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Mean charge states of solar energetic particles in impulsive events

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Abstract. The calculation of the mean charge states of various ion stages of abundant elements is the first step in understanding and modelling the X-ray emission from hot astrophysical plasmas such as stellar coronae. 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.

1 Introduction

Evidence for particle acceleration in hot plasmas as solar flares is provided by direct solar energetic particle (SEP) measurements by detectors on board spacecrafts and by the detection of neutral radiation, produced by accelerated particles interacting with the solar atmosphere.

To account for the charge states behaviour of SEP under an acceleration mechanism, a huge amount of acceleration scenarios may be postulated, either with *continuous* acceleration in 1-*phase* or *episodical* acceleration in 2- and 3- acceleration *phases*. One-*phase* acceleration is frequently associated to *direct electric field acceleration*, while 2- and 3-acceleration *phases* are rather associated with *stochastic* and *shock wave acceleration*. On the previous basis, impulsive solar energetic particles (ISEP) events are better described in terms of acceleration by stochastic turbulence low in the solar corona, whereas gradual solar energetic particles (GSEP) are usually explained by shock wave acceleration (Klecker , 1999).

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), (Mobius 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/n, 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 due to the low ion statistic in this kind of events.

Concerning the computational approaches to the study of these topics, only a few models have been found in the literature. The model of Barghouty et al. (Barghouty and Mewaldt , 1999) and that of Stovpyuk and Ostryakov (1999) include shock-induced acceleration and have been proposed for typical large solar events (GSEP) while the model developed by Rodríguez-Frías et al. ((2000), (2001)) and that of Kartavykh and Ostryakov (1999) include stochastic acceleration to account for ISEP events. The difference between these two ISEP models relays in the turbulence chosen. As it is very well known many types of turbulence are ineffective in accelerating particles because only energy diffusion takes place. That is why Rodríguez-Frías et al. ((2000), (2001)) have chosen as turbulence a 2nd-order Fermi-type magnetohydrodinamic turbulence, instead of an Alfven wave turbulence as Kartavykh and Ostryakov (Kartavykh and Ostryakov , 1999) have done.

We hope in a nearly future to have accurated ISEP charge state measurements to check the range of validitity of our model.

2 ESCAPE code

In previous works (Rodríguez-Frías, del Peral and Pérez-Peraza (2000), 2001), we have fully developed a code (ESCAPE), to follow the behaviour of the charge states of ions in impulsive solar events. In this work we have concentrated our efforts on stochastic acceleration which results from interaction of the ions with waves of the various modes which can exist in a magnetized plasma. Our main aim is not to study if the ac-

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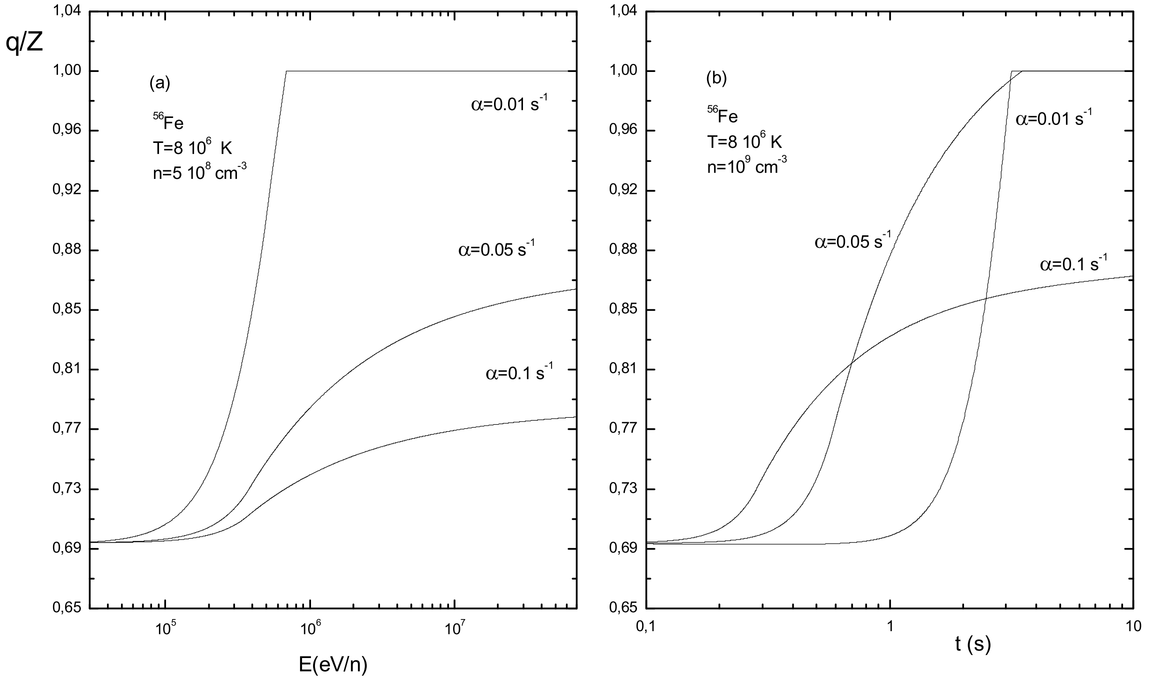

FIGURE 1

Fig. 1. a) Fractional mean charge state, q/Z, of ^{56}Fe ions versus kinetic energy E(eV/n) for $T = 810^6$ K, n=5 10^8 cm^{-3} and three different acceleration efficiencies: $\alpha = 0.1, 0.05$ and 0.01 s^{-1}. b) Temporal profile of the fractional charge state of ^{56}Fe ions for $T = 10^7$ K, n=5 10^8 cm^{-3} and three different acceleration efficiencies: $\alpha = 0.1, 0.05$ and 0.01 s^{-1}.

celeration mechanism has enough efficiency to accelerate a reasonable number of particles to 100 MeV/n. We have implemented a 2nd-order Fermi stochastic acceleration under a magnetohydrodynamic turbulence that has been previously found to be highly efficiently, and also the particle spectrum under these acceleration mechanism has been reproduced.

Energized ions travelling 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 cosidered: electron ionization, autoionization after electron excitation, radiative recombination and dielectronic recombination. Moreover, these energized ions lose energy due 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 have been obtained by the interaction of the ion projectil with the free plasma electrons, while ion-ion interactions have been neglected. For a detailed description of the ESCAPE code see (Rodríguez-Frías, del Peral and Pérez-Peraza , 2000).

Here, our analysis is focussed on projectil ions accelerated from the background thermal plasma, where their initial velocities and charge states correspond to that of the thermal plasma. For the thermal charge states, q_{th}, we merely rely in calculations based on astrophysical plasma ionization fractions given by Arnaud and Rothenflug (1985) and updated for Fe ions by Arnaud and Raymond (1992), as tables of equilibrium ionization of plasma ions for coronal conditions.

As acceleration mechanism, the Fermi type acceleration has been implemented, that account mainly for ISEP events, better described in terms of acceleration by *stochastic turbulence*. Deceleration effects have been explicitely taken into account (Rodríguez-Frías, del Peral and Pérez-Peraza , 2000). The stochastic acceleration may be described by either a diffusion equation in momentum space or a Fokker-Planck equation in energy space. The α parameter is obtained from the diffusion coefficient $D(p)$ of the momentum diffusion equation, that for stochastic acceleration is (Ramaty , 1979)

$$D(p) = \alpha \frac{p^2}{3\beta} \quad (1)$$

where p is the ion momentum, α is the efficiency of the acceleration mechanism involved and β is the ion velocity in terms of the light speed.

The convection and diffusion coefficients A and D, respectively, of the Fokker- Planck equation are

$$A = \frac{dE}{dt} \quad (2)$$

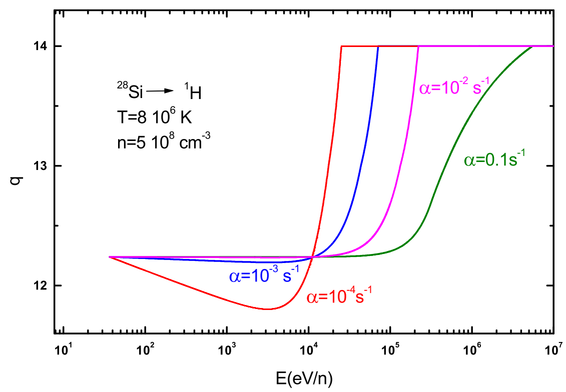

Fig. 2. Evolution of the energy dependence of ^{28}Si charge states under different acceleration efficiencies, α.

$$D = \frac{dE^2}{dt^2} \tag{3}$$

and of course may be related to $D(p)$ in the momentum space, obtaining

$$A = \frac{1}{p^2}\frac{\partial(vp^2D(p))}{\partial p} \tag{4}$$
$$D = 2v^2D(p) \tag{5}$$

Therefore from (1), (2) and (4) we can obtain the acceleration rate as

$$\frac{dE}{dt} = \frac{1}{p^2}\frac{\partial(vp^2D(p))}{\partial p} = \frac{4}{3}\alpha pc = \frac{4}{3}\alpha(E^2+2mc^2E)^{1/2} \tag{6}$$

As can be seen α has dimension T^{-1} and is the acceleration efficiency. The α parameter depends on the specific MHD turbulence, the wave number, the total turbulent energy density and the magnetic energy density, and can roughly be taken as a time-independent and energy-independent parameter.

3 Results and discussion

3.1 Implications on charge dependence of the acceleration mechanism

To show how the efficiency of the acceleration mechanism affects the charge state behaviour, we have plotted in Figure 1 the evolution of the fractional charge states of Fe and Si ions while they are accelerated under an acceleration mechanism. Information on particle acceleration may be inferred from high energy charge states, since higher energies generally require longer trapped times in the acceleration site. Figure 1 (a) shows how for low acceleration efficiencies (i.e. $\alpha = 0.01\ s^{-1}$) the acceleration takes place slowly and the projectil has time to become completelly stripped. From Figure 1 (b) it can be seen how under such low efficiencies, $\alpha = 0.01\ s^{-1}$, the ion charge state remains invariant during the first second, due to the equilibrium between electron capture and ionization. Later, ionization dominate the electron capture and finally the ion becomes completelly ionized.

In Figure 2 it can be seen how the obtained mean charge states may either be enhanced or depressed, depending on the acceleration efficiency of the acceleration mechanism involved. These acceleration efficiencies, lower than 0.1 s^{-1}, have no physical meaning and have been plotted only to show that this stochastic acceleration model allows the projectiles to pick-up electrons, instead of lose them. Therefore depending on the parameters one can reproduce with the model, situations where the charge state dimish, and therefore electron capture instead of ionization is dominant. Of course we have to move in the range of α parameters consistent with solar source conditions, to reproduce the particle energy spectrum experimentally observed.

3.2 Implications on source parameters

To analyse the dependence of the ionization states on source parameters as the density or the temperature, we have plotted in Figure 3 the temporal evolution of the charge states of Fe and Si ions for two different source densities. Also the energy dependence of the charge states under different densities are shown. As can be seen higher densities mean higher ionization states, and for Si ions they become full stripped at lower energies and earlier in time than when they are accelerated in a lower density source.

It is usual to assume a single equilibrium temperature for the source of the ISEP events, from the experimental charge states values measured, following the calculations of Arnaud and Rothenflug (1985), updated for Fe ions by Arnaud and Raymond (1992).

3.3 Implications on energy dependence of the charge states

We have found energy variations in the ionization states. This energy dependence is more pronounced for heavier ions than for lighter ones as can be seen in Figure 3 (b).

3.4 Comparison with previous works

Meanwhile for GSEP events many papers have reported on ionization states for major elements, for ISEP events those are scarced and only for Si and Fe ions. The ionic charge states for ^3He-Fe-rich ISEP events are significantly higher than those observed at $\sim$ 1 MeV/n in typical GSEP events (Mason et al. , 1995).

Moreover, ionization states ranging between 19.4 and 20.0 for Fe ions and between 13.5 and 14 for Si ions are consistent with a $q_{Si} \simeq 14$ and $q_{Fe} \simeq 20$ reported for impulsive events (Klecker et al. (1984), Luhn et al. (1987)).

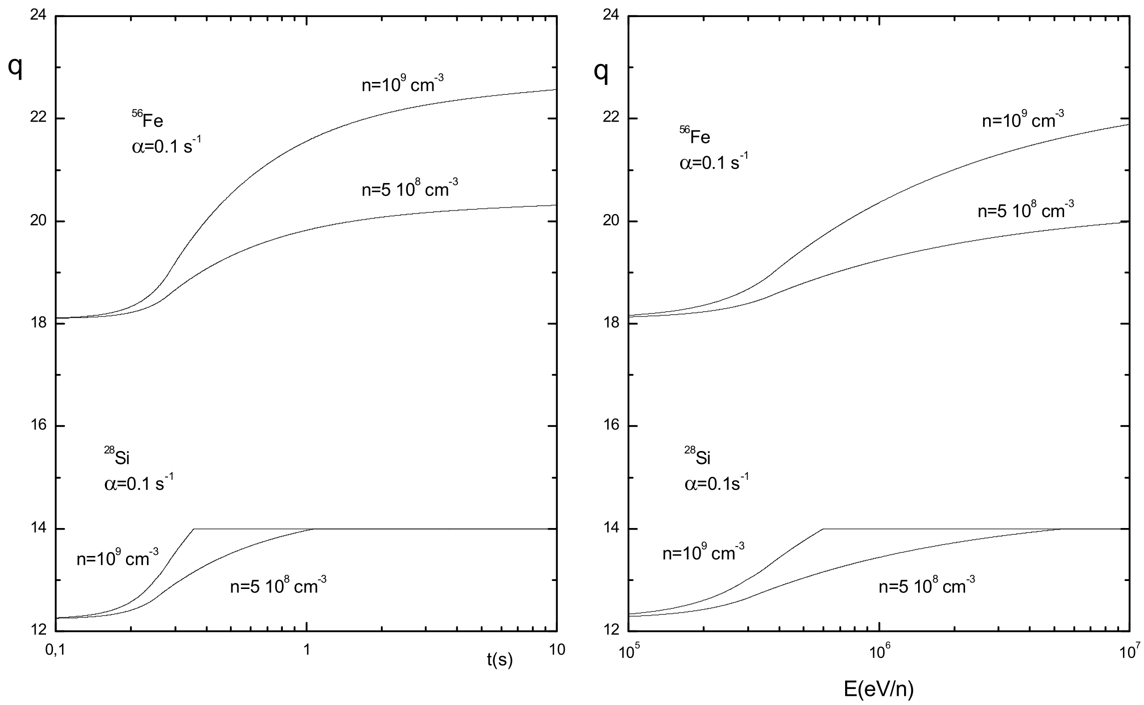

FIGURE 3

Fig. 3. Mean charge states of Fe and Si ions versus kinetic energy for $T = 810^6$ K and two density numbers, n.

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