SH 1.5.14

Plasma Diagnostics by the Charge Distributions of Heavy Ions in Impulsive Solar Flares

Yu.Yu.Kartavykh and V.M.Ostryakov

Phys.-Techn. Department, St.Petersburg State Technical University, St. Petersburg 195251, RUSSIA

Abstract

We consider stochastic acceleration of heavy ions (Fe as a sample species) by the Alfven wave turbulence in impulsive solar flares. The processes of Coulomb losses and ion stripping during the energy gain are taken into account. The properties of charge distribution function are influenced by the plasma parameters such as temperature, number density and spectral index of turbulence. General dependences of the mean charge, dispersion and asymmetry of charge distribution on plasma parameters are investigated. These simulations could be important in the light of new experimental data from ACE spacecraft that is able to measure charge distribution for an individual impulsive event.

1 Introduction:

It is well known that impulsive and gradual solar energetic particle (SEP) events differ in the mean charge of heavy ions. Namely, mean charge of iron in impulsive events is higher ($\overline{Q}_{Fe}$~20) than that for gradual ones ($\overline{Q}_{Fe}$~14, see *Luhn et al.*, [1987]). This parameter of ions contains very important information on the processes of acceleration and propagation in a solar plasma. For impulsive solar flare events detailed measurements of ionization states could give particularly useful information because they occur in rather dense and compact regions in the low corona. Therefore, stripping effects and energy losses become extremely important [*Yoshimori et al*., 1999]. As a result, the charge state distribution of escaping heavy ions does not reflect the equlibrium charge distribution of thermal plasma (which is characterized by a temperature) but rather the grammage of matter traversed before escape from the inner corona. Unfortunately, there are not so numerous results to date on the charge states of ions in impulsive events because of very low fluxes of ions there. Previous data were obtained by averaging over a number of events to improve statistics [*Luhn et al*., 1987].

In the present paper we try to apply our model for heavy particle acceleration by stochastic mechanism [*Kartavykh et al*., 1998] to investigate in detail the influence of plasma parameters (temperature and number density) on the charge distributions of ions. This model takes into account the Coulomb losses of ions and the possibility to change the charge during the acceleration and propagation in a plasma. This in turn strongly affects the acceleration efficiency and spatial diffusion through diffusion coefficients. We call such a model as a charge-consistent model for a generation of energetic heavy particles. We perform our simulations only for Fe as a sample species. First, it is one of the most abundant element in solar cosmic rays (SCRs) and, second, for Fe we have all the cross sections of its ionisation (stripping) by protons. The latter process are shown to be the most important one when considering nonthermal heavy ion propagation in plasmas [*Kharchenko and Ostryakov*, 1987; *Kartavykh et al*., 1998].

2 Simulation model:

In this section we briefly discuss our model for stochastic acceleration (the methodology was also described previously in the paper of *Kartavykh et al*. [1998]). Thus, we start with the conventional one-dimensional Fokker-Planck equation for particle acceleration and spatial diffusion along the x ($0<x<L$):

$$-\frac{\partial F_Q}{\partial t}+\frac{\partial^2}{\partial E^2}\left(\varphi F_Q\right)-\frac{\partial}{\partial E}\left(\psi F_Q\right)+\chi\frac{\partial^2 F_Q}{\partial x^2}-\frac{\partial}{\partial E}\left(\frac{dE}{dt}F_Q\right)-\frac{F_Q}{\tau_{Q,Q+1}}+\frac{F_{Q-1}}{\tau_{Q-1,Q}}=0 \quad (1)$$

with the functions $\varphi(D_p)$, $\psi(D_p)$ from *Kartavykh et al*. [1998] and the coefficients:

$$D_p=D_0(Q/A)^{2-S}\,E^{(S-1)/2}, \qquad \chi=\chi_0(Q/A)^{S-2}\,E^{(3-S)/2} \quad (S<2), \tag{2}$$

which describe the interaction of ions with homogeneous Alfven wave turbulence. For S>2 only an expression of χ is changed and is shown to be $\chi=\chi_0(Q/A)^{S-2}E^{1/2}$ [*Schlickeiser and Steinacker*, 1989]. Here F_Q is the distribution function for a particle of charge Q and atomic mass number A; E is the energy (p is the momentum) and S is the power law index of turbulence with the energy density $W(\mathrm{k})=W_0\,\mathrm{k}^{-S}$. The term d$E$/d$t$ denotes any kind of particle energy losses when propagating in media. In our simulations we include only Coulomb losses which are apparently the most important ones for the solar flare plasma [*Korchak*, 1980] implying further $\mathrm{d}E/\mathrm{d}t\equiv(\mathrm{d}E/\mathrm{d}t)_{Coul}$.

The values of $\tau_{Q,Q+1}$ are the characteristic ionization times due to stripping effects by ambient particles, thermal electrons and protons as constituents of the surrounding plasma. These processes dominate under conditions discussed in the present paper [*Kharchenko and Ostryakov*, 1987; *Yoshimori et al*., 1999]. As to the recombination (dielectronic and radiative), according to our estimations it is negligible if we plan to apply our results to a rather hot plasma. Thus, $\tau_{Q,Q+1}$ could be expressed by the formula:

$$\tau_{Q,Q+1}{}^{-1}=\sum\nolimits_i N_i V \sigma_{Q,Q+1}(E)\ . \tag{3}$$

Here V is the relative velocity between the accelerated Fe ion and species i (electrons or protons); N_i is their number density and $\sigma_{Q,Q+1}(E)$ is the corresponding cross section for the stripping effect dependent on ion charge and collision energy E. Interaction with electrons can be readily obtained making use of the data of *Arnaud and Raymond* [1992], and for protons we have performed additional cross section calculations based on the scaling approach of Sidorovich and Nikolaev (see, e.g., *Kartavykh et al*., [1998] and references therein).

3 Influence of plasma parameters on the energy spectra and charge distribution of Fe:

As one can see from the Eq. (3), plasma number density N_i is one of the parameter when considering electron loss of Fe provided the characteristic acceleration time is of the order of (or greater than) $\tau_{Q-1,Q}$ ($\tau_{Q,Q+1}$) times. Only in this case stripping can affect both energy and charge spectra of heavy ions resulting in a redistribution and charge shift of the initial (injected) charges. The Coulomb energy losses is also proportional to the value of N_i . Importance of each of the four effects considered here (acceleration, Coulomb losses, spatial diffusion and charge changes) strongly depends on the relation of their characteristic times $\tau_a\sim p^2/D_p\propto(Q/A)^{S-2}$, $\tau_{Coul}\sim E/\left|(\mathrm{d}E/\mathrm{d}t)_{Coul}\right|\propto A/Q^2$, $\tau_d\sim L^2/\chi\propto(Q/A)^{2-S}$ and $\tau_{Q-1,Q}$ ($\tau_{Q,Q+1}$), respectively. Both energy and charge losses may cause energy spectra alterations. Particularly, the shape of $(\mathrm{d}E/\mathrm{d}t)_{Coul}$ has a pronounced maximum for various ions at $E\approx1\div10$ MeV/nucleon leading correspondingly to the peculiarities (dips) in their energy spectra. Analytical and numerical analyses show that those spectra can be hardened or softened due to the Coulomb losses depending on plasma parameters within accelerating site. As to the charge change atomic reactions, they mainly result in the ionic states redistribution giving rise to appearance of multicharged ions as energy increases.

Fig. 1 demonstrates dependence of the mean charge $\overline{Q}_{Fe}$ on energy calculated at various number densities N for S=1.5 and S=2.5. It is clearly seen that even at $N\sim3\times10^8$ cm^{-3} ($\chi_0\sim2.5\times10^{16}$ cm^2/s and $L\sim8\times10^8$ cm) the iron stripping is essential because injected ions spend enough time in the acceleration region to reach high charge states. For example, $\tau_a/\tau_d\sim28$ for Fe^{+8} and $\tau_a/\tau_d\sim11$ for Fe^{+21} at $E\sim1$ MeV/nucleon while $\tau_a/\tau_{15,16}\sim160$ and $\tau_d/\tau_{15,16}\sim11$ at the same energy. So, electron loss effect is evidently very important. This is a reason of the similarity of the curves in Fig. 1 (for S=1.5) that start with the higher mean charge as the number density grows. At the same time the Coulomb losses are not so important

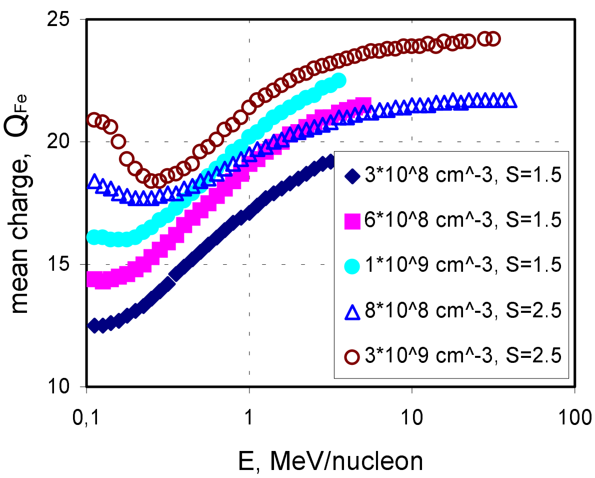

Figure 1: Mean charge of Fe versus energy for different number densities, spectral index of turbulence and $T=10^6$ K (see inserted panel).

because $\tau_a/\tau_{Coul} \leq 1$ for all ions Fe^{+Q} ($Q \leq 15$) when S=1.5 (Fig. 1). If we choose, however, $\tau_a/\tau_{Coul} \geq 2 \div 3$ the energy loss influence can be displayed in the $\overline{Q}_{Fe}(E)$ dependence as depressions at low energies (~0.2÷0.5 MeV/nucleon), as well as in the ion energy spectra. With this respect one should point out recent observations of Fe charge states for the November 7, 1997, SEP event [*Mőbius et al.*, 1999]. These data hint that charge bump at Q~20÷25 gradually evolves within the energy interval E=0.18÷0.54 MeV/nucleon according to this dependence, slightly shifting to a smaller charge in the middle of this range. Unfortunately, the observed count rates were dominated by the overlapping gradual SEP event having much greater intensity. Therefore, this experimental support is not statistically reliable. We hope that ACE instrumentation will allow to obtain those data for individual impulsive event in the near future.

The subsequent figures (Figs. 2a-c) show the influence of plasma temperature on the properties of charge distribution of heavy particles. This parameter gives initially different distribution of the injected ions according to thermal equilibrium [*Arnaud and Raymond*, 1992]. For example, $\overline{Q}_{Fe}^{inj}$ ~13.7 at T~2×10^6 K and $\overline{Q}_{Fe}^{inj}$ ~15.6 for T~3.2×10^6 K. The second (dispersion) and third (asymmetry) moments of the distribution function are also depicted in Figs. 2b,c. In most simulated cases both dispersion and asymmetry are larger at low energies evolving to smaller values for high energies $E \geq 1$ MeV/nucleon. This is in a qualitative agreement with the recent observations onboard the ACE spacecraft for the (gradual) event of November 7, 1997 [*Mőbius et al.*, 1999]. For the impulsive event of May 2, 1998, the dispersion of charge distribution at E=0.28-0.38 MeV/nucleon can be obtained based on the experimental data of *Mőbius and Popecki* [1998], $\sigma_{Fe}^2 = 11.7$. This value is higher than any value simulated theoretically, $\sigma_{Fe}^2 \leq$7-9 for various plasma parameters. Note also that if mean charge of accelerated particles is high enough, $\overline{Q}_{Fe} \geq 23$, asymmetry has a negative sign at low energies. This is due to abrupt cross section decrease when transitions from Q=23 (L shell) and from Q=24 (K shell) (or from Q=15, M shell, and Q=16, L shell) are involved into consideration. However, the negative asymmetry can not be seen in a charge distribution provided diffusion time within acceleration region is high: $\tau_{23,24} < \tau_d$.

One should also point out that the energy dependence of $\overline{Q}_{Fe}$ for high T becomes softer, Fig. 2a. This is due to the fact that at such temperatures the acceleration deals with higher Fe charge states, for which $\tau_{Q-1,Q}$ ($\tau_{Q,Q+1}$) times are dramatically increased. As a result, stripping effects turn out to be less important. In Fig. 1 one can also see the influence of varying power law index of turbulence, S. Because $\tau_a/\tau_d \propto (Q/A)^{2S-4}$ and $\tau_a/\tau_{Coul} \propto (Q^2/A)(Q/A)^{S-2}$ a variation of the turbulence spectra slope is almost identical to a variation of acceleration efficiency, τ_a^{-1}. Namely, for some $Q \sim \overline{Q}_{Fe}$ the larger S the greater is τ_a^{-1} and vice versa because $Q/A<1$. Different slopes in dependencies of the mean charge on energy is caused by dependence of the acceleration time on E ($\tau_a \propto E^{0.5/2}$ for S=2.5 and $\tau_a \propto E^{1.5/2}$ for S=1.5). Since we consider normalization of τ_a to E=1 MeV/nucleon, τ_a (S=2.5)>τ_a (S=1.5) at E<1 MeV/nucleon and τ_a (S=2.5)<τ_a (S=1.5) at E>1 MeV/nucleon.

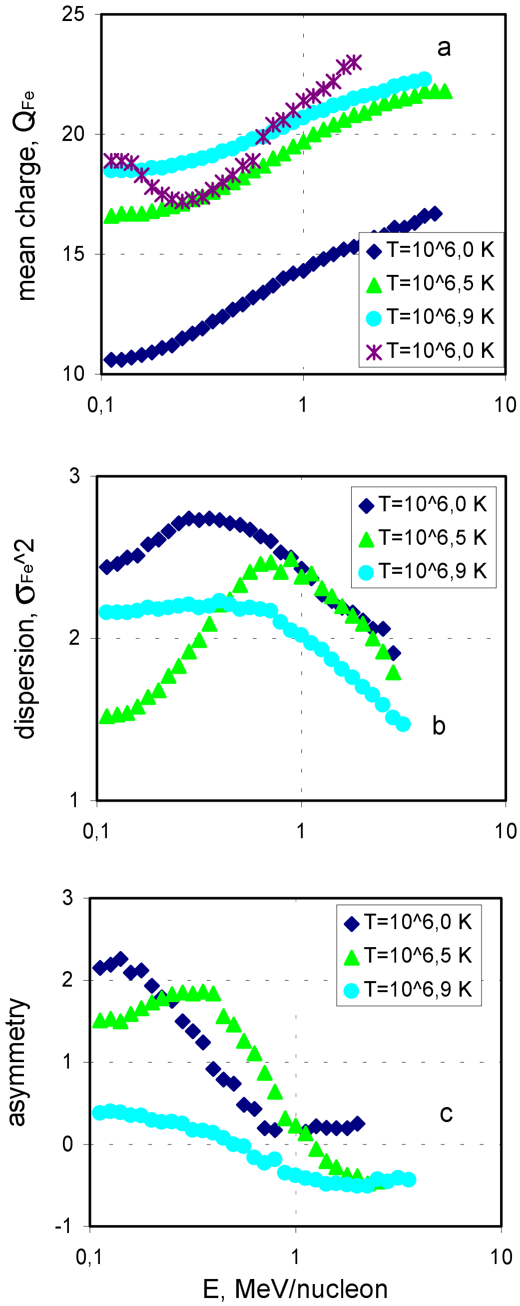

Figure 2: Mean charge (a), dispersion (b) and asymmetry (c) of iron charge distribution versus energy for different temperatures (see inserted panels), S=1.5, N=10^8 cm^{-3} (crosses - simulations for N=3×10^9 cm^{-3}).

4 Conclusion:

We present here the model of stochastic acceleration of Fe ions which takes into account their spatial diffusion, Coulomb losses and stripping. This model can successfully explain the dependence of the mean charge of iron on energy. The latter effect was already observed for gradual events. Unfortunately, we are aware of only one of the impulsive events where the charge distribution of iron was measured individually [*Mőbius and Popecki*, 1998]. We hope that the ACE spacecraft instrumentation will soon supply those data for analysis. In addition to energy spectra and mean charge, our model results in charge distribution of ions which may differ significantly from those of the injected ions. At the same time, theoretically obtained dispersion of charge distribution is systematically lower than that from the available observations. First, it may still be a result of experimental errors in charge determination. The second source of such a descrepancy may be caused by our assumption about conservation of charge distribution of thermal plasma up to the injection energies (E_0~50-100 keV/nucleon). If this is not the case the charge distribution can be widened even at preacceleration stage before the principal acceleration starts working. This effect has to be studied considering "preheating" of particles from thermal plasma.

The authors are thankfull to Prof. M.Yoshimori for his interest to our work and valuable discussions. We are also indebted to I.Yu.Stepanov for providing us proton ionization cross sections data. This work was supported by the Center of Fundamental Research of St.Petersburg State University (grant 97-3.1-3).

References

Arnaud, M. & Raymond, J. 1992, ApJ 398, 394
Kartavykh, Yu.Yu., Ostryakov, V.M., Stepanov, I.Yu., Yoshimori, M. 1998, Cosmic Research 36, 437
Kharchenko, A.A. & Ostryakov, V.M. 1987, In: Proc. of 20th ICRC (Moscow) 3, 248
Korchak, A.A. 1980, Solar Phys. 66, 149
Luhn, A., Klecker, B., Hovestadt, D., Möbius, E. 1987, ApJ 317, 951
Möbius, E., Popecki, M., Klecker, B. et al. 1999, Geophys. Res. Lett. 26, 145
Möbius, E. & Popecki, M. 1998, http://www.srl.caltech.edu/ACE/ACENews/ACENews23.html
Schlickeiser R. & Steinacker, J. 1989, Solar Phys. 122, 29
Yoshimori, M., Ostryakov, V.M., Kartavykh, Yu.Yu., Stepanov, I.Yu. 1999, Adv. Space Res., in press.