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Model of ionic charge states of impulsive solar energetic particles in solar flares

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Abstract. We have fully developed a computational model (ESCAPE) to follow the behavior of the mean charge state of ions in solar energetic particle events while the ions are accelerated. Our model combines acceleration with energy loss and charge stripping low in the corona. Therefore we have taken into account explicitly the second-order Fermi-type stochastic acceleration under a magnetohydrodynamic turbulence. We have found that the mean ionic charge states depend sensitively on plasma parameters as source temperature or density and on acceleration parameters as efficiency or the timescales for acceleration. Our model finds a systematic increase of the ionic charge states with energy for all the ions studied. This energy dependence differs between ions, and in the energy range of observations this dependence is stronger for heavy ions.

1. Introduction

The calculation of the mean charge states of various ion stages of abundant elements is the first step in understanding and modeling the X-ray emission from hot astrophysical plasmas such as stellar coronae. From the charge state behavior of solar species, information may be inferred on parameters, as, for example, the ion rigidity or the source confinement time, on which the amount of emission of any element depends. A successful model needs to accurately reproduce observed particle behavior. As we will show in section 3 the mean ionization states should be a valuable tool for studies of the possible sources at the acceleration site of these ions but also for how the acceleration mechanism may affect particles with different rigidity.

Our nearest astrophysical plasmas are the solar corona and the solar wind. Particle acceleration in these plasmas has been stated from UV, RX, and solar energetic particle (SEP) measurements. Nowadays, it is well assumed a rough division of the SEP events into gradual solar energetic particle (GSEP) events and impulsive solar energetic particle (ISEP) events. ISEP events are compatible with high charge states for Fe ions ($q \sim 20$), and most of the ions lighter than Si appear fully stripped. From these observations a common plasma source temperature of $T \sim 10^7$ K has been assumed for these events. GSEP events are characterized by lower Fe charge states ($q \sim 11-15$), and most of the ions have charge states typical of an equilibrium temperature $T \sim 2x10^6$ K for the plasma source [*Klecker*, 1999]. Moreover, it has been stated that ISEP events are dominated by particles accelerated low in the corona by stochastic acceleration, while GSEP events are dominated by particles accelerated by coronal mass ejection (CME)-driven shocks [*Klecker*, 1999].

Models that include shock-induced acceleration and have been proposed for typical large GSEP events [*Barghouty and Mewaldt*, 1999; *Kartavykh and Ostryakov,* 1999], combining different acceleration mechanisms with energy loss and charge stripping, try to reproduce the observed ion charge states.

New direct measurements of SEP ionic charge states, with high sensitivity of the new instrumentation, have been obtained rencently, in particular, from ACE [*Stone et al.*, 1998; *Möbius et al.*, 1999] and SAMPEX [*Mazur et al.*, 1999]. These new experiments have provided charge states information in a wider energy range, even up to 60 MeV nucleon^{-1}, and for single SEPs, instead of the event averages provided by earlier measurements. Up to now they have mainly reported on ionic charge state distributions of GSEP, while those from ISEP have been scarce, mainly because of the low ion statistic in this kind of event. We hope in the near future to have accurate charge state measurements from ISEP to check the range of validitity of our model.

Mazur et al. [1999, p. 79] have pointed out the following: "Recent measurements of SEP ionization states in large events suggest more complexity in how the acceleration process affects particles of different rigidity than indicated in the charge state survey by Luhn et al. [1987]." Indeed, Luhn et al. present numerical calculations of the mean equilibrium charge of energetic ions,

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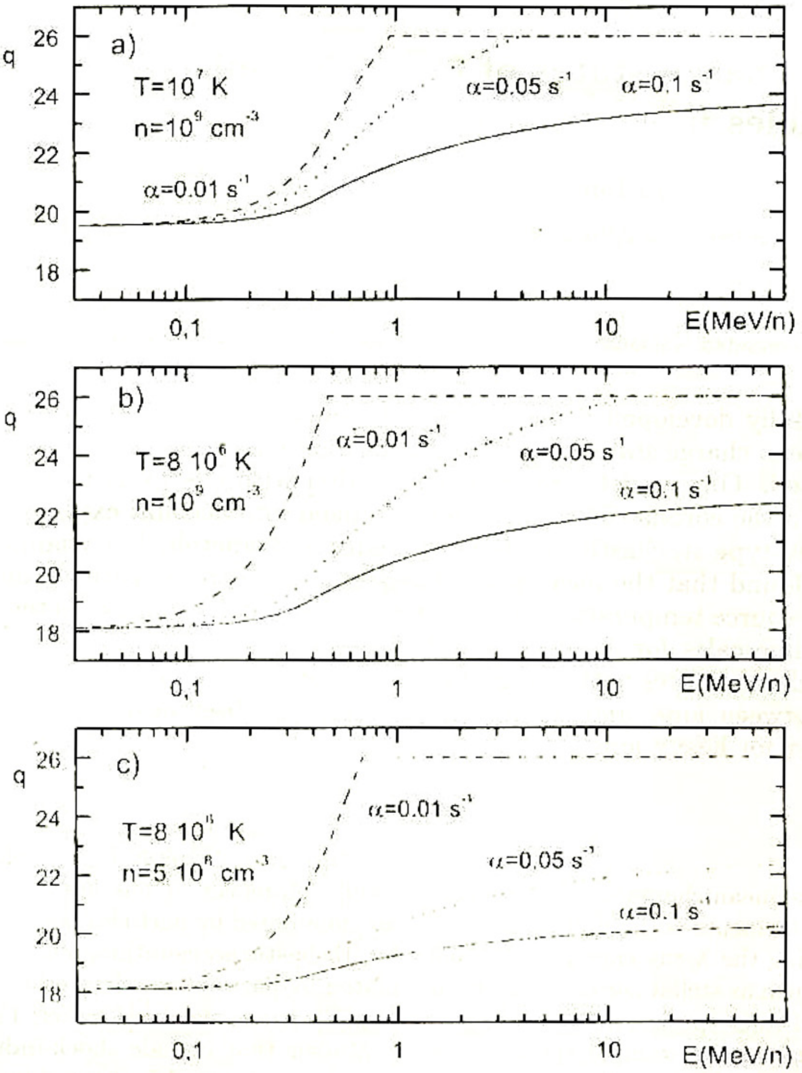

Figure 1. Energy dependence of the charge state, q, of Fe ions. (a) $T = 10^7$ K, n=10^9 cm^{-3}, $\alpha = 0.01, 0.05, 0.1$ s^{-1}. (b) $T = 8 \times 10^6$ K, $n = 10^9$ cm^{-3}, $\alpha = 0.01, 0.05, 0.1$ s^{-1}. (c) $T = 8 \times 10^6$ K, $n = 5 \times 10^8$ cm^{-3}, $\alpha = 0.01, 0.05, 0.1$ s^{-1}.

after passing through a hot, tenuous plasma. In their calculations they deal with energetic ions but they do not account explicitly for ion acceleration. Therefore what we attempt is to obtain the ionic charge state distributions of SEP events, modeling the particle acceleration at the source and taking explicitly into account what acceleration mechanism is acting.

We have focused our study on 12 astrophysically abundant elements (C, N, O, Ne, Na, Mg, Al, Si, S, Ca, Fe, and Ni), and we have covered a very wide energy range, from the thermal equilibrium up to 1 GeV nucleon^{-1}. The source plasmas are the solar flares, regions of low-β ($\beta \sim 10^{-3}$), hot ($T = 10^7$ K) plasma with high density ($n = 10^9$ cm^{-3}), short magnetic confinement times ($\tau = 0.01 - 10$ s), high magnetic field ($B = 100$ G), and high Alfvèn speed ($v_A \sim 10^4$ km s^{-1}). To model the projectile behavior under acceleration, the source plasma has been modeled as a plasma of protons and free electrons, where the heavy ions are just test particles.

2. Effective Charge Behavior Under Stochastic Acceleration

Energized ions traveling inside a plasma at velocity v may undergo two charge exchange processes. They can capture or lose electrons while they interact with the ambient plasma. Therefore the following processes have to be considered: electron ionization, autoionization after electron excitation, radiative recombination, and dielectronic recombination. For a detailed description see the work of *Rodríguez-Frías et al.*[2000]. Moreover, these energized ions lose energy owing to Coulomb collisions with the electrons of the medium, where the Bethe-Bloch equation gives the energy loss rate due to ionization. Therefore the charge state distribution of the projectiles has been obtained by the interaction of the ion projectile with the free plasma electrons, while ion-ion interactions have been neglected.

Here, our analysis is focused on projectile ions accelerated from the background thermal matter, in a way

Table 1. Mean Fe Charge States q in a Source of Temperature T and Density Number n Under an Acceleration Efficiency α

T,K	n,cm^{-3}	α,s^{-1}	E^a	q	t_a,s^b
10^7	10^9	0.01	>1	26.0	1.9
		0.05	2	25.0	1.3
		0.05	50	26.0	1.8
		0.10	2	22.3	0.7
		0.10	50	23.6	3.3
8×10^6	10^9	0.01	>0.5	26.0	3.2
		0.05	2	23.8	1.3
		0.05	50	26.0	3.5
		0.10	2	21.0	0.7
		0.10	50	20.1	2.2
8×10^6	5×10^8	0.01	>0.7	26.0	3.8
		0.05	2	21.0	1.3
		0.05	50	22.3	6.7
		0.10	2	19.5	0.6
		0.10	50	20.1	2.2

[a] E is the ion kinetic energy in MeV nucleon^{-1}.

[b] t_a is the acceleration time the ion takes to reach a charge state q.

that their initial velocities and charge states correspond to that of the thermal plasma. For the thermal charge states, q_{th}, we merely rely on calculations based on astrophysical plasma ionization fractions given by

Current theories of acceleration mechanisms in solar flares directly relate ISEP events with stochastic acceleration [*Reames,* 1999]. Therefore we have modeled the effects of stochastic acceleration, a second-order Fermi-type mechanism, from the acceleration site, which in our case could be the solar flares that account for ISEP events, involving as turbulence the low-frequency magnetohydrodynamic waves, where energy from MHD turbulence is transferred to particles by wave-particle resonant interactions (Fermi-like process). Assuming this scenario, we have restricted our model to the study of charge state variations and possible temperature conditions at the source of ISEP events.

If the acceleration mechanism at the source site is not taken into account, the energy loss contribution will cause the particle to thermalize. Nevertheless, when an acceleration mechanism is present, it will transfer energy to the given particle at a rate that for stochastic acceleration by the fast MHD mode is [*Gallegos-Cruz and Pérez-Peraza,* 1995]

$$\left(\frac{dE}{dt}\right)_{acc} = \left(\frac{4}{3}\right)\alpha(E^2 + 2mc^2E)^{1/2}, \qquad (1)$$

where m is the ion mass, c is the light speed, E is the projectile kinetic energy, and α (s^{-1}) is the efficiency of the acceleration mechanism involved. The α parameter depends on the specific MHD turbulence, the wave number, the total turbulent energy density, and the magnetic energy density, and α can roughly be taken as a time-independent and energy-independent parameter [*Pérez-Peraza and Gallegos-Cruz,* 1994].

Once the rate of energy gain due to acceleration is higher than that accounting for losses, the ion is accelerated from the thermal matter, starting with an averaged thermal charge state q_{th}. While the ion is accelerated, the charge state, q^*, evolves iteratively in each acceleration step, according to the equation

$$\begin{aligned} q^* &= q_0 + n_t t_a \Delta q_i \int_0^c [\sigma_{\text{ioniz}}(v)]\, v f(v) dv \\ &= -n_t t_a \Delta q_c \int_0^c [\sigma_{\text{capture}}(v)]\, v f(v) dv, \end{aligned}$$

where q_0 is the charge state of the ion at the beginning of each acceleration step in electron charge units (for the first acceleration step $q_0 = q_{th}$), Δq_i and Δq_c are the average charge exchange in each ionization and capture process, respectively, $f(v)$ is the plasma electron distribution, which is a Maxwellian function in the rest frame of the source plasma, σ_{ioniz} is the total cross section for electron loss, σ_{capture} is the total cross section for electron capture, and t_a is the time spent in each acceleration step [*Rodríguez-Frías et al.,* 2000]:

$$t_a = \frac{2}{\sqrt{2mc^2}\alpha}\left(\sqrt{E_f} - \sqrt{E_i}\right), \qquad (2)$$

where E_i and E_f are the initial and final kinetic energies of the ion for each acceleration step.

Concerning propagation effects and additional acceleration in the interplanetary medium, we have assumed they do not significantly affect the charge state distributions obtained, owing to the rather low density of the interplanetary plasma. Therefore we have not taken into account any contribution derived from these effects.

Semiempirical parameterizations for the mean equilibrium charge of projectiles after passing through neutral gases may be found in the literature, where particles preserve their original charge states without interaction with the source [*Betz,* 1980]. The semiempirical formula of Barkas-Blume, accounting for source temperature, is

$$q^* = Z[1 - \xi\exp(-b\ \beta/\alpha\ Z^{2/3})], \qquad (3)$$

where q^* is the ion charge state, Z is the nuclear charge, β is the ion velocity relative to the light speed, α is the fine-structure constant, $b = 0.93$, and ξ is a temperature-dependent parameter. For laboratory plasma experiments, $\xi = 1$, while for an astrophysical plasma at temperature T, $\xi = \exp(-130kT/mc^2)$.

3. Results and Discussion

To show how the efficiency of the acceleration mechanism affects the charge state behavior, we have plotted in Figure 1 the charge states of Fe ions versus the kinetic energy of the ion. In Figure 1a we have taken as input parameters a source temperature and density number of $T = 10^7$ K and $n = 10^9$ cm^{-3}, respectively. We have considered three acceleration efficiencies, and as it can be seen in Figure 1a, in all cases our model predicts Fe charge states higher than experimental ones, as can be seen in Table 1. The mean charge states may either be enhanced or be depressed [*Rodríguez-Frías et*

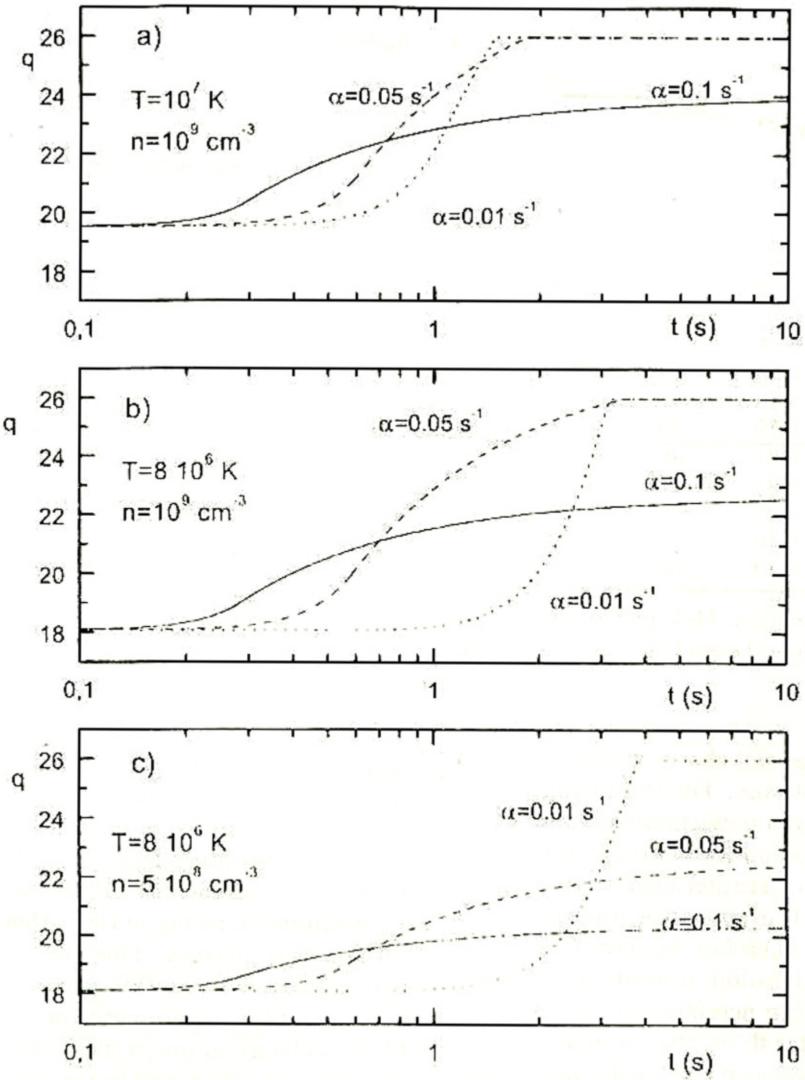

Figure 2. Temporal profiles of the charge state, q, of Fe ions. (a) $T = 10^7$ K, n=10^9 cm^{-3}, $\alpha = 0.01, 0.05, 0.1$ s^{-1}. (b) $T = 8 \times 10^6$ K, $n = 10^9$ cm^{-3}, $\alpha = 0.01, 0.05, 0.1$ s^{-1}. (c) $T = 8 \times 10^6$ K, $n = 5 \times 10^8$ cm^{-3}, $\alpha = 0.01, 0.05, 0.1$ s^{-1}.

al., 2000], depending on the acceleration efficiency of the acceleration mechanism involved. Under $\alpha = 0.01$ s^{-1} and $\alpha = 0.05$ s^{-1}, Fe ions appear fully stripped at $E \sim$ MeV, the energy scales of experimental observations. Only under more efficient stochastic acceleration, $\alpha = 0.1$ s^{-1}, do Fe ions remain partially ionized, but the charge state they preserve is higher than observations. Therefore we have tried in Figure 1b a lower source temperature $T = 8 \times 10^6$ K. Again, the charge state q/Z remains lower than 1 for $\alpha = 0.1$ s^{-1} but higher than the experimental values (Table 1). Our model reproduces the experimental Fe charge states reported for ISEP events under the source parameters $T = 8 \times 10^6$ K and $n = 5 \times 10^8$ cm^{-3}, presented in Figure 1c, and an $\alpha = 0.1$ s^{-1} for the acceleration efficiency. Table 1 gives the numerical values obtained for the mean Fe charge states.

From X-ray and γ-ray data for solar flares one can conclude that the particle acceleration timescale may be about several seconds [*Zirin,* 1989, p. 384] if a strong turbulence is assumed, as we have done. Therefore to reproduce the experimental charge states, the values predicted by our model have to be consistent with this temporal scale. Figures 2a - 2c present the time profiles of Fe charge states under different source conditions and stochastic acceleration efficiencies. The temporal range of seconds should give a charge interval compatible with experimental values. Table 1 presents our model estimations of the timescale needed to achieve the Fe charge states obtained. We have found that these acceleration times are consistent with solar flare observations.

Figure 3 shows the charge state behavior of Fe ions, assuming two source temperatures, two different density numbers, and an acceleration efficiency $\alpha = 0.1$ s^{-1}. Our model predicts ionization states higher than the mean charges of ions at rest and in thermal equilibrium with the plasma. These higher charge states should be produced in the low corona, where the density is high enough to ionize ions to these ionization states. Therefore if one tries to relate charge state measurements to a common equilibrium temperature, the source tem-

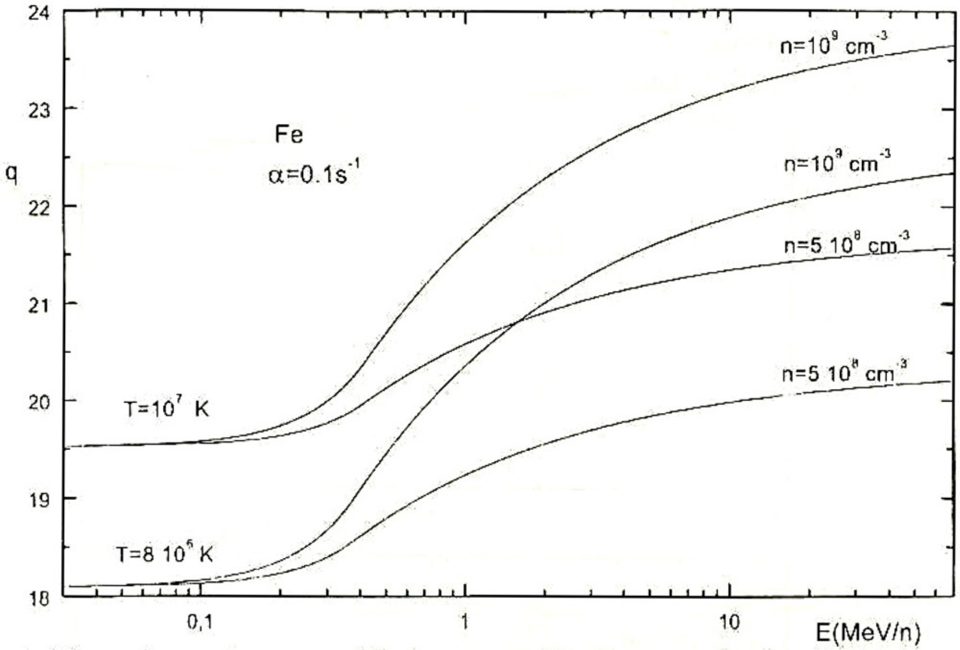

Figure 3. Mean charge states, q, of Fe ions versus kinetic energy for two source temperatures and two number densities, with $\alpha = 0.1$ s^{-1}.

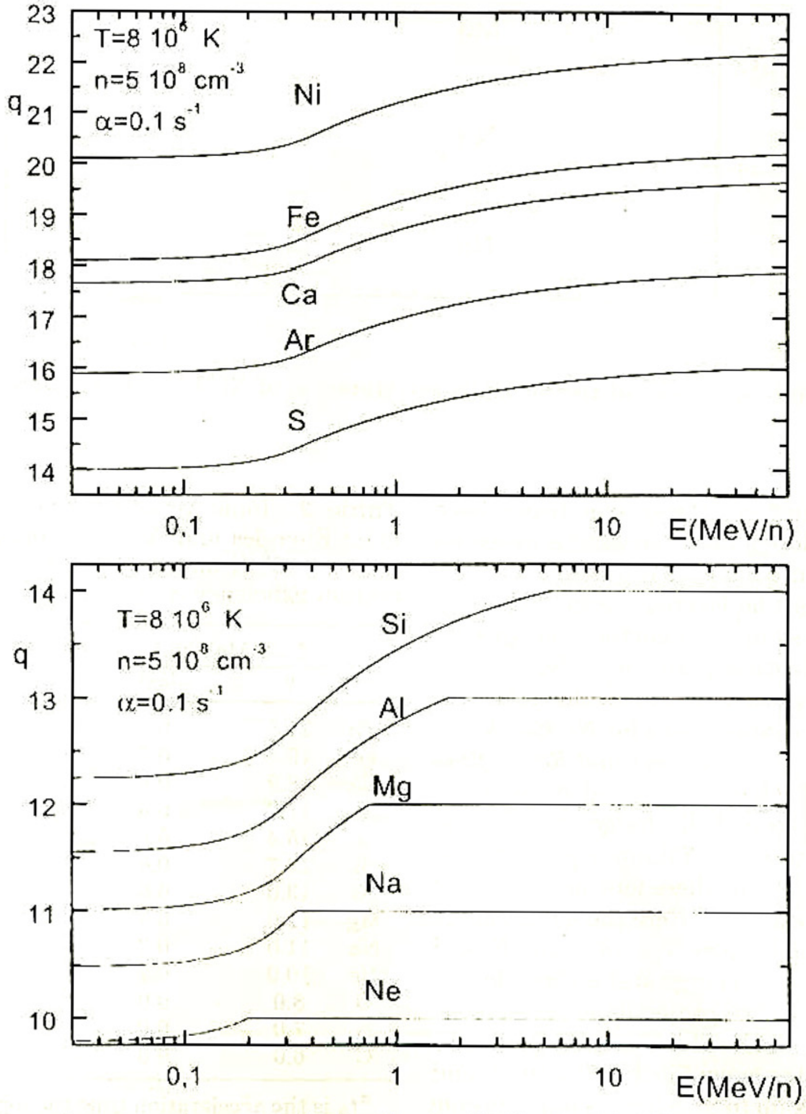

Figure 4. Mean charge states, q, of Ni, Fe, Ca, Ar, S, Si, Al, Mg, Na, and Ne versus projectile kinetic energy E(MeV nucleon^{-1}).

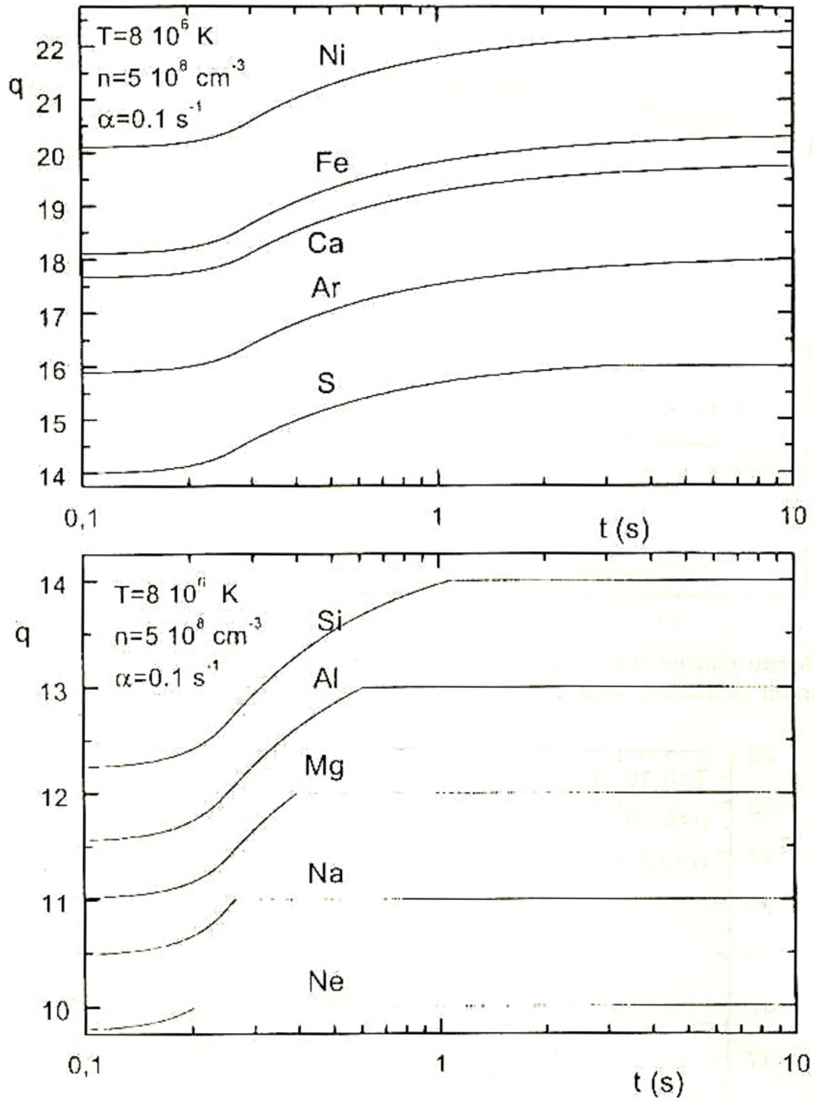

Figure 5. Temporal profiles of the mean charge states, q, of Ni, Fe, Ca, Ar, S, Si, Al, Mg, Na, and Ne ions.

perature will be overestimated. We systematically have found a source temperature lower than what is expected from the equilibrium source temperature.

Once we have analyzed the Fe charge state behavior, we have found that the source parameters that give Fe charge states consistent with experimental observations are $T = 8 \times 10^6$ K and $n = 5 \times 10^8$ cm^{-3}. Therefore we have obtained the ionic charge states for Ni, Ca, Ar, S, Si, Al, Mg, Na, and Ne. From *Arnaud and Rothenflugs* [1985] results, C, N, and O have $q/Z = 1$ at these source temperatures and then keep their charge state during the entire acceleration process. Figure 4 presents the ionic charge state behavior for these ions in the energy range $(0.5 - 70)$ MeV nucleon^{-1}. Here the mean charge states have been modeled under $T = 8 \times 10^6$ K and $n = 5 \times 10^8$ cm^{-3}. The ionic charge states show dependence on kinetic energy of the projectile under acceleration for all the ions studied. This energy dependence on the mean charge states is confined to a narrow and low-energy range for ions up to Si, which mainly become fully stripped at energies around 1 MeV nucleon^{-1}, and

Table 2. Ionic Mean Charge States for Different Kinetic Energies and Acceleration Times, in a Source of $T = 8 \times 10^6$ K and $n = 5 \times 10^8$ cm^{-3}, Under an Acceleration Efficiency $\alpha = 0.1$ s^{-1}

Ion	E=2 MeV nucleon^{-1}		E=50 MeV nucleon^{-1}	
	q	t_a,s ^{a}	q	t_a,s ^{a}
Ni	21.5	0.6	22.1	2.4
Fe	19.5	0.7	20.1	2.0
Ca	18.9	0.6	19.6	2.6
Ar	17.2	0.6	17.8	2.4
S	15.4	0.6	16.0	2.4
Si	13.7	0.6	14.0	1.1
Al	13.0	0.6	13.0	0.6
Mg	12.0	0.4	12.0	0.4
Na	11.0	0.3	11.0	0.3
Ne	10.0	0.2	10.0	0.2
O	8.0	0.0	8.0	0.0
N	7.0	0.0	7.0	0.0
C	6.0	0.0	6.0	0.0

[a] t_a is the acceleration time the ion takes to reach a charge state q.

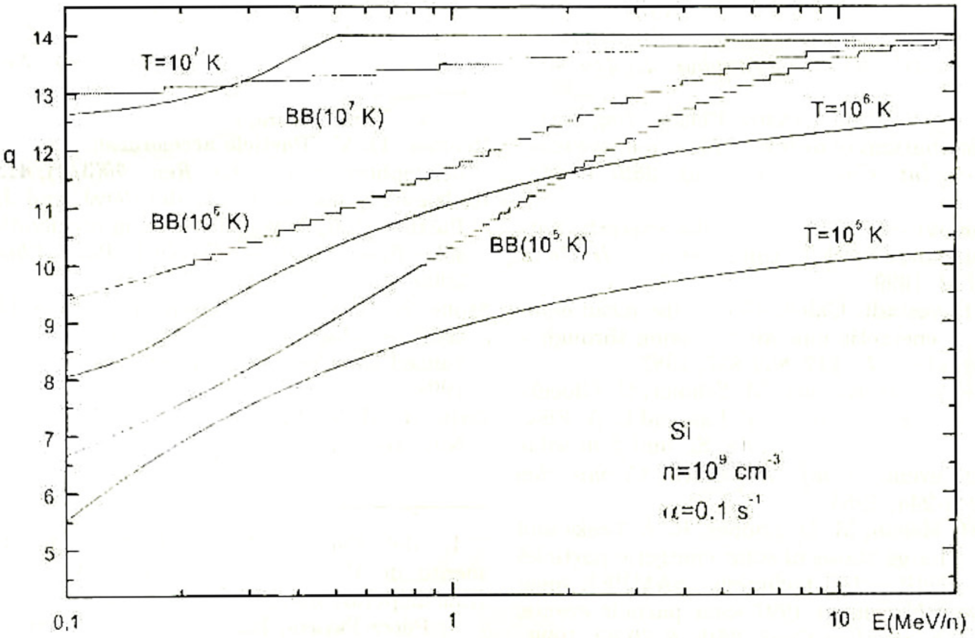

Figure 6. Mean charge state, q, of accelerated Si ions as a function of the kinetic energy. Dashed curves are the semiempirical approximation of Barkas-Blume (BB) (equation (3)) for different source temperatures.

broaden out with the increase of energy for Si, S, Ar, Ca, Fe, and Ni, which remain in high ionization states at energies higher than 1 MeV nucleon^{-1}. That is in accordance with ISEP measurements where all elements up to Si are fully ionized (E. Möbius and M. Popecki, http://www.srl.caltech.edu/ACE/ACEnews 1998). The energy dependence found is stronger for higher-Z ions with a maximum slope in the 0.3-0.9 MeV nucleon^{-1} energy range. Moreover, the maximum change in charge state is ~ 2 charge units, found for higher-Z ions.

Figure 5 shows the time profile of the mean ionic charge states for all the ions under consideration in the temporal interval 0.1-10 s. As can be seen for acceleration times around several seconds, all ions up to Si appear fully stripped. Table 2 presents the numerical values of the ionic mean charge states for all the ions studied at two different energies and the acceleration times needed to achieve ions with such charge states.

Following Figure 1 of *Luhn and Hovestadt* [1987], we have plotted the charge state of Si in the energy range 0.1-10 MeV nucleon^{-1} for three source temperatures. As a semiempirical approximation we have plotted the Barkas-Blume equation with the source temperature dependence (Figure 6). As can be seen, the steps they obtain due to shell effects, here are blurred by the acceleration mechanism that we have explicitly taken into consideration. Moreover, they obtain Si fully stripped for all the source temperatures studied at $E > 7$ MeV nucleon^{-1}, while our model predicts only fully ionized Si at 10^7 K. Experimentally, Si has been reported in high ionized states but is not fully stripped for ISEP events (E. Möbius and M. Popecki, http://www.srl.caltech.edu/ACE/ACEnews 1998). Moreover, Figure 6 shows the difference between the semiempirical approximation of Barkas-Blume and the model charge states evolution, owing to the fact that the Barkas-Blume equation is an approximation where the targets are neutral gases.

It is usually assumed that the charge state of cosmic rays corresponds to the ionization equilibrium of the plasma where they undergo acceleration. That is how experimentalists have found, for example, a rough consistency of GSEP ionization states with quiet coronal source temperatures, $T = 1.5 - 3 \times 10^6$ K. What we attempt to demonstrate with our model is that the acceleration mechanism involved modifies the equilibrium charge states of projectiles under stochastic acceleration to higher ionization states. Therefore the source temperature inferred from charge states observations should be slightly overestimated.

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