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Finite Time Shock Acceleration and Fits to ESP Ion Spectra

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Energetic storm particles (ESP) of various ions species have been shown to comprise suprathermal seed ions accelerated by traveling interplanetary shocks. The observed spectral rollovers at $\sim$ 0.1 to 10 MeV/nucleon can be attributed to the finite time available for shock acceleration. Using the locally measured shock strength parameters at ACE as inputs we have successfully fitted the energy spectra of carbon, oxygen, and iron ions measured by the ULEIS instrument during three ESP events. We find evidence in favor of enhanced acceleration by proton-amplified waves for very intense ESP events.

1. Introduction

The solar system is pervaded by energetic particles, including Galactic cosmic rays and particles from various sources within and around the solar system. All of these particles, with the exception of those from impulsive solar flares, are believed to result from the Fermi acceleration mechanism [1], later developed into the theory of diffusive shock acceleration [2, 3, 4]. The basic theory predicts a power-law spectrum $N(p) \propto p^{-\gamma}$, such as that observed for Galactic cosmic rays. However, in many cases the observed spectrum of particles from sources within the solar system rolls over at a certain energy, E_c, i.e., the power-law does not persist to high energies. A spectrum that rolls over is often fit to a form suggested by [5]: $j(E) \propto p^{-\gamma} \exp(-E/E_c)$. They suggested that various physical mechanisms could possibly lead to such a rollover, and each mechanism could yield a different value of E_c.

The present work is motivated by observed spectra of particles of enhanced intensity in association with the passage of interplanetary shocks, known as energetic storm particles (ESP) [6]. These typically exhibit spectral rollovers at 0.1 to 10 MeV nucleon^{-1} [7, 8]. We consider that the physical origin of such rollovers is the finite time available for shock acceleration. This effect was discussed by [9] and [10], and is also evident in Monte Carlo simulations of particles injected at low energy [11]. The present work derives a simple model of finite-time shock acceleration (FTSA) and explores implications for the composition dependence of the spectrum. Given that recent composition measurements argue for a seed population at substantially higher energies than the solar wind [12], we use the ambient spectrum as an input to the FTSA model. We then fit spectra for carbon, oxygen, and iron ions for 3 ESP events as measured by the Ultra-Low-Energy Isotope Spectrometer (ULEIS) instrument on board the *Advanced Composition Explorer* (*ACE*) spacecraft. We are able to infer a key parameter of shock acceleration, the scattering mean free path in the acceleration region, as well as its rigidity dependence.

2. Finite Time Shock Acceleration Model

We have developed a finite-time shock acceleration (FTSA) model [13] based on the probabilistic model of [2, 3]. The key quantities are the number of acceleration events, n, the rate of acceleration events, r, the rate of escape ϵ, and the duration of the shock acceleration process, t.

We develop a numerical model that can be used to fit observed spectra of energetic storm particles (ESP). In particular, we aim to input observed seed spectra and use realistic formulae for r and ϵ as a function of energy at an oblique shock. Since the energetic ions mostly travel along magnetic field lines, we consider a fixed set of field lines (a flux tube) and the evolution of $N(p,t)$, the momentum distribution of ions in the acceleration region within that flux tube as the shock propagates outward.

We define an acceleration event as one cycle of diffusion back and forth across the shock. On average, after n acceleration events we have

$$p_n = p_{n-1}\left[1 + \frac{4}{3}\frac{u_1 - u_2}{v_{n-1}\cos\theta_1}\right], \tag{1}$$

where v_n and p_n are the velocity and momentum after n times, u is the fluid speed along the shock normal, θ is the magnetic field-shock angle, and subscripts 1 and 2 are for upstream and downstream, respectively [3]. The typical time for an acceleration event is

$$\Delta t_n = \frac{4}{v_n}\left\{\frac{\kappa_1 \sec\theta_1}{u_1} + \left[1 - \sqrt{1 - (B_1/B_2)}\right]\frac{\kappa_2 \sec\theta_2}{u_2}\right\}, \tag{2}$$

where κ is the spatial diffusion coefficient along the shock normal and B is the magnetic field magnitude. The factor in square brackets is the fraction of upstream particles that is transmitted downstream. We then set $r_n = 1/\Delta t_n$. We use formulae from [14] in the limit that $\lambda = \lambda_1$, the upstream parallel mean free path, is much greater than the gyroradius:

$$\kappa_1 = \frac{v\lambda}{3}\cos^2\theta_1 \qquad \kappa_2 = \frac{v\lambda}{3}\frac{\cos^3\theta_2}{\cos\theta_1}. \tag{3}$$

Finally, the escape rate ϵ is slightly modified from [2] and [3] to account for the convective flux upstream:

$$\epsilon_n \quad = \quad \left[\frac{v_n\cos\theta_1}{4u_2}\left(1 + \frac{u_1}{v_n\cos\theta_1}\right)^2 - 1\right]^{-1} r_n. \tag{4}$$

The processes of inflow of the seed population, acceleration, and escape can be expressed in a Fokker-Planck equation as follows:

$$\frac{\partial N(p,t)}{\partial t} = I(p,t) - \frac{\partial}{\partial p}\left[R(p,t)\,N(p,t)\right] - \epsilon(p,t)N(p,t), \tag{5}$$

where $N(p,t)$ is the momentum distribution of ESP, $I(p,t)$ is that of inflowing ions, and $R(p,t)$ is the acceleration rate, equivalent to $r_n(p_{n+1} - p_n)$. In practice, we discretize this as an initial-value system of ordinary differential equations:

$$\frac{dN_n(t)}{dt} = I_n - (r_n + \epsilon_n)N_n(t) + r_{n-1}N_{n-1}(t). \tag{6}$$

If there were no shock, we would have $N = N_{seed}$, the seed spectrum, and the inflow would balance escape from the region of interest with $I = \epsilon N_{seed}$. Therefore we use this inflow condition and set the initial condition to $N = N_{seed}$. When performing numerical simulations to fit observed shock-accelerated spectra, we fix the shock acceleration parameters over the duration of the ESP acceleration process, simply because their time variation is not precisely known. Thus the parameters r_n, ϵ_n, and λ represent average values experienced by the measured ESP particles. We consider λ, the upstream scattering mean free path along the magnetic field in the shock acceleration region, to be

$$\lambda = \lambda_0 \left(\frac{P}{1\ \mathrm{MV}} \right)^{\alpha}. \tag{7}$$

We use the fourth-order Runge-Kutta method to solve the system of equations (6), and convert the result to a spectrum in energy per nucleon (E/A).

For non-relativistic ions, we expect a rollover in energy per nucleon at

$$\frac{E_c}{A} = \frac{Q^2}{A^2} \frac{e^2}{2m_0 c^2} \left[P_0^{\alpha+1} + (\alpha+1) C \frac{A}{Q} t \right]^{2/(\alpha+1)}, \tag{8}$$

where A and Q are the ion mass and charge numbers respectively, m_0 is an atomic mass unit, e is an elementary charge, P_0 is the minimum rigidity, and C is a constant independent of P, A, and Q. For a rollover well above the injection threshold,

$$\frac{E_c}{A} \propto \left(\frac{Q}{A} \right)^{2\alpha/(\alpha+1)} t^{2/(\alpha+1)}. \tag{9}$$

Note that [15] has discussed a power-law dependence on Q/A for solar energetic particles.

3. Results and Discussion

Figure 1 show results of FTSA simulations of C, O, and Fe ions in IP shock Event#1 (June 26, 1999), Event#2 (September 22, 1999) and Event#3 (October 5, 2000). In Event#1 we use parameters u_1 = 131.0 km/s, u_2 = 56.5 km/s, θ_1 = 50°, θ_2 = 73°, B_1/B_2 = 2.2, t = 84.3 hours, λ_0 = 0.004 AU, and α = 0.07. In Event#2 we use parameters u_1 = 131.0 km/s, u_2 = 54.6 km/s, θ_1 = 64°, θ_2 = 79°, B_1/B_2 = 2.3, t = 60.5 hours, λ_0 = 0.042 AU, and α = 0.10. In Event#3 we use parameters u_1 = 188.0 km/s, u_2 = 78.3 km/s, θ_1 = 66°, θ_2 = 80°, B_1/B_2 = 2.3, t = 99.3 hours, λ_0 = 0.240 AU, and α = 0.18.

Using the observed upstream spectrum as the input seed spectrum and using the measured shock geometry, the FTSA model provides a good fit to spectra of C, O, and Fe ions observed by *ACE*/ULEIS for three energetic storm particle (ESP) events. In practice, when the shock-accelerated spectra are fit to the spectral form of [5], the parameters γ and E_c can vary erratically from element to element [7] and may incorporate properties of both the seed spectrum and shock acceleration. Our FTSA fits provide a physical parameter, the scattering mean free path $\lambda = \lambda_0 (P/\mathrm{MV})^{\alpha}$ in the acceleration region.

The inferred values of the local scattering mean free path λ in the acceleration region are important for qualitative understanding of shock acceleration in the interplanetary medium. Our fits to ion spectra of Event 1 (1999 June 26) indeed yield a low λ for this major ESP event, with $\lambda = 4.0 \times 10^{-3}$ AU at 1 MV. For Events 2 and 3, λ is similar to typical IP conditions. This confirms that proton-amplified waves [16] are apparently significant for ion acceleration in major ESP events but not for weaker ESP events.

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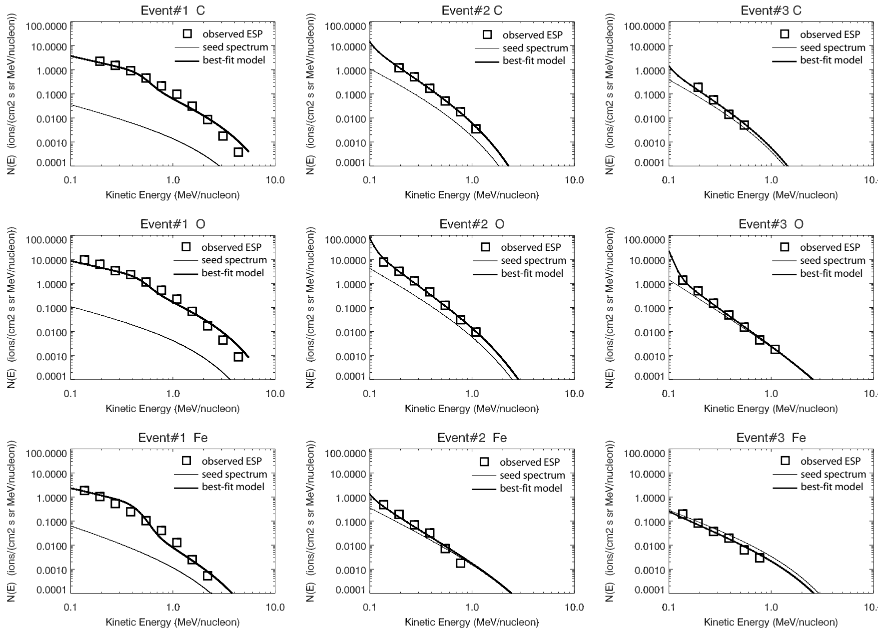

Figure 1. Observed shock-accelerated spectra, observed seed spectra, and model shock-accelerated spectra for C, O, and Fe ions in three interplanetary shock events.

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