SH 1.4.01

# Shock Acceleration of Iron with Account of Its Stripping in Gradual Solar Energetic Particle Events


**M.F.Stovpyuk and V.M.Ostryakov**

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



**Abstract**

The energy spectra and charge distribution of Fe ions accelerated by parallel shock wave in gradual events are numerically calculated. Stripping of Fe ions by thermal electrons and protons during ion acceleration in the solar corona results in the dependence of its mean charge on energy. We consider the influence of varying plasma parameters (temperature T, number density N and spectral index of turbulence S) on charge distribution of iron. Our results are compared with the available observations. The theoretically obtained properties of charge distribution of iron could be important in the light of new ACE spacecraft data.


## 1 Introduction:

Contrary to energy spectra of solar cosmic rays (SCRs) in various kinds of solar energetic particle (SEP) events, charge state measurements until the recent time have not been so numerous. As follows from the available experimental data there are event-to-event fluctuations in mean charge of iron, $\overline{q}_{Fe}$. It is important to note that it turns out to be systematically larger of its typical solar wind (SW) value, where $\overline{q}_{Fe}$ ≈10.5÷13. In the present paper we find plasma temperature, T, and number density, N, that result in importance of charge change reactions occurring during acceleration in the corona. Such a problem of heavy particles acceleration with their simultaneous charge changes was analytically considered for regular (Kurganov & Ostryakov, 1991) and stochastic (Ostryakov & Stovpyuk, 1997) mechanisms. We call this approach as a charge-consistent energization mechanism, within of which Yoshimori et al. (1999) have performed fitting of the experimental data for three impulsive flares. Acceleration by shocks is usually attributable to gradual events. Therefore, we use methods of the papers mentioned above to consider a regular acceleration self-consistently (by charge). Here presented is a numerical model, which allow one to obtain the energy spectra and charge distribution of heavy ions. From our point of view, the calculations within this approach could be important in the light of new data from ACE spacecraft, one of the aims of which is the measurement of charge distribution of heavy ions in SCRs. Those new Fe charge spectra from ACE have been recently presented by Möbius *et al*. (1999).

## 2 Statement of the problem:

In this section we formulate in general way the problem of charge-consistent acceleration of heavy ion by parallel shock wave with account of charge transfer processes. Let us consider planar geometry in which the shock front ($x$=0) separates plasma onto upstream region ($x$ <0, marked below as $i$=1) and downstream region ($x$ <0, $i$=2). The iron ions of charge $q$ are injected on shock front and are accelerated there. The corresponding distribution function is denoted by $f_q \equiv f_q\left(x, p\right)$. For the injection momentum $p = p_o$: $f_q\Big|_{x=0} = f_{q\,o}$ for $q$=0,..., $q_{max}$. We describe our model more generally than will be utilized in the present paper. Namely, during the acceleration both ionization and recombination are included. Their characteristic times are as follows $\tau^{-1}_{qq+1} = \sum_i n_i V \sigma_{qq+1}(E)$ and

$\tau^{-1}_{qq-1} = \sum_i n_i V \sigma_{qq-1}(E)$, respectively. Here $n_i$ is the number density of reactants which result in ion charge changes; $V$ is the collision velocity practically coincident with the energetic ion velocity; $\sigma_{qq+1}(E)$, $\sigma_{qq-1}(E)$ are the corresponding energy and charge dependent cross sections.

As a result, for each ion of charge $q$ the diffusion equation (in our case one-dimensional) can be written for both upstream and downstream regions:

$$\frac{\partial}{\partial x} D_{q\,i} \frac{\partial}{\partial x} f_q - u_i \frac{\partial f_q}{\partial x} - \frac{f_q}{\tau_{q\,q+1}} - \frac{f_q}{\tau_{q\,q-1}} + \frac{f_{q-1}}{\tau_{q-1\,q}} + \frac{f_{q+1}}{\tau_{q+1\,q}} = 0 \quad , \; q=0,..., q_{max}, \qquad (1)$$

where for $q$=0 ($q=q_{max}$) only stripping (recombination) terms are present. For the hydrodynamic velocity we have

$$u(x) = \begin{cases} u_1 \quad , & x < 0 \\ u_2 = u_1 \dfrac{2 + M_1^2(\kappa - 1)}{M_1^2(\kappa + 1)} \; , & x > 0 \end{cases} \quad , \qquad (2)$$

where $\kappa$ is the adiabatic index, $M_1$ is the upstream Mach number. The spatial diffusion coefficients $D_{qi}$ in Equations (1) are chosen to be (Schlickeiser, 1989):

$$D_{q\,i} = D_{o\,i} \cdot \left(\frac{q}{A}\right)^{S-2} \times \begin{cases} E^{(3-S)/2} & , \; S < 2 \\ E^{1/2} & , \; S > 2 \end{cases} \quad , \qquad (3)$$

where $A$ is the atomic mass number, $D_{oi}$ are the constants taking into account the difference in diffusion coefficients between regions "1" and "2", and $S$ is the power law index of turbulence, $W(k) = W_o \cdot k^{-S}$.

As to the boundary conditions, it is necessary to restrict solution at infinity. At the shock wave front the number densities and the fluxes of particles are continuous:

$$f_{q\,1}\big|_{x\to -o} = f_{q\,2}\big|_{x\to +o} \; , \qquad (4)$$

$$D_{q1} \frac{\partial f_q}{\partial x}\Big|_{x\to -o} - D_{q2} \frac{\partial f_q}{\partial x}\Big|_{x\to +o} = -\frac{u_1 - u_2}{3} p \frac{\partial f_q}{\partial p}\Big|_{x=o} + Q_{qo} \cdot \left(\frac{p}{p_o}\right)^{-\alpha_o} . \qquad (5)$$

The last term in the right hand side of Equations (5) takes into account, for example, the possibility of stochastic preacceleration before injection into the regular acceleration mechanism at shock wave front, $Q_{inj} = Q_{qo}\left(p/p_o\right)^{-\alpha_o}$ and $Q_{qo} \sim f_{qo} u_1$. Here $f_q$ is normalized according to $4\pi \int f_q(x,p) p^2 dp dx = N_q$, $N_q$ being a total number of accelerated particles of charge $q$. Thus, we have the system of Equations (1) with the boundary conditions (4), (5) to solve this problem, i.e. to find not only the energy spectra of ions but also their charge distribution. In our approach the latter characteristics significantly differs from that of the injected ions.

## 3 Influence of stripping processes on the charge spectra of iron:

The main idea of the present paper is to include to our consideration the charge change processes which affect the energy and charge spectra of heavy ions in SCRs. The timescale of regular acceleration is expressed by $T_a$=3($D_{q1}/u_1$+$D_{q2}/u_2$)/($u_1$-$u_2$). If $T_a$ is comparable to or even greater than characteristic charge change times in Equations (2), we have to deal with both processes jointly. In this case transfer between charge states can influence both energy and charge spectra of escaping ions. From X-ray and $\gamma$-ray data for solar flares one can conclude that particle acceleration timescale is about several seconds. Based on this value we have estimated that the main stripping processes in the solar corona are collisions of heavy ions with electrons (Arnaud & Raymond, 1992) and protons (see, e.g., Kartavykh *et al*., 1998).

In the present paper we solve the problem, described in Section 2, making use of the finite difference method with the implicit scheme over momentum. More details about numerical simulations and energy spectra fitting can be found in the journal publication of Ostryakov & Stovpyuk (1999). Shown in Figure 1 is a dependence of the mean charge $\overline{q}_{Fe}$ on energy at varying plasma number density N and spectral

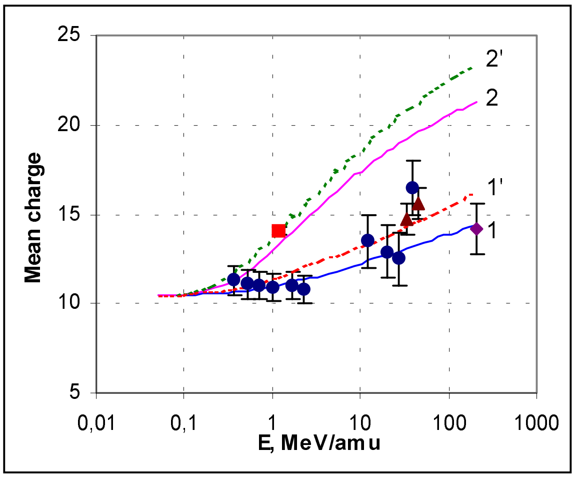


**Figure 1:** Dependence of the mean charge $\overline{q}_{Fe}$ on energy for $S$=5/3 (solid lines), $T_a$≈1.7÷1.2 s and N=5·10$^8$ cm$^{-3}$ (1), N=5·10$^9$ cm$^{-3}$ (2); for $S$=3 (dashed lines), $T_a$≈1÷3.3 s and N=5·10$^8$ cm$^{-3}$ (1'), N=5·10$^9$ cm$^{-3}$ (2'). For all runs the temperature was chosen to be T=1.26·10$^6$ K. Also shown are the experimental data: ● – Oetliker et al. (1997), ■ – Luhn et al. (1984), ▲ – Leske et al. (1995), ◆ – Tylka et al. (1995).

index $S$. One can see that N growth, which yields proportional increase in the collisional ionisation rates, results in a significant stripping of accelerated ions. Also depicted is a sensitivity of the results to the variation of the parameter $S$. Namely, for $S$>2 the mean Fe charge at fixed N increases faster with energy than for $S$<2. This effect is determined by the dependence in $D_{qi}$ on $S$, see (4), implying that particles of higher charge states at $S$>2 are accelerated less efficiently than for $S$<2. Transition to higher charge states evidently slows down when $\tau_{qq+1}$ is greater than $T_a(q)$. At the same time, the inequality $\tau_{q+1q+2}>\tau_{qq+1}$ is always valid at fixed energy. All this means that for $S$<2 transitions to high ionic charge states become insignificant at less energies than for $S$>2. Figure 1 also indicates available experimental data on mean charge of iron in a number of gradual SEP events. The temperature of the acceleration region for our simulations was chosen to be T=1.26·10$^6$ K. This value is a typical one though subsequent heating of a flaring plasma may provide T≈10$^7$ K.

Finally, we have performed the simulations of Fe charge spectra for four different energy ranges (Figure 2). On these panels also shown are the recent experimental data of Möbius *et al*. (1999) for the November 7 - 9, 1997, gradual SEP event. One can see that our calculations could explain the growth of the mean (and peak) charges with energy for the plasma parameters N=10$^{10}$ cm$^{-3}$, T=1.26·10$^6$ K. As to the presence of high "charge tail" in the experimental data, there could be two reasons. Either this is caused by insufficient resolution of the detector, or by contribution to the observations from an impulsive event (Möbius *et al*., 1999). We should also note here that additional acceleration, which could occur on the interplanetary shock waves, does not result in the essential changes in charge spectra, because the number density of interplanetary plasma is rather low.

# 4 Conclusion:

The main inferences of our consideration are as follows. The energy spectra of accelerated multicharged ions in a charge-consistent model, which takes into account stripping effects, may differ essentially from those within a test particle approach (no charge changes). The energy dependence of the mean charge is strongly affected by the plasma parameters T, N and spectral index of turbulence $S$. Particularly, for T≈10$^6$ K and N≈(0.5÷1)·10$^{10}$ cm$^{-3}$ one can easily explain the experimental data on $\overline{q}_{Fe}(E)$ for the available gradual events. We hope that the approach presented here is quite promising in accounting for the properties of charge distributions of heavy ions including dispersion, asymmetry etc.

The authors are thankful to Prof. I.N.Toptygin for his interest to our work. This work was partially supported by the Centre of Fundamental Research of St.Petersburg State University (Grant 97-3.1-3).

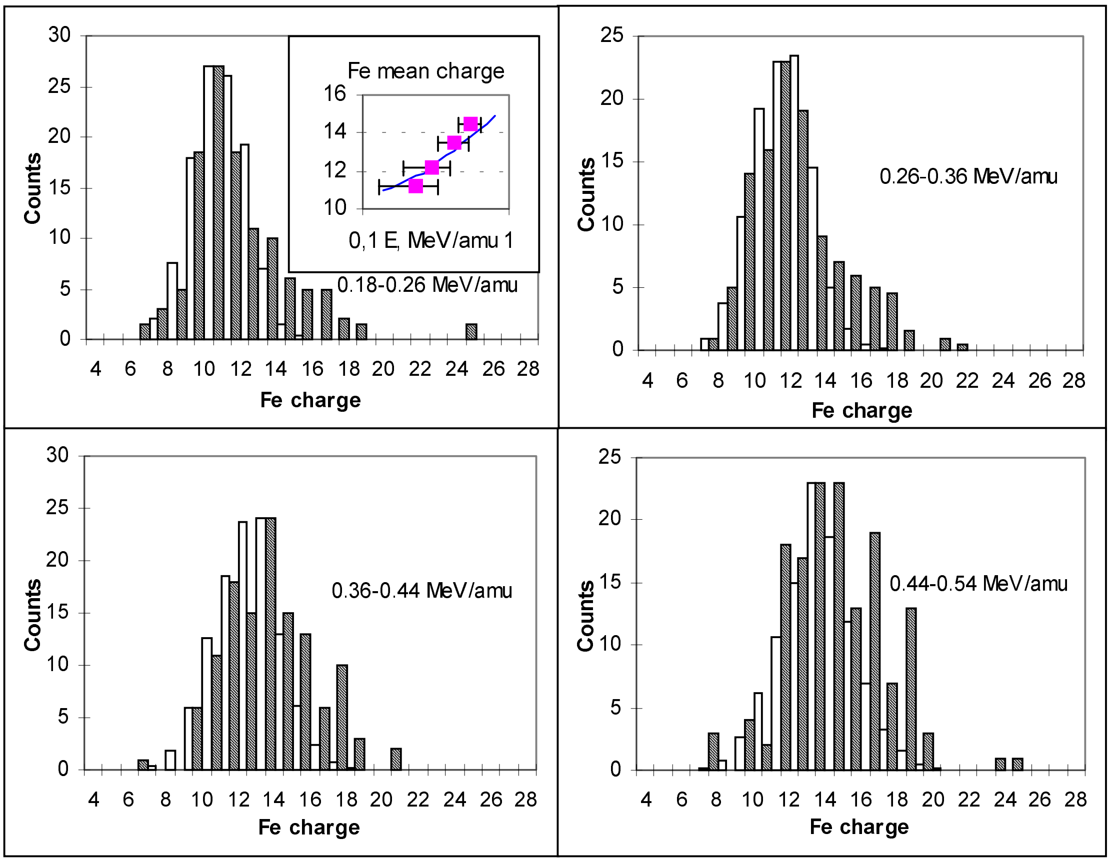


**Figure 2:** Simulated charge distributions of Fe for $S$=3, $T_a \approx 0.7 \div 2.2$ s, T=$1.26 \cdot 10^6$ K and N=$10^{10}$ cm$^{-3}$ for four different energy ranges (empty rectangles). Also shown are the experimental data of the SEPICA sensor from ACE for the November 7 - 9, 1997, event (shaded rectangles). Inserted panel is the experimental dependence of the Fe mean charge on energy for the same event; solid line - our simulations.

# References

Arnaud, M., & Raymond, J., 1992, ApJ 398, 394
Kartavykh, Yu.Yu. et al., 1998, Cosmic Res. 36, #5, 465 (in Russian)
Kurganov, I.G., & Ostryakov, V.M., 1991, Astron. Lett. 17, 77
Leske, R.A., Cummings, J.R., Mewaldt, R.A. et al., 1995, ApJ 452, L149
Luhn, A.M., Klecker, B., Hovestadt, D. et al., 1984, Adv. Space Res. 4, 161
Möbius, E., Popecki, M., Klecker, B. et al., 1999, Geophys. Res. Lett. 26, #2, 145
Ostryakov, V.M., & Stovpyuk, M.F., 1997, Astron. Reports. 41, #3, 386
Ostryakov, V.M., & Stovpyuk, M.F., 1999, Astron. Lett. (in press)
Oetliker, M., Klecker, B., Hovestadt, D. et al., 1997, ApJ 477, 495
Tylka, A.J., Boberg, P.R., Adams, J.H. et al., 1995, ApJ 444, L109
Schlickeiser, R., 1989, ApJ 336, 264
Yoshimori, M., Ostryakov, V.M., Kartavykh, Yu.Yu., 1999, Adv. Space Res. (in press)