# Particle Acceleration at Coronal Mass Ejection-driven Shock Waves: Modeling of Enhancement in Low-energy Range of a Proton Flux

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**Abstract**

We study time evolution of an energy spectrum of a proton flux in the range of 47 - 4750 keV for the energetic particle event occurred on 255 DOY in 1999. It is found that the energy spectrum in lower energy range, less than 0.5 MeV, enhanced faster, that is, the spectrum gets softer. We also analyze the magnetic field data to find energy dependence of a diffusion coefficient. We perform modeling this event by numerical simulations using Stochastic Differential Equation method. Our simulation results suggest that insufficiently accelerated particles may exist around 1 AU to explain the evolutionary behavior of the energy spectrum.

## 1. Introduction

Coronal Mass Ejection (CME)-driven shock accelerated particle events are roughly divided into two groups, large X-ray solar flares are associated with the source CMEs, or not. We called Type 2 events for the former, and Type 1 events for the latter in our classification of energetic particle events (Den, et al. 2001, call Paper 1 hereafter, also see Kallenrode, 1996, and Reames, 1999 for general review). In Paper 1, we studied shock accelerated energetic particle events with energies ranging from 47 keV to 4.75 MeV using particle data observed by the Electron, Proton and Alpha Monitor (EPAM) onboard the ACE spacecraft and pointed out that the maximum energy of accelerated particles classified in Type 1 is less than 10 MeV and that of accelerated particles classified in Type 2 is greater than 10 MeV.

In this paper, we present a report of analyses of the energetic particle event occurred on 255 DOY in 1999 which is considered as a typical Type 1 event. We investigate the interplanetary magnetic field fluctuations, and obtain time evolution of the energy spectrum using MAG and EPAM data respectively. Numerical simulation results of particle acceleration process are presented to explain the

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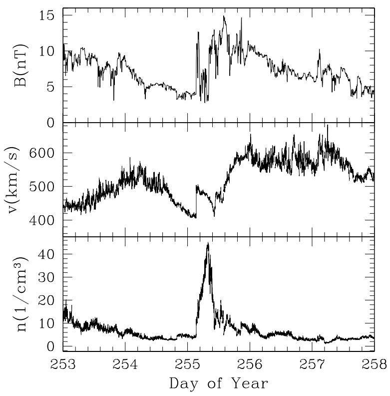


Fig. 1. Intensity of an interplanetary magnetic field, the solar wind speed and the density for the period 253 to 257 DOY.

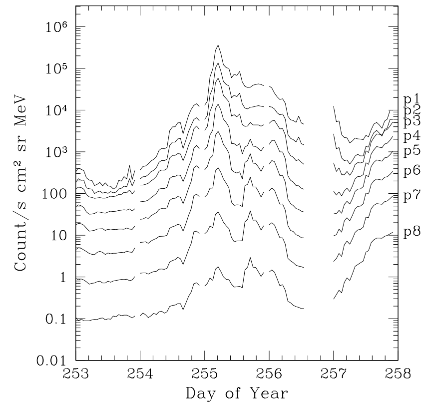


Fig. 2. Intensity-time profile of particles with eight energy channels, p1-p8, for the same period as Figure 1.

energy spectrum, and implication of injection models is discussed.

## 2. Observation

We study the observation of the energetic particle event have occurred on 255 DOY, 1999, and used the data obtained by SWEPAM, MAG and EPAM onboard the ACE. Figure 1 shows the solar wind data from 253 to 257 DOY, 1999. The interplanetary shock wave passed at 03:22 UT on 255 DOY. The compression ratio of the solar wind density is 2.4. Figure 2 is time profile of the particle flux with the energy range, p1 47-65 keV, p2 65-112 keV, 112-187 keV, p4 187-310 keV, p5 310-580 keV, p6 580-1060 keV, p7 1060-1910 keV and p8 1910-4750 keV. The flux began to enhance about two days in advance of the shock passage and this behavior can be used to predict the shock arrival. Time evolution of the energy spectrum obtained from the observational data is presented in Figure 3. It is pointed out that the flux in the lower energy range increases faster than the one in higher energy range. We return this point in next section.

Wave excitation is important for diffusive shock acceleration, and we investigate the interplanetary magnetic field fluctuations. A diffusion coefficient parallel to the field, $\kappa_{||}$, is $\sim (1/3) r_g v B_0^2 [k P_{AA(k)}]^{-1}$, where $v$, $B_0$, $r_g$, $k$ are a particle speed, a background magnetic field, a gyroradius and a wave number respectively (Drury, 1983). The spatial power spectrum of the field irregularities, $P_{AA}(k)$, or $P_{AA}(f)$ with $k = 2\pi f / V_w$ is the Fourier transformation of the correlation function of the magnetic field fluctuations, $C_{AA}(\tau) =< B_1(t) B_1(t+\tau) >$, where $B_1(t) = B(t) - B_0$ and $V_w$ is a solar wind velocity (Jokipii, 1973). Figure 4 shows the spatial spectrum. We obtained $P_{AA}(f) \propto f^{-1}$ and $k P_{AA}(k) \sim$ const., therefore $\kappa_{||} \propto (1/3) r_g v \propto E$ where $E$ is a kinetic energy of a particle. This dependence of a diffusion coefficient indicates the lower energy particles are

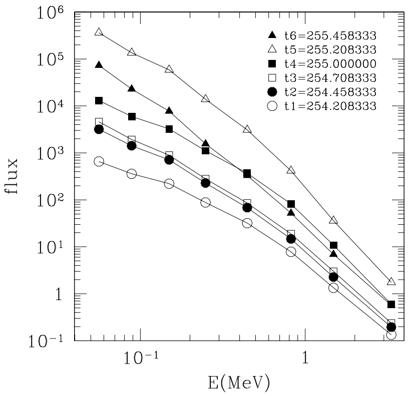


Fig. 3. Evolution of an energy spectrum for the event 1999 Sep. 12 (255 DOY).

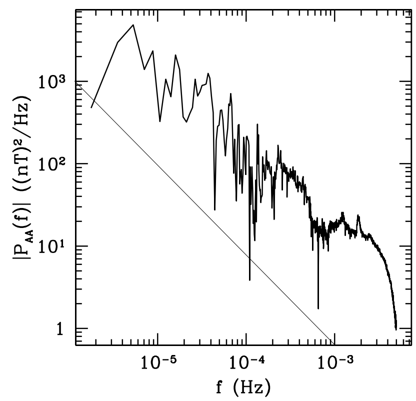


Fig. 4. The spatial power spectrum of the interplanetary magnetic field irregularities.

accelerated in the shorter acceleration time, that is, the lower energy particles are accelerated faster than the higher energy particles and this effect makes the spectrum harder.

## 3. Numerical simulations and results

We use Stochastic Differential Equation method to solve Fokker-Planck equation, and particle splitting method is coupled to keep resolution for higher energy particles (see Paper 1 or Den et al., in press). To clarify effect of different injection models, we adopt simple assumptions: the space is spherical symmetry, the shock speed $V_{\text{shock}}$ and the diffusion coefficient $\kappa$ are constant and uniform. We used observational data as $V_{\text{shock}} = 396$ km/sec and $\kappa = 8.45 \times 10^{18}$ cm$^2$/sec which was obtained by fitting the solution of the ideal diffusive shock acceleration, $f_p \propto \exp(-x/(\kappa/V_{\text{shock}}))$, to the observational particle flux where $f_p$ and $x$ is the particle flux and spatial length respectively (Blandford and Ostriker, 1978).

Two kind of injection of particles can be considered, continuously and impulsively injection for the simulation method used here. We present two models in this report. Model A: The whole particles with 20 keV are injected continuously. Model B: 20 % of the whole particles with 100 keV are injected impulsively at 0.9 AU and the remains with 20 keV are injected continuously. Both Figures 5 and 6 present simulated energy spectra obtained by the particles placing around 1 AU for Model A and Model B respectively. It should be noted that evolution of the energy spectrum obtained by the whole particles is different from that obtained by the particles placing around 1 AU (see Den, et al., submitted). In Figures 5 and 6, the dashed line indicates the spectrum at the shock passage time. Model A cannot explain the energy spectrum of the observation because the energy spectrum evolves to be harder, on the other hand, in Model B, the flux at the shock passage time is highest and the spectra are not hard, therefore

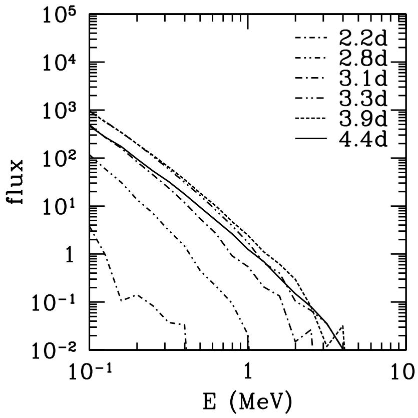


Fig. 5. Simulated evolution of the energy spectrum for Model A.

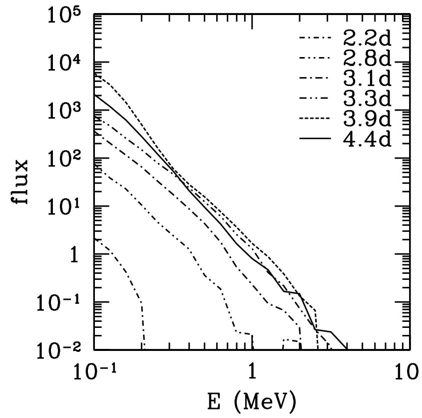


Fig. 6. Simulated evolution of the energy spectrum for Model B.

Model B is one of proper injection models.

## 4. Concluding remarks

We have investigated the interplanetary magnetic field fluctuations and have performed modeling of typical events classified in Type 1. We obtained that the diffusion coefficient is in proportion to the particle energy. Our simulation results suggest that insufficiently accelerated particles with about 100 keV near 1 AU are needed to explain the time evolution of the energy spectrum for Type 1 events. Modeling including energy dependent diffusion coefficient and/or an evolutional shock speed is future work.

**Acknowledgements.** We would like to thank the ACE EPAM, SWEPAM and MAG teams for providing their data.

## 5. References

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