Simulation of the Charge State and Energy Spectra of Solar Energetic Iron

A.F. Barghouty[1] **and R. A. Mewaldt**
California Institute of Technology, MC 220-47, Pasadena, CA 91125, USA

Abstract

In a nonequilibrium model that includes shock-induced acceleration, we simulate the charge state and energy spectra of solar energetic iron. In this model the mean charge state exhibits an energy dependence seen in recent large solar events by SAMPEX and ACE. The simulated energy spectrum is a power-law and charge distributions are roughly Gaussians. The density distributions are smooth in charge-momentum space, suggesting that the accelerated ion retains no memory of its initial charge as well as momentum conditions.

1 Introduction:

Recent measurements (Oetliker et al. 1997; Mason et al. 1999; Mazur et al. 1999; Möbius et al. 1999) of the charge states of solar energetic ions (up to Fe) over a wide energy range (up to few tens of MeV/nucleon) show a clear energy dependence of the inferred mean charge $\langle q \rangle$. Higher energy ions, especially iron, seem to have a higher $\langle q \rangle$. According to the notion of a "frozen-in" seed population, the observed mean charge state can be a sensitive probe of the coronal plasma temperature and mean electron density. The use of equilibrium ionization temperatures to infer the coronal plasma temperature from the measured mean charge suggests, however, different temperatures for different ion species (Luhn & Hovestadt 1985; Oetliker et al. 1997).

On the basis of a nonequilibrium calculation with shock-induced acceleration, a quantitative explanation for the observed energy dependence of $\langle q \rangle$ has recently been suggested by Barghouty & Mewaldt (1999). Their explanation is based on the time scales for charge changing, due to ionization-recombination, and shock-induced acceleration. It was suggested that when the time scales are comparable the interplay between the two processes can give rise to the observed energy dependence of $\langle q \rangle$.

Here, the same model is employed to calculate the charge distribution as a function of energy as well as the energy spectrum of solar energetic iron. Phase-space density distributions as functions of momentum and charge are also presented. In part, these simulations, especially the latter, are motivated by the analytic, but steady-state, model of Kurganov & Ostryakov (1991). Their calculated spectra of light ions are power-laws, consistent with shock-induced acceleration, and the charge distributions are Gaussians. More interestingly, their model appears to describe a 'diffusion' in the charge-momentum space. This dynamic should be more pronounced for iron due to its numerous charge states. Coupled with constraints due to the conservation of both charge and momentum, this may prove significant to plasma acceleration of charged particles in general.

2 Simulation Model:

Details of the simulation model are described by Barghouty & Mewaldt (1999). For the sake of the results presented here, below we describe only the main and relevant aspects of the model.

The model was developed to follow the evolution in both time and momentum of the charge states of iron from a typical large solar event. Acceleration at the coronal site was modeled as due to a large scale shock as well as diffusion in momentum space. Propagation effects to 1 AU are ignored. The charge-changing and energy-changing processes for all the 27 charge states of iron are treated consistently. The model equation is

$$\frac{\partial f^q}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 D_{pp}(p)\frac{\partial f^q}{\partial p}\right] - \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 \frac{dp}{dt} f^q\right] - \frac{f^q}{t_{\text{esc}}} + Q^q_{ir}(p,t) \; , \qquad (1)$$

where $f^q(p,t)$ is the phase-space density function of ion with charge q as a function of momentum p and time t. The coupling term, $Q^q_{ir}(p,t)$, due to ionization and recombination processes, is given by

[1] Permanent address: Physics Dept., Roanoke College, Salem, VA 24153, USA.

$$Q^q_{ir}(p,t) = n_e\Big[R_i^{q-1}(T)f^{q-1} + R_r^{q+1}(T)f^{q+1} - (R_i^q(T)f^q + R_r^q(T)f^q)\Big]\ , \tag{2}$$

where n_e is the mean electron density and T the electron temperature. The temperature-dependent ionization and recombination rates, R_i and R_r, are calculated using the formulation of Arnaud & Raymond (1992).

The physical parameters of a typical active coronal region are taken to be as follows: The characteristic electron temperature T_e is 2.5 MK (T for the initial distribution in q is 1 MK), the characteristic electron density n_e is 10^9 cm^{-3}, and the strength of the magnetic field at the acceleration site is 10^2 G. The strength of the local diffusion coefficient is 10^{21} cm^2/s, and the spectral index of the magnetic turbulence is 3/2.

The initial distribution $f^q(p, t=0)$ is taken to be a Maxwellian in p characterized by the electron temperature T_e. The initial distribution in q is taken to be that for an equilibrated distribution corresponding to some $T < T_e$. Due to the diffusive nature of the acceleration, however, the nonthermal, steady-state solutions $f^q(p)$ are insensitive to the exact form of either distribution of the seed population. Details of the numerical solution of Eq. (1) can also be found in Barghouty & Mewaldt (1999).

3 Sample Results for Fe:

Fig. 1 shows the mean charge and its variance $\langle q\rangle \pm (\langle q^2\rangle)^{1/2}$ as functions of the ion's kinetic energy, where $\langle q\rangle(p) = \sum_q q f^q(p)/\sum_q f^q(p)$, and similarly for $\langle q^2\rangle(p)$. The equilibrium value $\langle q\rangle_{eq}$ refers to the steady-state value ignoring acceleration. In this solution of Eq. (1), the time scale for acceleration ($t_c \sim \int_{p_o}^{p_c}(dp/dt)^{-1}dp$, where $p_o \sim$ the Alvén momentum and $p_c = 10 \times p_o$) and equilibration (t_{eq} as $\partial f^q/\partial t = Q^q_{ir}(p,t) \to 0$) are comparable ($\lesssim 10^2$ s). Fig. 2 shows the steady-state charge distribution at different energies. The dashed curves represent Gaussian distributions defined by $\langle q\rangle$ and $(\langle q^2\rangle)^{1/2}$, where they appear to be a reasonable representation of the steady-state distributions of Eq. (1).

Fig. 3 shows the iron steady-state energy spectrum summed over all charge states. The break in the spectrum around .2 MeV/nucleon corresponds to the Alvén momentum in the model, where the shock acceleration becomes effective for those ions pre-accelerated by diffusion in momentum space. The power-law behavior for energies beyond this break is evident. In Fig. 4 contour plots of the initial and steady-state, shocked distributions are shown. It is included here to highlight the process of 'diffusion' in q-space as well as in p-space, due to the coupling of the charge and energy changing processes. The steady-state model of Kurganov & Ostryakov (1991) is similar to ours, but because of their emphasis on deriving tractable analytic expressions, their treatment of the charge-changing processes was over simplified. However, their finding that there are no distinctive spectral features corresponding to particles with the injected charge is consistent with Fig. 4, where the spectrum appears smooth, indicating that the accelerated ion forgets its initial charge as well as momentum conditions (Ivanov et al. 1987). This diffusion-like behavior in q-p space clearly deserves further study.

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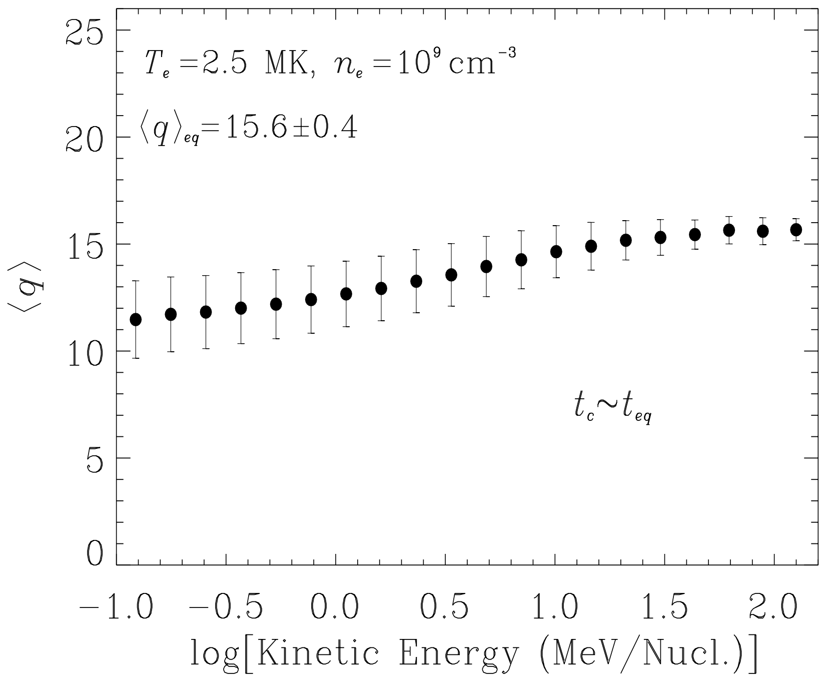

Figure 1: Mean charge of iron and its variance as functions of energy. [From Barghouty & Mewaldt, 1999.]

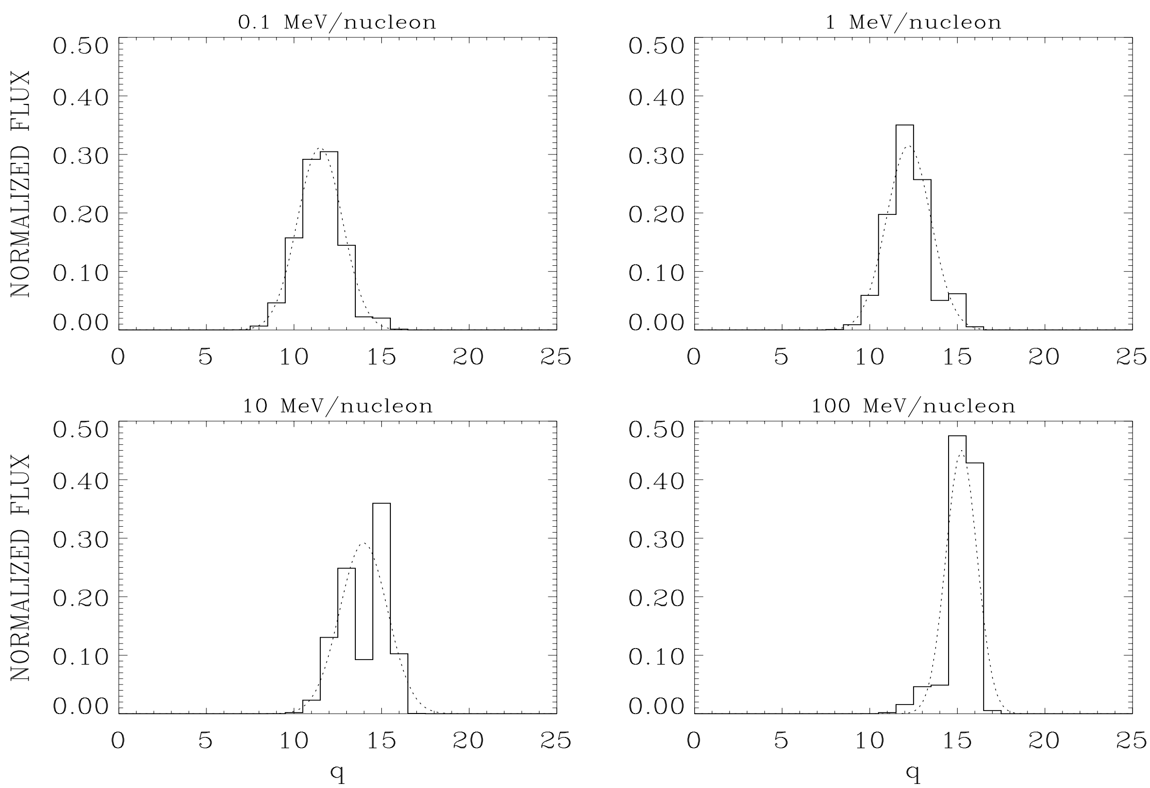

Figure 2: Steady-state charge distribution of iron at different energies.

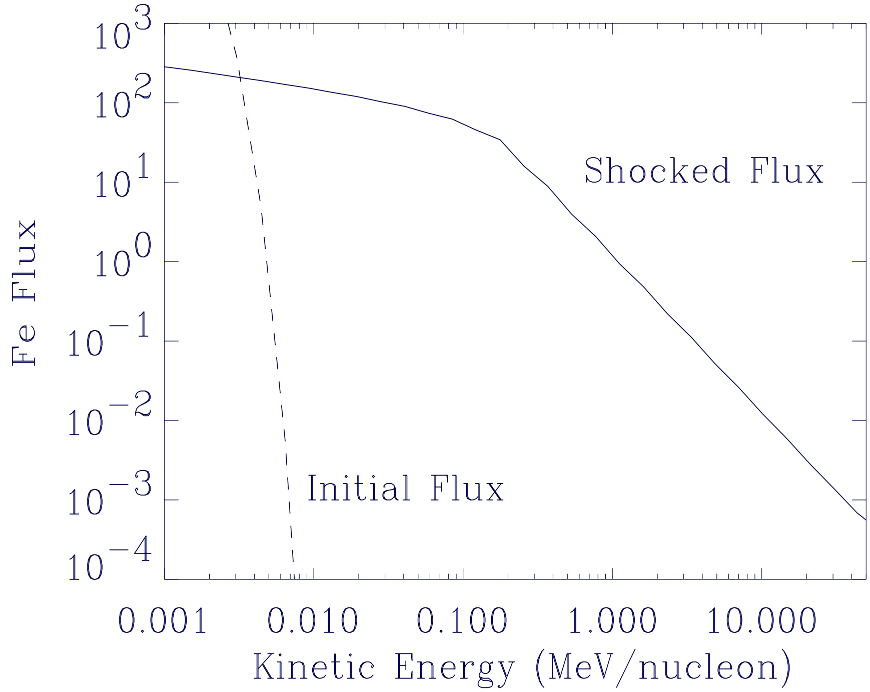

Figure 3: Energy spectrum of iron summed over all charge states, i.e, $j(p) = \sum_q p^2 f^q(p)$.

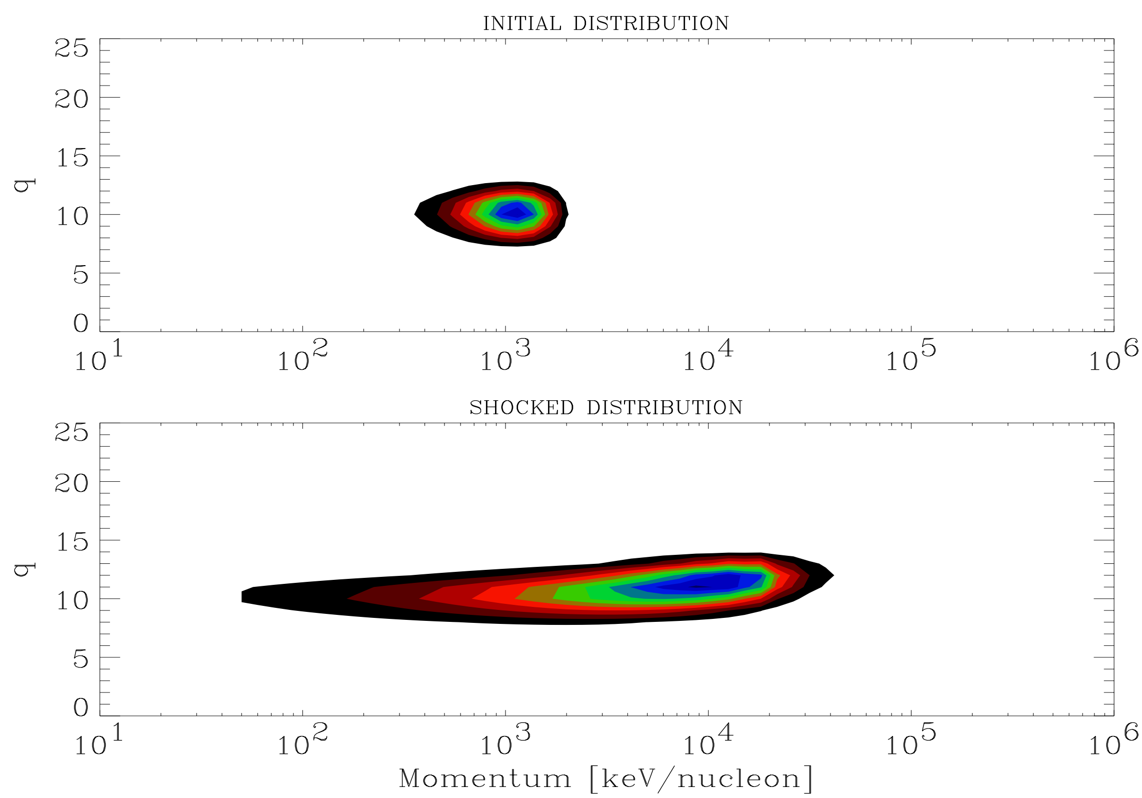

Figure 4: Contour plots of the initial and steady-state, shocked distributions.