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Acceleration and transport modeling in the 2000 May 1 SEP event

Y.Y. KARTAVYKH[1], W. DRÖGE[2], B. KLECKER[3], G.M. MASON[4].

[1]*Ioffe Physical-Technical Institute, St. Petersburg 194021, Russia*
[2]*Institut für Theoretische Physik und Astrophysik, Universität Würzburg, D-97072 Würzburg, Germany*
[3]*Max-Planck-Institut für extraterrestrische Physik, Garching, Germany*
[4]*Johns Hopkins University, Applied Physics Lab., Laurel, MD 20723*
julia.jarc@mail.ioffe.ru

Abstract: Using instruments on the ACE and Wind spacecraft, we investigate the temporal evolution, spectra, and ionization states of Fe ions in the impulsive Solar Energetic Particle event of 2000 May 1. Proton and electron intensities and anisotropies were used to help constrain the characteristics of the interplanetary propagation taking account of focusing, pitch-angle scattering, adiabatic deceleration, and convection. We find that the event was nearly scatter-free, with an interplanetary scattering mean free path larger than 1 AU. The form of the Fe energy spectrum is consistent with stochastic acceleration, but the observed increase of the ionization state of Fe between 200-600 keV/n is larger than can be explained using a single temperature source even after including the effect of adiabatic deceleration in the solar wind. A two-temperature source region is required to fit the observed range of Fe charge states, with the bulk (>80%) of the particles coming from a T$\sim 10^6$K region, and the remainder from a region with T$\sim 1.6 \times 10^7$K.

Introduction

Observations of charge state distributions of ions accelerated in solar flares offer a unique opportunity to obtain information about the mechanisms of particle energization and propagation in the flare region, as well as about the background temperature and density of the ambient plasma. Two basic classes of solar particle events have been identified as so-called "gradual" and "impulsive" events. It is widely believed that particles from impulsive events originate from stochastic acceleration in the flare region, whereas in gradual events particles are predominantly accelerated at a shock wave in the higher corona and in interplanetary space. Mean iron charge states were initially measured by the ISEE-3 mission at $< Q_{Fe} > \sim 14$ in gradual and $< Q_{Fe} > \sim 20$ in impulsive events. Under the assumption that the ions had been accelerated from a plasma in thermal equilibrium, the above values were consistent with a temperature of ~ 2 MK, similar to that of the corona for gradual events, and of ~ 10 MK for impulsive events. New observations over a large energy range with improved instruments on board the ACE spacecraft have shown that charge states exhibit broad distributions, which for iron typically are $< Q_{Fe} >= 10 - 15$ in gradual and $< Q_{Fe} >= 17 - 20$ in impulsive events. A number of models, explaining the formation of charge states of heavy ions were developed for impulsive events, where stochastic acceleration is usually assumed and combined with charge changing processes during acceleration ("charge consistent acceleration models"). Recent high-sensitivity measurements by the SEPICA instrument on boad the ACE spacecraft revealed a strong energy dependence of the mean charge of iron in impulsive events in the energy range 0.18-0.55 MeV/n [1, 2]. These data had shown an increase in the Fe mean charge at lower energies than would be expected based on the charge-consistent acceleration models. Energy losses by adiabatic deceleration in the solar wind which is especially important for particles with energies below ~ 1 MeV/n was suggested as a possible reason for the discrepancy and studied in the approximation of particle propagation as spatial diffusion [3, 4]. A realistic propagation
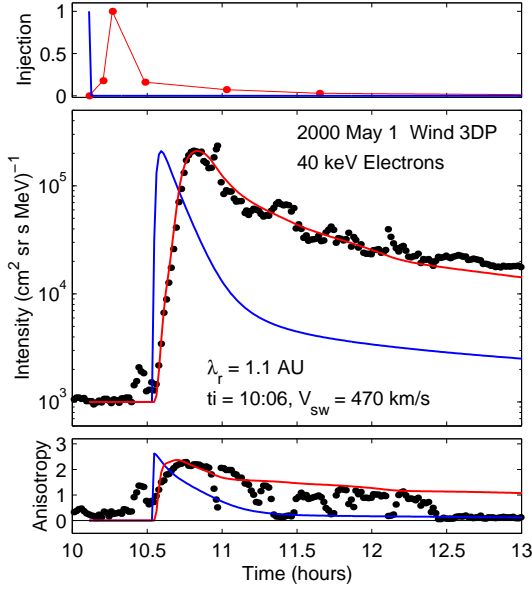
Figure 1: Fits to the time-intensity and anisotropy profiles of 40 keV electrons observed on Wind after the 2000 May 1 flare, assuming a constant $\lambda_r = 1.1$ AU.
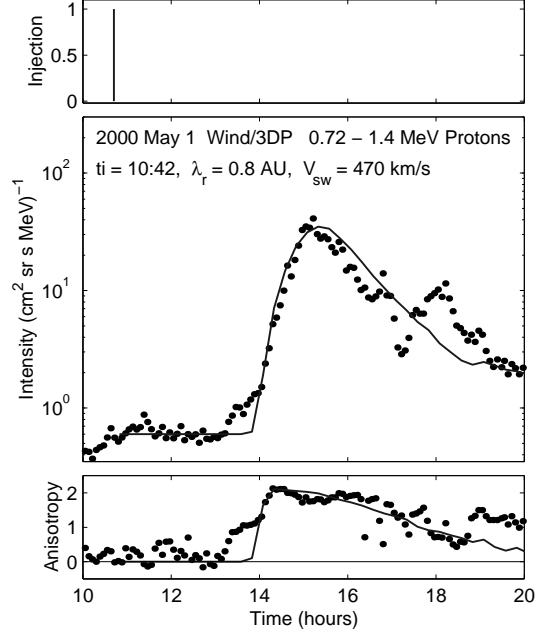

Figure 2: Fits to the time-intensity and anisotropy profiles of 0.72 - 1.4 MeV protons observed on Wind after the 2000 May 1 flare, assuming a spatially constant radial mean free path of $\lambda_r = 0.8$ AU.

model taking into account anisotropic pitch-angle scattering in interplanetary space transport was applied to investigate the 1998 September 9 event [5]. On the basis of a comprehensive analysis of electron, proton and iron data they concluded that a homogeneous acceleration model could not reproduce the observations. In particular, to explain the observed iron charge spectrum one should consider the existence in the acceleration site of (at least) two temperature regions, $\sim 10^6$ and $\sim 1.6 \times 10^7$ K. In order to investigate whether such inhomogeinity is inherent for impulsive events more events need to be analyzed. This paper presents an analysis of high-energy emission data, particle and solar wind observations during the 2000 May 1 event, which is characterized by a nearly scatter free interplanetary particle transport. We will demonstrate that our transport model can handle propagation effects under both strong and weak scattering conditions well and allows us to draw conclusions about the particle source at the Sun.

Particle acceleration and transport

Particle acceleration at the Sun was considered in the frame of charge-consistent stochastic acceleration model, where the acceleration process is desribed by the system of Fokker-Planck equations which contain acceleration, spatial diffusion, Coulomb losses and charge changing processes. The main parameters are the ratio of the characteristic acceleration (τ_A) and diffusion (τ_A) times τ_A/τ_D; the product $\tau_A N$ (N is the number dencity of ambient electrons; the plasma temperature T used to specify the initial charge distribution and the ionization/recombination rates [6, 7].

This equations system was solved numerically making use of a Monte Carlo approach to obtain a time-integrated spectrum of released particles. The subsequent interplanetary transport of the particles was modeled by using a Monte-Carlo technique to obtain solutions of the equation of pitch-angle dependent transport which accurately han-

dles pitch-angle diffusion, focusing in the diverging magnetic field, and additionally the effects of convection and adiabatic deceleration in the solar wind [8]. We used the charge and energy spectra from the charge-consistent acceleration model as the injection spectrum close to the Sun. The electrons, for which solar wind effects and velocity dispersion within an energy channel of the instrument are of minor importance were fitted with solutions obtained by finite differences scheme [9].

The existence of different particle data allowed us first to infer the mean free path in interplanetary space from time profiles and directional data and then to apply this mean free path to derive the charge and energy spectra close to the Sun.

Results and Conclusion

We made an attempt to model the iron observations during 2000 May 1 in a self-consistent manner, i.e., the fits to the intensity profiles and the charge and energy spectra were based on a single set of parameters for the acceleration and transport processes and not adjusted individually. From the time profiles and anisotropy data we could conclude, that for electrons the radial mean free path was $\lambda_r = 1.1$ AU. Blue curves on Figure 1 show time profiles in case of impulsive injection (vertical line on the upper panel). The red curve on the upper panel shows the inferred injection function, and time profiles corresponding to this injection are shown by red curves on lower panels. For protons and iron ions it was found that $\lambda_r = 0.8$ AU (Figure 2). This value was applied to fit the energy and charge spectrum of iron, together with its time profiles, observed by ULEIS in four energy ranges.

Similarly to our analysis of the 1998 September 9 event [5] we found that a homogeneous acceleration model that assumes single values for the parameters density, temperature, and acceleration and escape time scales in the acceleration can not provide a satisfactory modeling of the steep charge spectrum of the 2000 May 1 event. The best fit to the spectrum of the measured mean ionic charge of iron in the energy range 0.18 - 0.55 MeV/n we were able to obtain for the one-region model, indicated by the red lines in Figure 3, clearly is too flat. We therefore employed the two-region inhomogeneous acceleration model and obtained a best overall modeling, including fits to the time profiles, energy and charge spectra for the combination: Region 1 - $T = 10^6 K, \tau_a/\tau_d = 0.08, \tau_a N = 9 \times 10^{10} cm^{-3}s$ and Region 2: $T = 1.58 \times 10^7 K, \tau_a/\tau_d = 0.2, \tau_a N = 10^{11} cm^{-3}s$. It was assumed that particles were injected homogeneously into both regions, and Region 1 produced 86 % of the total number of particles, while a hotter Region 2 produced 14 % of the total number of particles.

The prediction from the two-region model, shown as the black lines in Figure 3, gives a good fit to the charge spectrum of iron observed at 1 AU. Because of the nearly scatter free particle transport in this event the shift of the charge spectrum due to adiabatic deceleration is smaller than in the 1998 September 9 event, but nonetheless the inclusion of this effect is essential in modeling the observed data and deriving plasma parameters in the acceleration region. Figure 4 shows the observed energy spectrum of iron in the May 1 event, together with the prediction of our acceleration model for 1 AU. We used 15 hours accumulation time in our model, corresponding to the time span between the flare onset and the observed cut-off of the particle intensities on May 2, 01:00 UT. The fit to the energy spectrum is consistent with the fits to the ULEIS intensity profiles.

Our detailed analysis of the 2000 May 1 event and the 1998 September 9 event [5] shows that the pitch-angle dependent transport model adequately describes the interplanetary transport in ^{3}He- and heavy ion-rich events for a wide range of scattering conditions, thus providing more accurate timing for the injection at the Sun than can be obtained with the assumption of rectilinear transport. With the combination of charge-consistent acceleration at the Sun and interplanetary transport we are able to reproduce both, the energy spectra and the energy dependent charge state of iron, if we assume two regions of different temperature for the acceleration site. So far this was found for two out of three events analyzed in detail; whether this is generally true for heavy ion-rich events and whether there is a relation to signatures at the Sun needs further investigation.
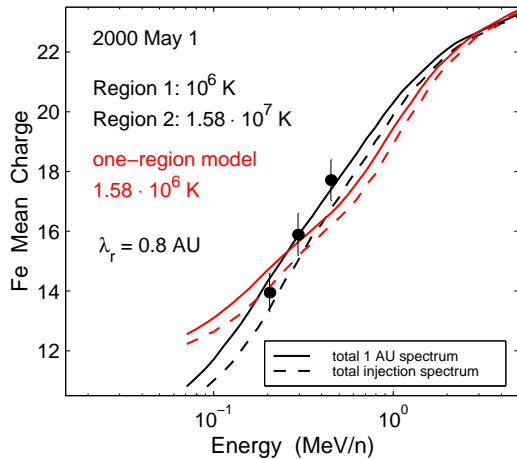
Figure 3: Calculated mean charge of iron at 0.05 AU (dashed line), and at 1 AU after the interplanetary transport assuming a constant radial mean free path $\lambda_r = 0.8$ AU (solid line). Filled circles denote ACE observations of the 2000 May 1 event.

Acknowledgements

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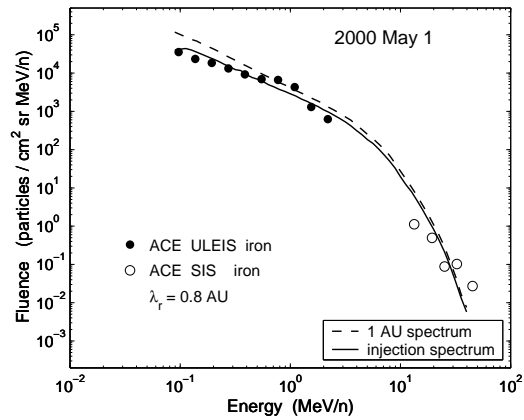

Figure 4: Observed energy spectrum of iron in the 2000 May 1 event together with the prediction of the present model; $\lambda_r = 0.8$ AU and the solar wind speed $V_{SW} = 470$ km/s

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