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Heavy ions from impulsive SEP events and constraints on the plasma temperature in the acceleration site

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Abstract. We compare the mean charge states of heavy ions (O, Ne, Mg, Si and Fe) as observed with ACE/SEPICA during several solar energetic particle events in 1998 with model calculations. A model of stochastic acceleration that includes a self-consistent treatment of the charge states of the affected ions is applied to estimate the plasma temperature in the acceleration site for 8 impulsive events. This model takes into account ionization due to collisions with electrons and heavy particles (protons and He) as well as recombination due to collisions with electrons. In general the temperatures obtained for Ne, Mg and Fe ions appear higher than those for O and Si. We briefly compare our results with the corresponding ionization temperatures for gradual events observed in previous solar cycles and in 1997-1998.

1 Introduction

Solar energetic particle (SEP) events are usually divided into two large classes: impulsive and gradual. The former are characterized by a short duration of X-ray and radio emissions, high *e/p* ratio and by enrichments in heavy elements with respect to their coronal abundance (as reviewed by Reames, 1990; Reames et al., 1994). In contrast, longer X-ray and radio emissions, low *e/p* ratios and abundance of heavy elements similar to coronal are inherent to gradual events. It is commonly accepted also that energetic ions are produced there via different acceleration mechanisms. Namely, energetic particles in impulsive events are generated due to stochastic mechanism operating in compact and dense regions, while in gradual events they are the result of acceleration at coronal or interplanetary shocks in rather dilute plasmas. As a result, impulsive events supply energetic heavy particles at higher ionization states (for example, the mean charge of Fe is about 17-20) as compared with those from gradual ones (Q_{Fe} ~11-14) (see, e.g., Luhn et al., 1987; Möbius et al., 1999). The ionic mean charge and charge distributions result from the competition of ionization and recombination processes during particle acceleration and propagation. Hence, they contain important information on the plasma properties.

Until recently measurements of heavy ions in impulsive events have usually been carried out by averaging over several parent flares because of the low particle fluxes. Due to high sensitivity of SEPICA onboard the ACE spacecraft it has become possible to observe charge states of different heavy elements during individual events.

In the present paper we analyse available data on heavy ions obtained by ACE/SEPICA in 1998 and derive constraints on the plasma temperature. Our procedure is based on a stochastic acceleration mechanism in the framework of a charge-consistent approach (Kartavykh et al., 1998; Ostryakov et al., 2000).

2 Experimental data and relevant model

During 1998, the ACE/SEPICA has observed a number of SEP events with measurable mean charges of different species (O, Ne, Mg, Si, Fe). Möbius et al. (2000) listed 18 such events, with charge states ranging from the solar wind values up to 18-19 for Fe and almost fully stripped for ions up to Mg. The measurements were performed at energies less than 1 MeV/nucleon (0.5 - 0.63 MeV/nucleon for O, 0.5 - 0.775 MeV/nucleon for Ne, 0.33 - 0.5 MeV/nucleon for Mg, 0.43 - 0.57 MeV/nucleon for Si, and 0.18 - 0.44 MeV/nucleon for Fe). For further detailed modeling we have selected 8 events with $Q_{Fe} \geq 17$ (events 11-18 of Möbius et al., 2000), bearing in mind that they could be associated with impulsive events, which are most likely connected with a stochastic acceleration mechanism.

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Our model takes into account second-order Fermi acceleration, spatial diffusion, Coulomb losses and possible changes of the ionic charge. The charge changing processes include ionization due to collisions with thermal electrons and ions (protons and He^{2+}) as well as recombination (both radiative and dielectronic) with surrounding electrons (for details see Ostryakov et al., 2000; Kartavykh et al., 2001). The main parameters of such modeling are the ratio of characteristic acceleration and diffusion times (τ_a^0/τ_d^0) and the product of the acceleration time and the number density of surrounding electrons or protons ($\tau_a^0 N$). Here and below the index "*0*" means that this parameter refers to protons. We have varied this product from 0.1×10^{10} $cm^{-3}s$ to 10×10^{10} $cm^{-3}s$, and assumed that the plasma temperature is $\geq 10^6$ K in active regions.

3 Results and discussion

In our study we follow the idea that the mean charge of accelerated ions at a given plasma temperature is between its thermal value Q_{th} and the equilibrium mean charge Q_{eq} (see, e.g., Ostryakov et al., 2000). Note that the Q_{eq} at a given temperature and energy 0.01 MeV/nucleon actually equals the thermal mean charge. Comparing the observed mean charge of O and its mean thermal value leads to the conclusion that for all the events listed (except event 17) this element was accelerated in a parent plasma of temperature below $10^{6.5}$ K. Similar constraints on the temperature can be derived from the observed mean charge of Si (except in events 14, 16, 18). More certain restrictions have resulted from detailed numerical simulations. The relative behaviour of the equilibrium mean charge for several elements in the energy range of measurements (see above) points out to the importance of a detailed modeling. For example, the calculated equilibrium charge of O (or Ne) corresponds to fully stripped ions already at a temperature $T\approx10^6$ K and the charge-consistent acceleration model is required to explain the observed charge states. Alternatively, if Q_{eq} nearly equals its thermal value in the energy range of observation (e.g., Mg at $T\geq10^{6.8}$ K), then the general restrictions could be inferred just from a comparison of the observed mean charge with the thermal value.

Simulated mean charges of O, Ne, Si and Fe at different temperatures and $\tau_a^0 N=0.1\times10^{10}$ $cm^{-3}s$, $\tau_a^0 N=10\times10^{10}$ $cm^{-3}s$ together with experimental data are presented on Figures 1-4. The constraints for temperature for all the considered events (taking into account the measurement uncertainty and the above $\tau_a^0 N$ range) are presented in Table 1. If the observed ionic mean charge was close to the nuclear charge we can derive a lower limit for T.

From this Table 1 it is clearly seen that the permitted plasma temperature inferred from the analysis of charge states of different ions is not uniform for all the events (except 14, 15, and 16, for which there are insufficient statistics). For example, O and Si mean charges are fitted by "low" temperatures; Ne, by "intermediate" temperatures; Fe and Mg, by "high" temperatures. Note that analogous results (higher ionization temperature for Mg and Ne as compared to those for O and Si) have been obtained for gradual events as well, based on a very different type of estimation (fitting with Q_{th}, not an acceleration model). In fact, all published, pre-SEPICA charge state measurements for these elements (which were for gradual events) have shown this behavior (Luhn et al., 1985; Leske et al., 1995; Mason et al., 1995; Oetliker et al., 1997). This is in spite of the conventional view that impulsive and gradual flare events involve completely different acceleration processes.

However, in SEPICA data for 1998 events, this behavior of the apparent temperature (based on Q_{th}) is not evident in what are believed to be gradual events (with a low Fe mean charge), perhaps because these are for a lower energy than most previous measurements.

We tried to identify the listed SEP events with solar flares in X-rays. Magnetically (western longitudes) or/and temporally connected flares were selected for analysis. For

Table 1. Temperature range derived from ACE/SEPICA observations of the mean charge of heavy ions for 8 impulsive events.

Event number	O log T (K)	Ne log T (K)	Mg log T (K)	Si log T (K)	Fe log T (K)
11	6.0-6.3	6.5-6.6	6.7-6.8	6.0-6.2	6.8
12	6.0-6.3	6.5-6.6	7.0-7.1	6.0-6.3	6.9
13	6.0-6.4	>6.7	6.9-7.1	6.0-6.8	6.9
14	6.0-6.7	6.5-6.6	>7.0	6.5-7.2	6.9
15			6.9-7.2		6.9-7.0
16	>6.0			>7.2	6.9-7.0
17	>6.4	>6.7	6.8-7.2	6.0-6.3	6.9-7.0
18	6.2-6.4	>6.8	>7.2	>6.9	7.0

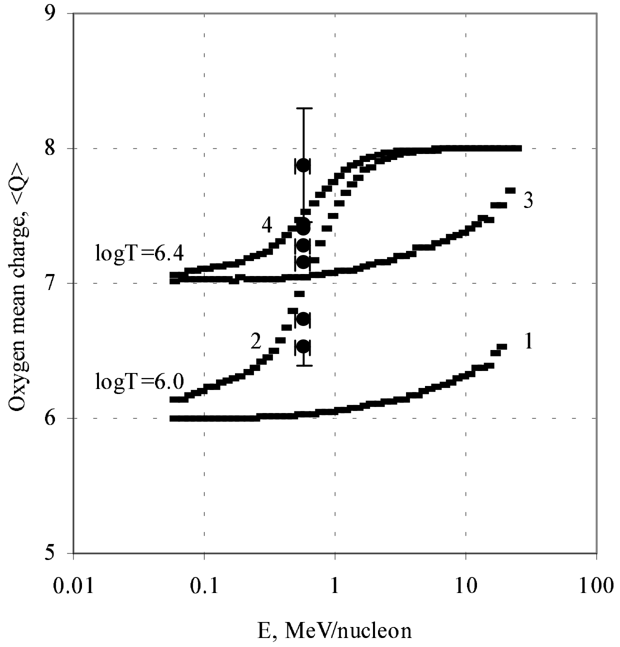

Fig. 1. Simulated mean charge of O: curve 1 - T=10^6 K, $\tau_a^{0}N=0.1\times10^{10}$ cm^{-3}s; 2 - T=10^6 K, $\tau_a^{0}N=10\times10^{10}$ cm^{-3}s; 3 -T=$10^{6..4}$ K, $\tau_a^{0}N=0.1\times10^{10}$ cm^{-3}s; 4 - T=$10^{6..4}$ K, $\tau_a^{0}N=10\times10^{10}$ cm^{-3}s. The observed mean charges of O are shown by filled circles.

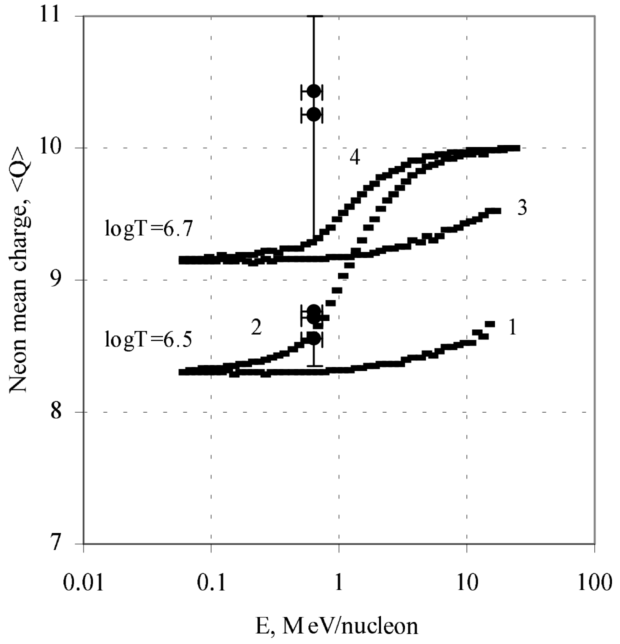

Fig. 2. Simulated mean charge of Ne: curve 1 - T=$10^{6.5}$ K, $\tau_a^{0}N=0.1\times10^{10}$ cm^{-3}s; 2 - T=$10^{6.5}$ K, $\tau_a^{0}N=10\times10^{10}$ cm^{-3}s; 3 -T=$10^{6..7}$ K, $\tau_a^{0}N=0.1\times10^{10}$ cm^{-3}s; 4 - T=$10^{6.7}$ K, $\tau_a^{0}N=10\times10^{10}$ cm^{-3}s. The observed mean charges of Ne are shown by filled circles.

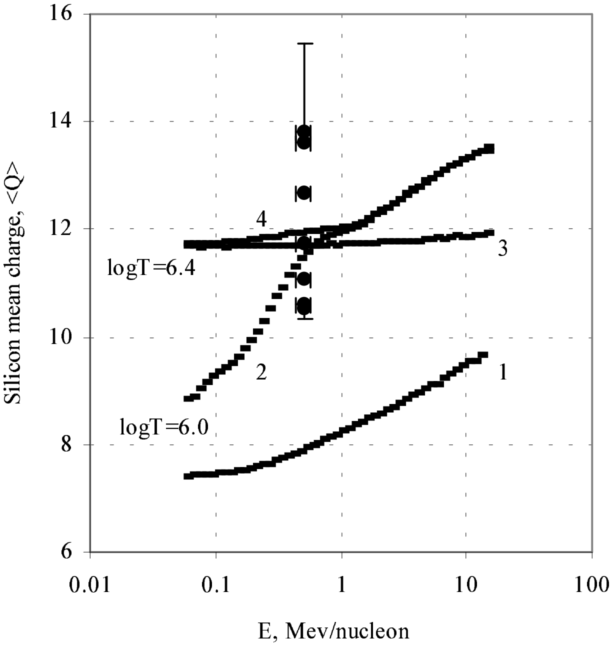

Fig. 3. Simulated mean charge of Si: curve 1 - T=10^6 K, $\tau_a^{0}N=0.1\times10^{10}$ cm^{-3}s; 2 - T=10^6 K, $\tau_a^{0}N=10\times10^{10}$ cm^{-3}s; 3 -T=$10^{6..4}$ K, $\tau_a^{0}N=0.1\times10^{10}$ cm^{-3}s; 4 - T=$10^{6..4}$ K, $\tau_a^{0}N=10\times10^{10}$ cm^{-3}s. The observed mean charges of Si are shown by filled circles.

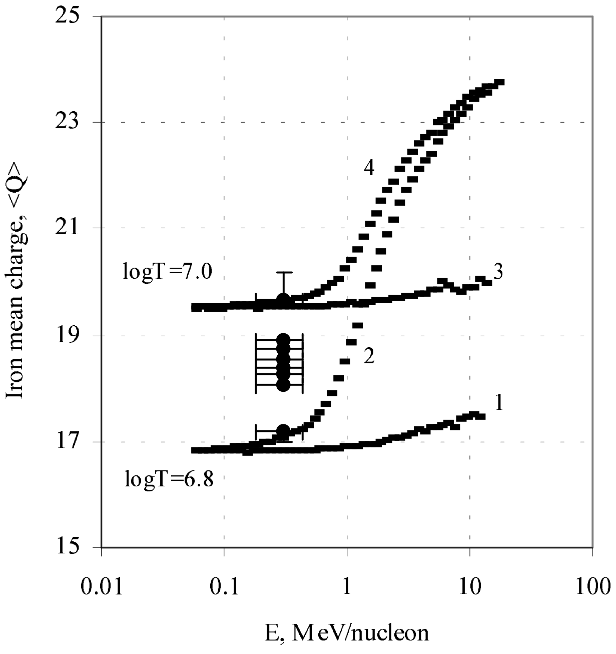

Fig. 4. Simulated mean charge of Fe: curve 1 - T=$10^{6.8}$ K, $\tau_a^{0}N=0.1\times10^{10}$ cm^{-3}s; 2 - T=$10^{6.8}$ K, $\tau_a^{0}N=10\times10^{10}$ cm^{-3}s; 3 -T=$10^{7.0}$ K, $\tau_a^{0}N=0.1\times10^{10}$ cm^{-3}s; 4 - T=$10^{7.0}$ K, $\tau_a^{0}N=10\times10^{10}$ cm^{-3}s. The observed mean charges of Fe are shown by filled circles.

events 11, 12, and 17, where the contrast in derived plasma temperatures is most clear, the more powerful flares in X rays (C6.0 – M2.8) have been observed. Moreover, the microwave radio bursts of types II and/or IV were registered during events 12, 15 and 17. It is believed that these types of radio emission are connected with the propagation of coronal (type II) or interplanetary (type IV) shocks.

Additional photoionization of ions by soft X-rays produced in relatively strong X-ray flares could explain the difference in effective source plasma temperatures (Mullan and Waldron, 1986). The photoionization rates are calculated as $R_{ph}=\Sigma_{nl} \int I/\varepsilon\ \sigma(\varepsilon)d\varepsilon$, where ε is the photon energy and $\sigma(\varepsilon)$ is the photoionization cross section (Verner and Yakovlev, 1995), $I \sim \varepsilon^{-2}$ – the flux of a soft X-ray emission. If one consider the flare importance M1.0, occuring within the compact active region (10^8 cm), then these rates turn out to be comparable with the characteristic acceleration rate. For example, the characteristic photoionization times for Ne^{+8}, Mg^{+10} and Fe^{+17} ions are 1.7×10^2 s, 5.6×10^2 s and 9.8×10^1 s, respectively, while for O^{+7} and Si^{+12} they are 1.4×10^2 s and 1.5×10^3 s. For comparison, the total collisional ionization times for the same ions are as follows: 2×10^3 s, 2×10^5 s, 10^3 s, 1 s, and 5×10^7 s (for $N=10^{10}$ cm^{-3}, $T=10^6$ K and $E\sim0.5$ MeV/nucleon). Detailed simulations will be necessary to clarify how well the Mullan and Waldron (1986) model fits these new observations.

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