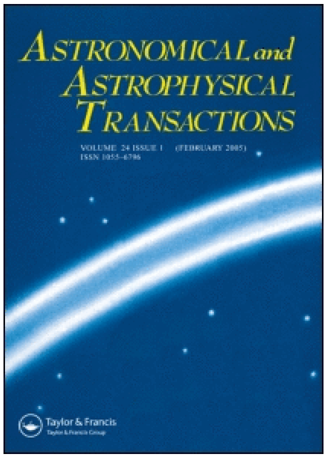

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PLASMA PARAMETERS FOR THE 6 NOVEMBER 1997 SEP EVENT DERIVED FROM THE CHARGE-CONSISTENT ACCELERATION MODEL

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Based on the recent data on charge state observations we deduce plasma parameters for the gradual solar energetic particle event of 6 November 1997. The dependence of the mean charge of several elements (C, O, Ne, Mg, Si and Fe) on energy is derived within the framework of charge-consistent acceleration model which is studied using Monte-Carlo approach. These simulations agree well with the experiment. The model incorporates ionisation and recombination processes during heavy ion propagation and acceleration by a parallel shock wave. To obtain good fits to observations we have to assume for the product of the characteristic acceleration time and number density $T^q_{ac}N \sim 10^{10}$ s cm^{-3} and temperature $T = 10^6$ K of a plasma, where the accelerated elements C, O, Ne, Mg, Si and Fe came from. However, a relatively abrupt increase in the Fe mean charge with energy is apparently in favour of admixture of this element originated from another (impulsive) event.

KEY WORDS Solar energetic particles, interplanetary plasma

1 INTRODUCTION

It is commonly recognized that solar energetic particle (SEP) events can be divided into two large classes: impulsive and gradual with different properties. The former are characterized by stochastic, and the latter – by regular acceleration mechanism on shock wave fronts (Cane *et al.*, 1986; Temerin and Roth, 1992). An additional particle energization process discussed in the literature is the acceleration in direct electric fields which arise due to the sudden current sheet disruption (Litvinenko and Somov, 1995). However, the relationship between those mechanisms in flaring plasma is still under discussion. In the present paper we consider heavy particle generation by a parallel shock wave within the charge-consistent model (Kurganov and Ostryakov, 1991; Ostryakov and Stovpyuk, 1999a, b). This approach takes into account the possibility of heavy ion to change its charge during acceleration and propagation, and this in turn determines the efficiency of energy gain of the ion. This model is capable quite naturally to account for the dependence of the mean charge of various elements on energy, $\bar{q}(E)$, which has been already detected for several gradual SEP events. Our simulation results will be applied to fit data from the 6 November 1997 SEP event which is most likely classified as a gradual event. The energy spectra of H, He, C, O, Fe, energy dependence of the mean charge of C, O, Ne, Mg, Si, Fe and charge distributions of Fe are available for analysis for this event (Möbius *et al.*, 1999; Dietrich and Lopate, 1999). The set of these comprehensive data for a separate event under consideration allows one to constrain plasma parameters in a flaring region (temperature and number density), where the acceleration of the above mentioned elements occurred. This would be possible to do even when dealing with the experimental data for one species (Ostryakov and Stovpyuk, 1999a). However, the more elements that are involved for analysis, the results that could be obtained, are likely to be more reliable.

2 ACCELERATION MODEL

For the first time the charge-consistent models were studied analytically in the papers of Kurganov and Ostryakov (1991), and also Ostryakov and Stovpyuk (1997) in the framework of regular and stochastic acceleration mechanisms, respectively. To obtain analytic solutions of the problem the authors had to restrict themselves to the energy and charge independent electron loss and electron gain atomic reaction rates. Even in this simplest case the energy dependence of the mean charge of heavy ions was clearly derived. More realistic (numerical) models were further developed by Kartavykh *et al.* (1998) (considering stochastic acceleration of He ions) and by Ostryakov and Stovpyuk (1999a, b) (regular acceleration of Fe). Note that in terms of atomic reactions apart from the impact-ionization (stripping) by thermal electrons and protons (Ostryakov and Stovpyuk, 1999a) we also include here radiative and dielectronic recombination, which are significant mainly at low energies. Stripping mostly affects the $\bar{q}(E)$ dependence if acceleration efficiency is high enough. In this case the charge distribution and the mean charge dependence on energy are far from their equilibrium values, which are determined by balancing the electron loss and electron gain processes (Kocharov *et al.*, 2000). This equilibrium charge distribution is the upper limit for $\bar{q}(E)$ because it results from the approximation when ions of a definite energy spend infinite time in the acceleration region.

One should also point out that the same approach was independently developed by Barghouty and Mewaldt (1999) who have considered iron acceleration. In their paper, however, a nonstationary regular acceleration mechanism was investigated incompletely. Firstly, the model does not result in the universal power-law particle spectra similar to the shock induced spectra. Secondly, the most important effect – stripping of energetic ion by thermal protons – was erraneously ignored. At the same time, in our previous paper (Ostryakov and Stovpyuk, 1999a) we have included only electron loss effects simulating stationary, time-independent, ion spectra (both by energy and charge). We avoid the former restriction in the present calculations.

Thus, the evolution of the distribution function, $f_q(E,x)$, of ions with charge q is governed by the following equation:

$$\frac{\partial f_q}{\partial t} = \frac{\partial}{\partial x} D_{qi} \frac{\partial f_q}{\partial x} - u_1 \frac{\partial f_q}{\partial x} + N_i(f_{q-1}S_{q-1} - f_q(S_q + \alpha_q) + f_{q+1}\alpha_{q+1}), \quad (1)$$

($q = q_{\min}, \ldots, q_{\max}$), where $S_q(\alpha_q)$ are the characteristic ionisation (recombination) reaction rates for the corresponding ionic state q (denoted by the subscript) in general averaged over the Maxwellian distribution of ambient electrons and protons. These rates depend on the electron temperature, T_e, and the ion velocity, V. Since thermal protons can be considered as particles at rest (with respect to a moving ion), their temperature, T_p, does not influence the $S_q(\alpha_q)$ parameters. Hence, we imply further $T \equiv T_e$. Here also u_i is the flow velocity in the upstream ($i = 1$) and downstream ($i = 2$) regions, respectively; $D_{qi} = D_{0i}(q/A)^{S-2}E^{(3-S)/2}$ ($S \leq 2$) is the spatial diffusion coefficient dependent on energy E and particle atomic mass number A ($m = Am_p$), S being a spectral index of turbulence; N_i is the plasma number density. The set of Eq. (1) together with the corresponding boundary conditions on a shock front was solved numerically making use of finite differences method for Fe ions (Ostryakov and Stovpyuk, 1999b). In this Section we also briefly describe the Monte-Carlo approach used in the present calculations (see also Kirk and Schneider, 1987; Achterberg and Krulls, 1992; Kartavykh *et al.*, 1998). One should note that the Monte-Carlo approach allows one to obtain more easily the energy and charge spectra of ions for more complicated boundary conditions than those from finite differences method including also nonstationary statement of the problem.

Initially, we deal with the charge distribution of heavy ions corresponding to the equilibrium one, f_{q0}, calculated for the moving particles at injection energy E_0, (see, e.g., Luhn and Hovestadt, 1987; Kocharov *et al.*, 2000). In the Monte-Carlo approach one should trace particles individually summing them in a series of time, energy and charge intervals. So, let the ion of initial energy E_0 (supposed here to be 10 keV nucleon^{-1}) and some charge q_0 is injected at the moment $t_0 = 0$ for further acceleration at shock wave front ($x = 0$). Then, the k-th time step (with the duration of Δt for each one, $t = k\Delta t$ – is the current moment of time) results in the spatial coordinate alteration:

$$x_k = x_{k-1} + u_i \Delta t + \sqrt{-4D_{qi}\Delta t \ln \delta_1} \cos(2\pi\delta_2), \quad (2)$$

where the random variables δ_1 and δ_2 are uniformly distributed in the range [0, 1]. The second term in the right-hand side of this equation is due to convective particle displacement. The third one determines its spatial diffusion resulting in the Gaussian distribution with zero mean and dispersion $(2D_{qi}\Delta t)^{1/2}$ (Sobol', 1973). Two-fold ion interaction with the shock front yields the energy gain (Berezhko *et al.*, 1988):

$$\langle E \rangle = 4(u_1 - u_2)\frac{\sqrt{2mE}}{3}, \quad (3)$$

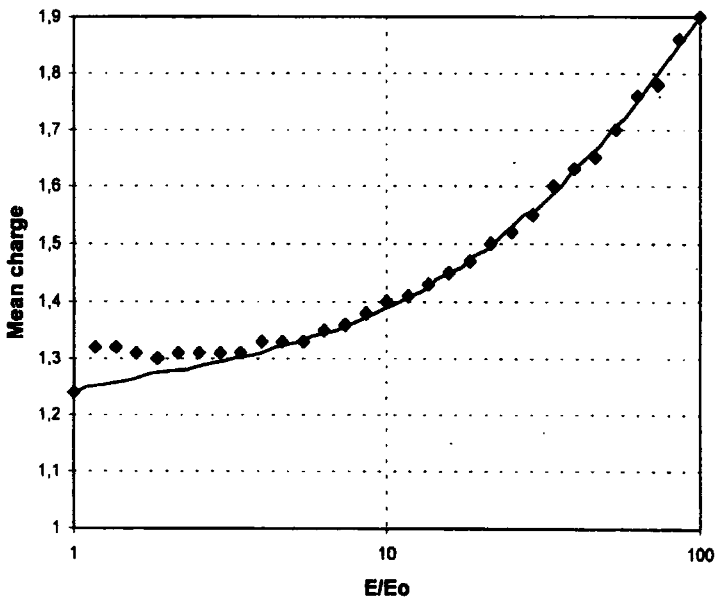

Figure 1 Energy dependence of the mean charge of accelerated ions (three-level model) simulated both by Monte-Carlo (rhombs) and by finite differences (solid line) methods for $r = 1.6$, $S = 5/3$, $T_{\rm ac}^{+2}/T_{\rm ac}^{+1} = 0.8$, $T_{\rm ac}^{+3}/T_{\rm ac}^{+1} = 0.7$, $\tau_{12}/T_{\rm ac}^{+1} = 0.7$, $\tau_{23}/T_{\rm ac}^{+1} = 1.4$, $\tau_{10}/T_{\rm ac}^{+1} = 10$, and $\tau_{21}/T_{\rm ac}^{+1} = \tau_{32}/T_{\rm ac}^{+1} = 8.6$ at $E = 100E_0$.

averaged over the particle flux $J(p) = f_q(p)V\cos\phi$ (ϕ is the particle pitch-angle). During the particle acceleration and propagation there is a probability for the ion to be ionised, $P_{\rm ion} = 1 - \exp(-\Delta t/\tau_{\rm ion})$, or to recombine with electron, $P_{\rm rec} = 1 - \exp(-\Delta t/\tau_{\rm rec})$. The value of $1 - P_{\rm ion} - P_{\rm rec}$ is the probability to save the charge at k-th time step; $\tau_{\rm ion}$ ($\tau_{\rm rec}$) is the characteristic ionisation (recombination) time, $\tau_{\rm ion} = (N_i S_q)^{-1}$ and $\tau_{\rm rec} = (N_i \alpha_q)^{-1}$. Our previous consideration was performed for the stationary ion spectra at shock wave front. This implies that ions reaching the energy E are trapped in the acceleration region within the characteristic acceleration time (Jokipii, 1987):

$$T_{\rm ac}^q(E) = \frac{3}{u_1 - u_2}\left(\frac{D_{q1}(E)}{u_1} + \frac{D_{q2}(E)}{u_2}\right). \tag{4}$$

It is during this time interval when atomic reactions with the ion occur. Therefore, to compare both methods (previous finite differences and present Monte-Carlo) we should count particles as soon as the following time condition $t \geq T_{\rm ac}^q(E)$ is satisfied independently on the ion location. The latter circumstance essentially improves statistical accuracy of the energy and charge spectra because the main part of the accelerated particles is in the downstream region and their energy distribution does not depend upon the x coordinate in planar geometry. However, we have also studied the sensitivity of the results to the boundary conditions considering, for

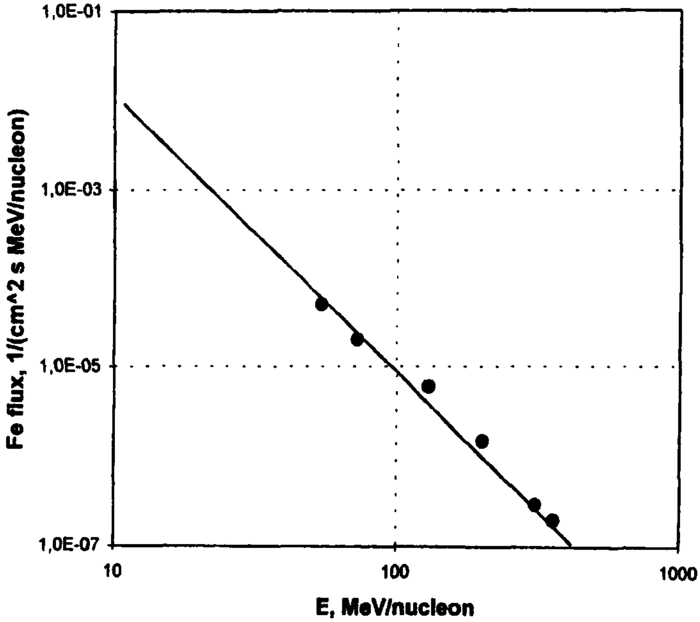

Figure 2 Fitting of the Fe flux summed over all charge states simulated for $r = 1.6$, $S = 5/3$; circles – experimental data from the IMP-8 satellite for the 6 November 1997 SEP event.

example, only particle population which crosses some boundary, $x_{\max}$, in the flow downstream (see Figure 4 below). To improve statistical accuracy of the energy distributions in the Monte-Carlo approach we have used in our simulations the well-known procedure as the trajectory splitting (see, e.g., Kirk and Schneider, 1987).

To compare the two methods (finite differences and Monte-Carlo) applied to solve Eq. (1) we have considered three ionic state system. Figure 1 shows the obtained difference between those solutions which is less than $\sim 6\%$ by charge at low energies. Even this small divergence is due to incorrect definition of the $T^q_{\rm ac}(E)$ value in the vicinity of the injection energy E_0 because Equation (4) is appropriate for the stationary conditions. As one can see from Figure 1, at energies slightly greater than E_0 those solutions are very close to each other (see also Figure caption for the parameters of these runs).

3 EXPERIMENTAL DATA FITS

Nowadays, there are several spacecrafts working in interplanetary space which carry out high quality measurements of particle fluxes in SEP events. These data are concerned with various properties of heavy particles integrated over separate events (mean charge in different energy bands, particle energy spectra etc.). Moreover, time profiles of the elemental abundances within an individual SEP event itself are currently available for analysis owing to the high sensitivity of the detectors onboard the WIND spacecraft (Tylka *et al.*, 1999).

Figure 2 shows the fit to the Fe flux measured onboard the IMP-8 satellite (Dietrich and Lopate, 1999). This was done using our model ($T^q_{\rm ac}(E)N \sim 10^{10}$ s cm^{-3}, see below) for the shock wave compression ratio $r \approx 1.6$ which provides the observed spectral index for the particle flux $\gamma = (r+2)/2(r-1)$. The value of $r \approx 1.6$ is a typical for the shock waves of solar origin (Sheeley *et al.*, 1985). Apart from energy spectra, we also analyse the energy dependence of the mean charge for C, O, Ne, Mg, Si and Fe measured for the same gradual event of 6 November 1997. Based on those data and on simulated results in the framework of our charge-consistent model for heavy ion acceleration, we can infer plasma parameters in the accelerating site. It is this approach which allows one to account for the dependence of the mean charge on energy for variety of elements. Any 'thermal' models of the mean charge origin fail facing this fact. Figure 3 shows the simulated theoretical curves for C, Ne, Si and Fe along with the available observations. It is surprising that all those data (including similar curves for oxygen and magnesium omitted in Figure 3) can be fitted using similar $T^q_{\rm ac}(E)N \sim 10^{10}$ s cm^{-3} parameter for all elements under consideration, $T^q_{\rm ac}(E)$ being determined at 10 MeV nucleon^{-1}. This magnitude is close to that found earlier neglecting recombination (Ostryakov and Stovpyuk, 1999a). As one can see from Figure 3, the simulated tendency of the mean charge growth for iron, $\bar{q}_{\rm Fe}(E)$, turns out to be slightly flatter than that the experimental points show. We discuss this peculiarity in the next Section.

4 DISCUSSION AND CONCLUSIONS

This paper deals mainly with the mean charge and its dependence on energy for heavy particles (C, O, Ne, Mg, Si and Fe) observed onboard the ACE spacecraft for the 6 November 1997 gradual SEP event. Because several elements are used for analysis it gives a more reliable basis for the reconstruction of plasma conditions in the accelerating site. Unfortunately, this period was likely to have been associated with another impulsive event which could mask those data (Möbius *et al.*, 1999). Indeed, it is well known that impulsive SEP events are usually characterized by elemental and charge anomalies compared with the gradual ones. In particular, they are highly abundant, on average, with iron which has a much greater mean charge (about +20, Luhn *et al.*, 1984). This, in turn, is in favour of more dense plasma where the acceleration of heavy particles takes place. So, if such overlapping of the events occur, there is a possibility that all the above mentioned elements have originated from the gradual event, and for Fe an admixture from the accompanying impulsive event is present. In this case, one can virtually expect more abrupt growth of the mean charge of iron with energy that is evidently closer to observations. Meanwhile, this possibility under discussion is still within an experimental error. In this respect, it is quite desirable to study 'pure' events (both gradual and

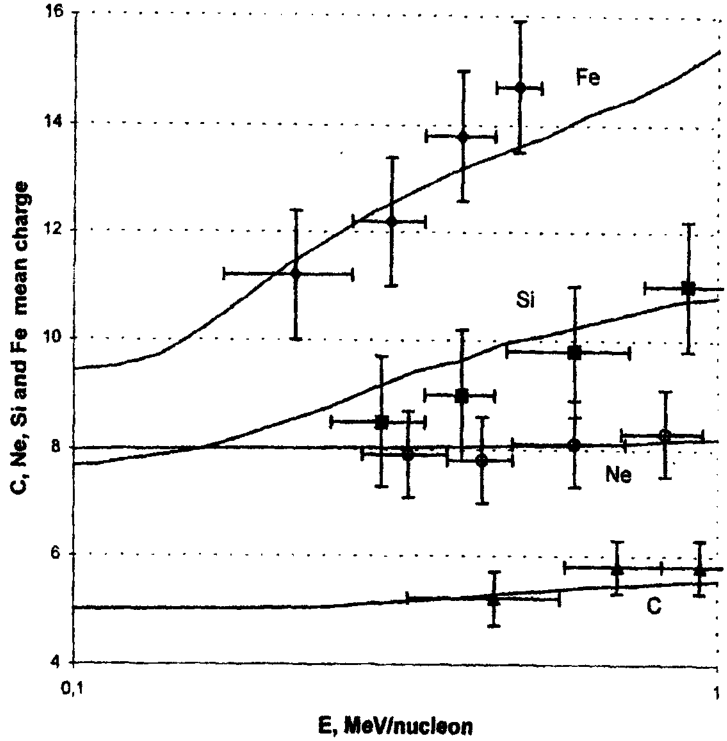

Figure 3 The mean charge of accelerated Fe, Si, Ne and C ions simulated for $r = 1.6$, $S = 5/3$ and $T = 10^6$ K; for iron $NT^q_{ac} = (1.2\text{–}0.8) \times 10^{10}$ s cm^{-3}, for silicon, neon and carbon $NT^q_{ac} = (0.9\text{–}0.8) \times 10^{10}$ s cm^{-3} (at 10 MeV nucleon^{-1}). Also shown are the observations from the ACE spacecraft for the 6 November 1997 SEP event (Möbius *et al.*, 1999).

impulsive). Alternatively, to explain the dependence of the ionic states on energy Reames (1999) has noted that it is probable that 'ions at higher energies are sampled from the corona close to the Sun while those at lower energies continue to be sampled at distance out into the solar wind'. This needs, however, more complicated nonstationary modeling of the heavy ion acceleration by shocks as they move in a nonhomogeneous medium. As a starting point, we consider here a simplest case of a homogeneous plasma.

Contrary to the above solution (Figure 3), which describes ion properties integrated over entire downstream region (one way of particle counting), it is also possible to calculate distribution function for ions which cross some boundary far downstream (another way). It is clear that only the charge distribution of ions has to be changed in this case because particle acceleration takes place as it crosses shock front. This crossing, however, occurs if the diffusion time (to $x_{\max}$) is long enough in comparison with the acceleration time. Clearly, the mean charge of escaping particles turns out to be larger because this population consists of ions effectively travelling a longer distance to reach this boundary without any energy

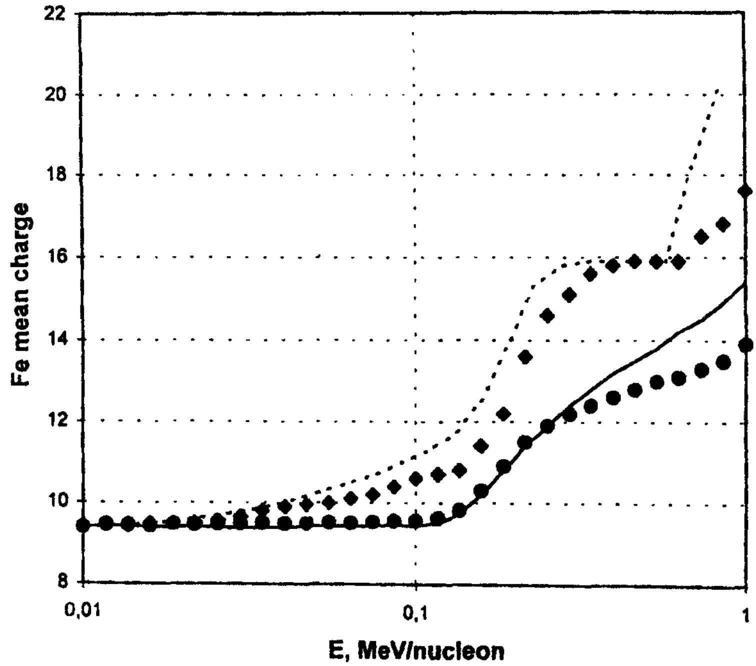

Figure 4 The mean charge of accelerated Fe ions simulated for $r = 1.6$, $S = 5/3$, $T = 10^6$ K and NT^q_{ac}(at 10 MeV nucleon^{-1}) $= (1.2\text{–}0.8)\times10^{10}$ s cm^{-3}. Dashed curve is the equilibrium Fe charge, solid line – the Monte-Carlo stationary solution (see text), circles and rhombs are the Monte-Carlo solutions for the particle population escaping the downstream boundary $x_{max} = 94D_{02}/u_2$ and $x_{max} = 625D_{02}/u_2$, respectively.

increase. As a result, the energy spectra are essentially the same for both ways of particles counting. The greater the distance this boundary is from the shock wave front (i.e., the longer the diffusion time to it) the closer the $\bar{q}(E)$ dependence to the equilibrium curves for each element, as an example see Figure 4 for iron. However, in the present paper we rely on the calculations which can be compared with our previous calculations.

In conclusion, one should note that the charge-consistent acceleration models are quite promising in accounting for the various properties of charge distribution of heavy elements. It refers particularly to the dependence of the mean charge on energy. Simulteneous fitting both charge and energy spectra of several elements observed for the same individual event is an effective tool for flaring plasma diagnostics on the basis of these data.

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