Energetic Electrons Associated with Transient Interplanetary Shocks: Evidence for Weak Interaction

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Abstract

Energetic Storm Particle (ESP) events are increases of energetic charged particle intensities observed upstream and downstream of interplanetary (IP) shocks. The solar wind plasma and magnetic field instruments on the ACE spacecraft have detected over 160 transient IP shocks during the period September 1997 to December 2001. More than a half of these shocks produced ESP signatures in the intensities of >47 keV ions, as measured by the EPAM instrument on ACE. However, only relatively few events (28) produced ESP signatures for >38 keV electrons. We studied the spectral indices of both ions and electrons in these electron ESP events and compared them to the steady-state diffusive shock-acceleration prediction based on the shock strength. We found that the majority of the measured events do not follow the prediction. In addition, both ion and electron spectra soften at the shock in the ACE data set, in agreement with a weak (single-interaction) shock drift acceleration. We therefore conclude that the shock interactions for >38 keV electrons and >47 keV ions at 1 AU are weak, and consequently that the strong interaction (i.e., multiple shock crossings) description is usually not applicable to ESP shock events.

1. Introduction

Traveling shocks in interplanetary (IP) space have been known to accelerate ions up to high energy (> MeV). There have been numerous statistical studies on ion acceleration at IP shocks [1,2]. However, there are far fewer reports on electron acceleration at shock-associated Energetic Storm Particle (ESP) events. The relatively few reports on electron acceleration associated with IP shocks show that enhancements of electrons with energies more than a few tens of keV are rare [1,3,4]. Statistical studies on IP shock acceleration for low energy (∼few keV) electrons were reported by Potter [3] and Tsurutani and Lin [1] using data from ISEE-3. We report here a statistical survey of 38-315 keV electrons associated with IP shocks for the solar cycle 23.

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2. Observations

Energetic ion and electron data from the Electron, Proton, and Alpha Monitor (EPAM) on board the Advanced Composition Explorer (ACE) spacecraft were used in this study [5]. ACE detected over 270 IP shocks from September 1997 through 2001, of which we analyzed 167 that are forward transient shocks. A study of the time-intensity profiles for both energetic ions and electrons and the timing of these shocks has been reported by Lario et al. [6]. The summary of that earlier study is that: (1) Over 60% (102 events) of IP transient shocks produced ion enhancements at 47 keV or above. (2) However, less than 17% (28 events) of IP transient shocks produced electron enhancements at 38 keV or above. (3) The peak intensity of both the energetic ions (>47 keV) and electrons (>38 keV) was usually delayed two minutes from the passage of the shock at the spacecraft. (4) Step-like post-shock increases are much more common in the electron than in the ion fluxes.

Here, we study the spectral indices of both ions and electrons for 28 IP shocks that have energetic electron (>38 keV) enhancements. The electron spectra in these ESP events are well characterized by a power-law with spectral indices between 2 and 3. Fig. 1a (1b) shows the spectral indices of electron (ion) spectra before the onset of the ESP event (i.e., ambient) and at the shock. The diagonal line indicates when the spectral slope at the shock is identical to that of the ambient particles. Only small changes in the spectral indices for both ions and electrons are observed at the shock. In addition, almost all of the events in both Fig. 1a and 1b lie above the diagonal line, which indicates that both ion and electron spectra soften at the shock.

We have calculated the local shock parameters for twelve of these 28 events as shown in Fig. 2. The solid line in the figure is the relationship predicted by steady-state diffusive shock acceleration theory: γ=(H + 2)/(2H - 2), where γ is the spectral index, and H is the shock density compression ratio. The majority of the measured events do not fall within the area of the prediction. This is contrary to what was found on ISEE-3, where 75% of the ion events were consistent with the predicted γ [2]. In a preliminary analysis of an event that enhanced both ions and electrons and had ion signatures consistent with the predictions of the diffusive shock-acceleration theory [7], we find that the expected increase in the magnetic wave power spectrum is missing at frequencies that would resonantly scatter energetic particles. Fig. 3 shows magnetic spectra upstream of the associated strong shock (H=3.62). At the indicated cyclotron frequency, we see neither excess wave energy nor a helicity signal, as would be expected. Wave excitation by injection of suprathermal protons is expected to be maximal at frequencies near the proton cyclotron frequency [7]. In many cases the helicity or polarization can be used to detect low amplitude wave growth not readily evident in the power spectrum.

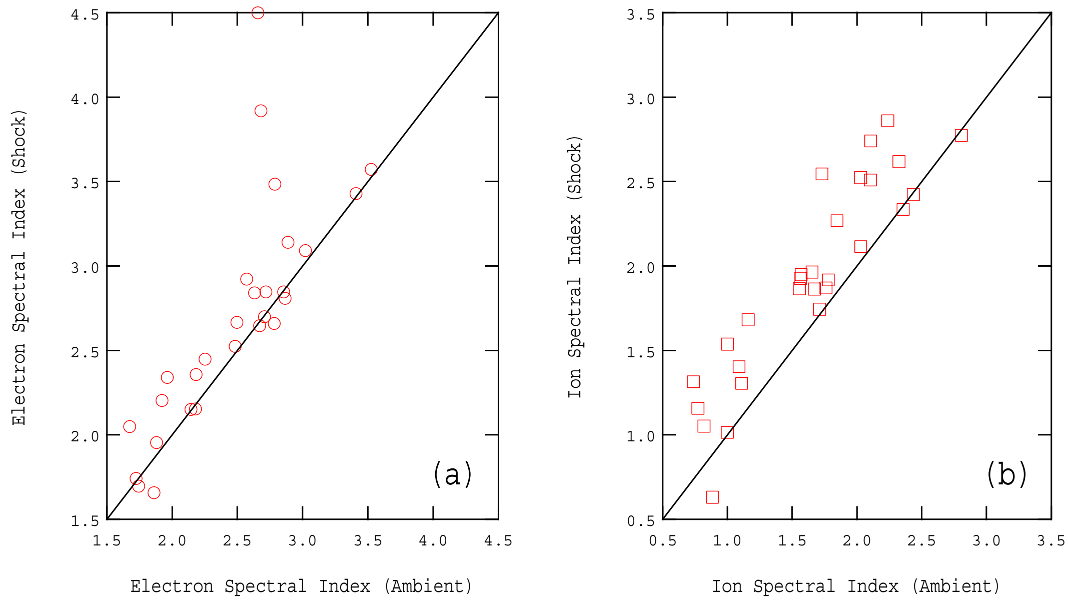

Fig. 1. Two-minute average spectral indices of electron (a) and ion (b) before and at the shock. All indices fall above the diagonal lines which indicate the spectra slope soften at the shock passage.

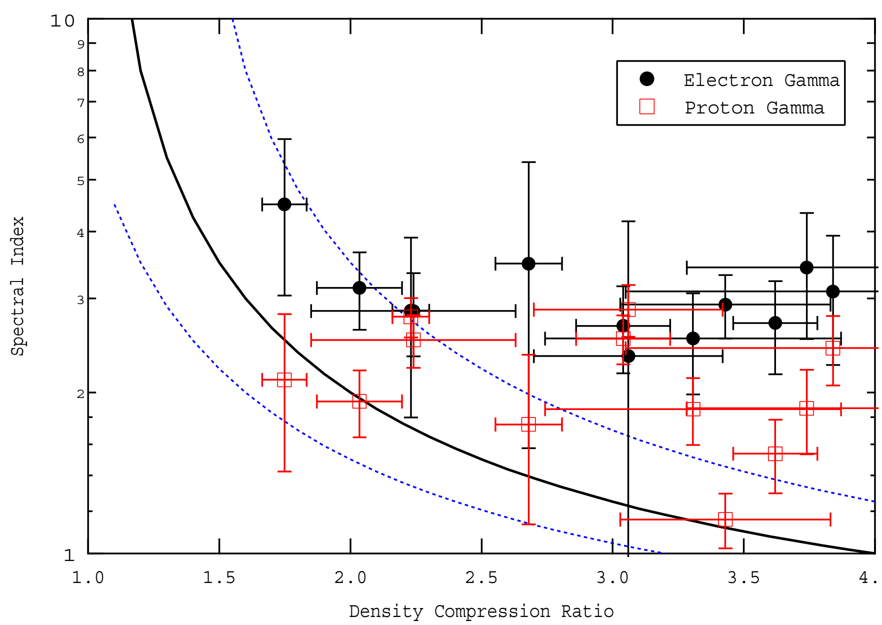

Fig. 2. Comparison of ion and electron spectral index of 12 ESP events with the shock compression ratio. The solid line is the predicted diffusive shock relationship, and dashed lines indicate a ±25% uncertainty.

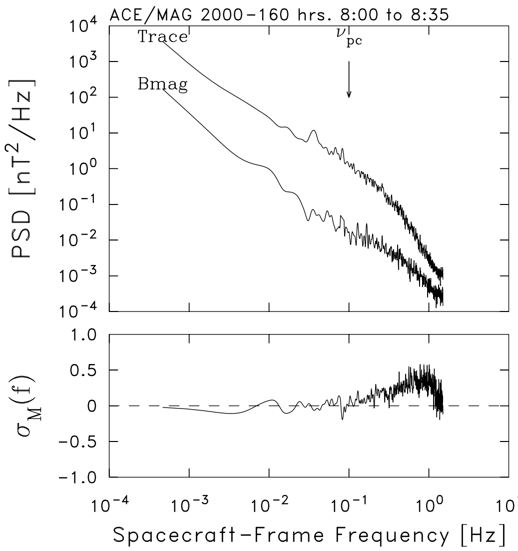

Fig. 3. Magnetic power spectrum (top) and normalized helicity spectrum (bottom) for 35-min interval immediately prior to crossing the shock on day 160 of 2000. Both the trace spectrum and the spectrum of the |B| time series are shown. The proton gyrofrequency is marked on the top panel. A narrow enhancement is seen in both curves in the top panel reflecting the spin tone of the spacecraft.

3. Summary

We report the spectral indices of 28 IP shocks that have electron enhancement at energies >38 keV. Both ion and electron spectra soften at the shock passage, which is in agreement with a weak (single-interaction) shock drift acceleration simulation [8]. In addition, the ion and electron spectra do not follow the diffusive shock theoretical prediction for an equilibrium spectrum (many shock interactions). The expected wave activity at frequencies near the proton cyclotron frequency is absent in one of the events we studied. Hence, we conclude, based on our statistical study, that the shock interactions for >38 keV electrons and >47 keV ions at 1 AU are weak, and consequently that the strong interaction description may not be applicable to ESP events in the current solar cycle.

4. References

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