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Energy dependence of the charge state distribution of accelerated ions in solar flares.

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Abstract. We have fully developed a computational model (ESCAPE) to follow the behaviour of the mean charge state of ions in Solar Energetic Particle (SEP) events while are accelerated. Our model takes into account explicitely the 2nd-order Fermi-type stochastic acceleration under a magnetohydrodynamic turbulence. We have found that the mean ionic charge states are strongly dependent on plasma parameters as source temperature or density and on acceleration parameters as efficiency or the time scales 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, but in the energy range of observations affects mainly to heavy ions.Este trabajo his work is a preliminary study of 18 solar energetic particle (SEP) events detected by SOHO/EPHIN between 1996 and 2000. Temporal profiles of Impulsive and Gradual SEP events have been parameterized to determinate differences among SEP events depending on the magnetic connection and Physical conditions of the interplanetary transport.

1 Introduction

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. The charge state enhancement of different species over the solar values shows that there are parameters on which the amount of emission of any element depends, as for example the effective charge, the ion rigidity, the source confinement time... Moreover, the fractional effective charge behaviour directly affects models that attempt to explain the abundance variations. As we will show later 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 ($q \approx 20$) and most of the ions lighter than Si appear fully stripped. From these observations, a common plasma source temperature of $T \approx 10^7$ K has been assumed for these events. GSEP events are characterized by lower Fe charge states ($q \approx 11$-15) and most of the ions have charge states typical of an equilibrium temperature $T \approx 2\ 10^6$ K for the plasma source. 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 CME-driven shocks. For a more quantitative approach see Pérez-Peraza et al., 1998.

New direct measurements of SEP ionic charge states, with high sensitivity of the new instrumentation have been obtained rencently, in particular from ACE (Cohen C. M. S. et al., 1999, Mobius E., et al., 1999) and SAMPEX (Luhn A. and Hovestadt D., 1987, Mazur J. E. 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. Anyway 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. We hope in a nearly future to have accurated charge state measurements from ISEP to check the range of validitity of our model.

We have foccused our study on 12 astrophysically abundant elements (C, N, O, Ne, Na, Mg, Al, Si, S, Ca, Fe, Ni) and we have covered a very wide energy range, from the thermal equilibrium up to 1 GeV/n. As source plasma, we are interested in the solar flares, regions of low-β, 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. To model the projectil behaviour under acceleration, the source has been modelled as a plasma of protons and free electrons.

2 Effective charge behaviour under stochastic acceleration

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. For a detailed description see Rodríguez-Frías M. D. , del Peral L. and Pérez-Peraza J., 2000, . 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.

Here, our analysis is focussed on projectil ions accelerated from the background thermal matter, in a way that 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 M. and Rothenflug R. 1985 and updated for Fe ions in Arnaud M. and Raymond J., 1992, as tables of equilibrium ionization of plasma ions for coronal conditions.

Current theories of acceleration mechanisms in solar flares, directly relate ISEP events with stochastic acceleration. Therefore we have modelled the effects of stochastic acceleration, a 2nd-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 magnetohydrodinamic waves, where energy from MHD turbulence is transferred to particles by wave-particle resonant interactions (Fermi-like process). Assuming this scenario, we have restricted ourselves 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 bring 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 A. and Pérez-Peraza J., 1995):

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

where m is the ion mass, c is the light speed, E is the projectil 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 can roughly be taken as a time-independent and energy-independent parameter (Pérez-Peraza J. and Gallegos-Cruz A., 1994).

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

$$q^* = q_0 + n_t t_a \Delta q_i \int_0^c \left[\sigma_{ioniz}(v)\right] v f(v) dv$$

$$- n_t t_a \Delta q_c \int_0^c \left[\sigma_{capture}(v)\right] v f(v) dv$$

where q_0 is the effective charge 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, $\sigma_{capture}$ is the total cross section for electron capture and t_a is the time spent in each acceleration step, obtained from (Rodríguez-Frías M. D. , del Peral L. and Pérez-Peraza J., 2000,

Concerning propagation effects and additional acceleration in the interplanetary medium, we have assumed they do not affect significatively the charge state distributions obtained, due to the rather low density of the interplanetary plasma.

It may be found in the literature semiempirical parametrizations for the mean equilibrium charge of projectiles after passing through neutral gases, where particles preserve their original charge states without interaction with the source. The semiempirical formula of Barkas-Blume, accounting for source temperature is:

$$q^* = Z\left[1 - \chi e^{-\frac{b\beta}{\alpha Z^{2/3}}}\right]$$

where q* is the ion effective charge, β is the ion velocity relative to the light speed, α is the fine-structure constant, b=0.93 and χ is a temperature dependent parameter. At laboratory scales $\chi=1$ while for an astrophysical plasma at temperature T, $\chi = \exp\left(-\frac{130kT}{mc^2}\right)$.

3 Results and discussion

To show how the efficiency of the acceleration mechanism affects the charge state behaviour, we have plotted in Figure 1 the fractional charge states of Fe ions versus the kinetic energy of the ion. In Figure 1(a) we have taken as input parameters a source temperature and density number of $T=10^7$ K and $n=10^9$ cm^{-3} respectively. These are the source parameters of ISEP events inferred from experimental measurements, where Fe charge states from q=18.11-19.66 were reported \citep{Mobius99}. We have considered three acceleration efficiencies, in all cases, our model predicts Fe charge states higher than experimental ones. The mean charge states may either be enhanced or depressed, 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 full stripped at $E \approx 1$ MeV, the energy scales of experimental observations. Only under more efficient stochastic acceleration, $\alpha=0.1$ s^{-1}, Fe ions remain partially ionized, anyway the charge state they preserve is higher than observations. Therefore we have tried a lower source temperature $T=8\ 10^6$ K. Again the fractional effective charge q/Z remains lower than 1 for $\alpha=0.1$ s^{-1} but higher than the experimental values. Our model reproduces the experimental Fe charge states reported for ISEP events under the source parameters $T = 8\ 10^6$ K and $n = 5\ 10^8$ cm^{-3}, 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 particle acceleration timescale is about several seconds. Therefore to reproduce experimental charge state values, the values predicted by our model have to be consistent with this temporal scale. Figures 2(a), 2(b) and 2(c) present the time profiles of Fe charge states under different source conditions and stochastic acceleration efficiencies. The temporal range of seconds should give the charge interval compatible with experimental values.

We have found that these acceleration times are consistent with solar flare observations. 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 charge states measurements try to be related with a common equilibrium temperature, the source temperature should be overstimated. 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 behaviour, we have found that the source parameters that give Fe charge states consistent with experimental observations are $T = 8\ 10^6$ K and $n= 5\ 10^8$ cm^{-3}. Therefore we have obtained the ionic charge states for Ni, Ca, Ar, S, Si, Al, Mg, Na and Ne. From Arnaud and Rothenflug results \citep{Arnaud85} C, N and O have q/Z=1 at these source temperatures and then keep their charge state during all the acceleration process. In the energy range ($5\ 10^4$-$7\ 10^7$) eV/n, the mean charge states have been modelled under $T = 8\ 10^6$ K and $n = 5\ 10^8$ cm^{-3}. The ionic charge states show dependence on kinetic energy of the projectil 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, that mainly become full stripped at energies around 1 MeV/n, and to broaden out with the increase of energy for S, Ar, Ca, Fe and Ni, that remain in high ionization states at energies higher than 1 MeV/n. That is in accordance with ISEP measurements where all elements up to Si are fully ionized \citep{Luhn87}.

From the acceleration times in the order of 1 s, all ions lighter than 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 \citet{Luhn87} we have compared the fractional effective charge of Si in the energy range (0.1-10) MeV/n for three source temperatures. As semiempirical aproximation we have used the Barkas-Blume equation with the source temperature dependence. As it can be seen the steps they obtain due to shell effects, here are blurred by the acceleration mechanism that we have explicitely taken into consideration. Moreover they obtain Si fully stripped for all the source temperatures studied at E>7 MeV/n, while our model predicts only fully ionized Si at 10^7 K. Experimentally, it has been reported Si in high ionized states but not fully stripped for ISEP events.

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, $T = (1.5\text{-}3)\ 10^6$ K. What we attemp 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 lightly overestimated.

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