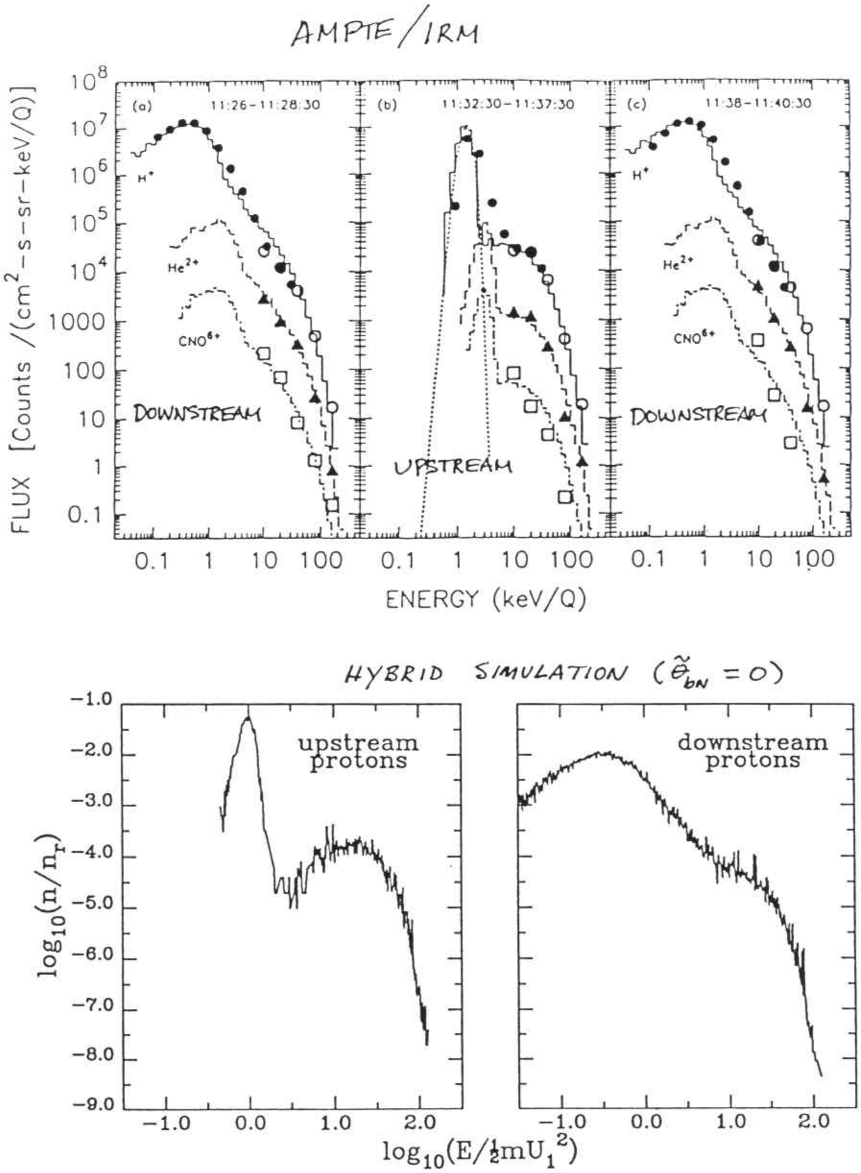

Figure 2. Upper panels: Observed differential fluxes of protons (and other elements) in the Earth's foreshock region (from Ellison, *et al.*, 1990). The left and right panels are downstream events, while the middle panel is upstream of the bow shock. Lower panels: Simulated proton distributions upstream (left panel) and downstream (right panel) of a "nominally" parallel shock. The energy is normalized to the plasma ramming energy.