Diagnostics of Interplanetary and Flaring Plasmas in Impulsive Solar Energetic Particle Events

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Abstract—Using instruments onboard the *ACE* and *Wind* spacecrafts, we study temporal evolution, spectra, and ionization states of Fe in the impulsive solar energetic particle (SEP) events of September 6, 1998 and May 1, 2000. Proton and electron intensities and anisotropies were used to constrain the particle mean free path in interplanetary space. The derived values were used to explain the observed energy and charge spectra of heavy ions. It is concluded that the sharp increase in the average charge of Fe ions in the range from 200 to 600 keV per nucleon observed in both events cannot be explained within the framework of the model of single-temperature source even if the effects of interplanetary propagation are taken into account. At least two acceleration regions with temperatures $\sim 10^6$ and 10^7 K should exist in the source.

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INTRODUCTION

Ion charge states in solar energetic particle (SEP) events are determined by both the number density and temperature of the plasma in the acceleration region, as well as by the effects of propagation of these ions in interplanetary space. In the first approximation, SEP events can be classified into impulsive and gradual. The particle generation in impulsive and gradual events is considered to be realized by stochastic acceleration in flares and acceleration in shocks high in corona or in interplanetary space, respectively. The average charge of Fe ions were measured for the first time by *ISEE* spacecraft and turned out to be $\langle Q_{\text{Fe}} \rangle \approx 14$ and 20 in impulsive events.

A number of best-fit models for the stochastic acceleration [1–3] were proposed to explain particle acceleration in impulsive events. At the same time, the latest high-sensitivity measurements with the SEPICA instrument onboard the *ACE* spacecraft [4, 5] revealed the strong energy dependence of average Fe charge in impulsive events which cannot be explained within the framework of these models. To explain such a discrepancy, it was assumed in [6, 7] that the SEP charge spectra change as a result of adiabatic deceleration of particles propagating through the expanding solar wind.

MODELING ACCELERATION AND INTERPLANETARY PROPAGATION

We apply the charge-consistent model [1, 3] for stochastic acceleration. It is valid for impulsive SEP events. In such models, the acceleration is described by the system of Fokker-Planck equations taking into account both the acceleration and diffusion along the x axis ($0 \leq x \leq L$), Coulomb losses, and the processes of charge exchange. The solution of this problem depends on the following parameters: the ratio τ_A/τ_D of the characteristic acceleration and diffusion times, the product $\tau_A n$ of the characteristic acceleration time and the ambient electron number density, and the plasma temperature T parameterizing the initial charge distributions and ionization/recombination rates, and the turbulence spectral index S . The system was solved numerically by the Monte-Carlo method. As a result, the spectrum of accelerated particles injected into interplanetary space was found [1].

An equation [8] describing anisotropic scattering off the magnetic irregularities and focusing was used to analyze particle propagation through the expanding solar wind. This equation was also solved by the Monte-Carlo method according to the procedure described in [9]. Adiabatic losses were obtained due to transformation from the solar wind system to the corotation system heliocentric coordinates. As the result of adiabatic losses by ions propagating through the solar

Fig.1. Charge spectra of Fe ions injected from the Sun (dashed line 1) and propagated to a distance of 1 AU (solid line 2) for $\lambda_r = 0.8$ AU. The circles are the ACE data for the event of May 1, 1998. The spectrum on the Sun was found at the following parameters: $T = 10^6$ K, $\tau_A n = 9 \times 10^{10}$ s cm $^{-3}$, and $\tau_A/\tau_D = 0.08$ for region 1 and $\tau_A/\tau_D = 0.2$ and $T = 1.58 \times 10^7$ K, and $\tau_A n = 10^{11}$ s cm $^{-3}$ for region 2.

Fig.2. Calculated energy spectrum of Fe on the Sun (dashed line 1) and on the Earth orbit (solid line 2). The circles show the energy spectrum of Fe measured by the ULEIS instrument onboard the ACE spacecraft in the event of May 1, 1998.

wind, the charge spectra are shifted towards lower energies. Moreover, this shift increases with decreasing mean free path [6, 7].

SEPTEMBER 9, 1998 EVENT

The SEP event of September 9, 1998 was related to an M2.8-class X-ray flare with coordinates S22W60 observed at approximately 5 UT [10]. In this event the pronounced velocity dispersion was observed. According to the time profiles and anisotropy of protons, the radial mean free path $\lambda_r = 0.2$ AU in the energy range 0.091–0.151 MeV, 0.3 AU for protons in the energy range 2.8–5.3 MeV, and 0.3 AU for Fe ions in the energy ranges 0.077–0.145 and 0.33–0.66 MeV/nucleon. Thus, the value $\lambda_r = 0.3$ AU should be used for modeling charge and energy spectra of Fe on the Earth orbit. In this event, the fast growth of the average Fe charge with the energy was observed. Taking a value of 0.3 AU for the mean free path, it is impossible to explain the observed charge of the Fe-ion spectrum within a homogeneous model of acceleration region. Hence, we assumed that the acceleration region is not isothermal and consists of at least two domains with different T and $\tau_A n$. This is a primitive model of magnetic-loop inhomogeneity in which a higher-temperature plasma at the center is surrounded by a lower-temperature plasma or when the top of a magnetic loop has the higher temperature. Thus, the charge and energy ion spectra observed in this event can be explained if the heterogeneous acceleration region consists of two

subregions: region 1 with $T = 10^6$ K, $\tau_A/\tau_D = 0.1$, and $\tau_A n = 10^{11}$ s cm $^{-3}$ provided for 76% of the accelerated particles and region 2 with $T = 1.58 \times 10^7$ K, $\tau_A/\tau_D = 0.1$, and $\tau_A n = 5 \times 10^{11}$ s cm $^{-3}$ provided for 24% of the accelerated particles.

MAY 1, 1998 EVENT

The source of this event was a flare with coordinates N20W54. The X-ray emission began at 10:16 UT, reached the maximum at 10:27 UT, and terminated at 10:34 UT. This event was characterized by a large mean free path (the so-called scatter-free interplanetary propagation of SEPs). When analyzing this event we used the same procedure as the September 9, 1998 event. Based on the data on the time profiles and particles anisotropy, a mean free path of 0.8 AU for Fe ions with energies of 1 MeV/nucleon was determined and used to fit the charge and energy spectra [12]. Similar to the previous event, the acceleration region was assumed to be heterogeneous consisting of two subregions. Region 1 with $T = 10^6$ K, $\tau_A/\tau_D = 0.08$, and $\tau_A n = 9 \times 10^{10}$ s cm $^{-3}$ provided for 86% of the accelerated particles. Region 2 with $T = 1.58 \times 10^7$ K, $\tau_A/\tau_D = 0.2$, and $\tau_A n = 10^{11}$ s cm $^{-3}$ provided for 14% of the accelerated particles. Figures 1 and 2 illustrate the measured charge and energy spectra.

BASIC CONCLUSIONS

Propagation of cosmic-ray ions in the interplanetary space alters the charge spectra even at mean free path of up to 1 AU. Thus, even scatter-free events require careful modeling. The observed charge and energy spectra of solar energetic particles are insufficient for flare-plasma diagnostics since these spectra are changed in the process of interplanetary propagation and it is necessary to know the degree of this change. Furthermore, the acceleration region is very often heterogeneous and comprises at least two (higher- and low-temperature) subregions.

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