Energy-dependent ionization states of shock-accelerated particles in the solar corona

D. V. Reames, C. K. Ng[1],

NASA/Goddard Space Flight Center, Greenbelt, MD

A. J. Tylka

Naval Research Laboratory, Washington, DC

Abstract. We examine the range of possible energy dependence of the ionization states of ions that are shock-accelerated from the ambient plasma of the solar corona. If acceleration begins in a region of moderate density, sufficiently low in the corona, ions above ~0.1 MeV/amu approach an equilibrium charge state that depends primarily upon their speed and only weakly on the plasma temperature. We suggest that the large variations of the charge states with energy for ions such as Si and Fe observed in the 1997 November 6 event are consistent with stripping in moderately dense coronal plasma during shock acceleration. In the large solar-particle events studied previously, acceleration occurs sufficiently high in the corona that even Fe ions up to 600 MeV/amu are not stripped of electrons.

Introduction

Element abundances and ionization states of energetic ions can provide a signature of the origin of a population of energetic particles [see *e.g.* review *Reames 1999*]. Yet, both of these measures often vary with energy in ways we must seek to understand. For example, the most definitive charge states we know are those of the singly charged "anomalous cosmic rays" (ACRs) that unambiguously point to their origin as interstellar pickup ions. However, even the ACRs become multiply ionized at higher energies by electron stripping during acceleration.

Ionization-state measurements have also played an important role in distinguishing sites of acceleration in solar energetic particle (SEP) events. While SEPs were once thought to be accelerated in flares, it has become clear that, in the large "gradual" events, the particles are actually accelerated at shock waves driven out by CMEs [*Gosling* 1993; *Kahler* 1994; *Reames* 1995, 1997, 1999]. One factor in the demise of the "solar-flare myth" was the early observation by *Luhn et al.* [1985, 1987] that, in large events, the ionization states of ions accelerated to 0.3-2 MeV amu^{-1} were similar to those of the corresponding ions in the corona or solar wind. For example, the mean charge of Fe was $<Q_{Fe}> = 14.1\pm0.2$ averaged over 12 large events, corresponding to a plasma with an electron temperature of ~2 MK. Even the lighter ions like C and O were not fully ionized. However, in the small "^{3}He-rich" events where ions *are* believed to be accelerated in impulsive flares, $<Q_{Fe}> = 20.5\pm1.2$ and lighter ions up to Si are fully ionized, corresponding to a plasma temperature >10 MK.

More-recent observations at 0.5-5 MeV amu^{-1} [*Mason et al.* 1995], 15-70 MeV amu^{-1} [*Leske et al.* 1995], and 200-600 MeV amu^{-1} [*Tylka et al.* 1995], have found the mean Q_{Fe} for large events to be in the approximate range 11-15. However, *Oetliker et al.* [1997] did report that Q_{Fe} increased modestly with energy from ~11 at ~0.5 MeV amu^{-1} to ~15 at ~15 MeV amu^{-1}. In a careful analysis of all these observations, *Ruffolo* [1997] concluded that the coronal residence time of these ions must be <0.03 s at the height of the coronal loops where the electron density is ~10^{11} cm^{-3}. At distances above 2 solar radii, where shock acceleration reaches maximum [*Kahler* 1994], electron densities are <10^5 cm^{-3} and ionization states will change little in 3×10^4 s. This time scale is ~100 times longer than the total residence time of a fast shock in the corona. Thus, in most large gradual SEP events, ionization states of the energetic ions remain similar to those of the source plasma of the corona or solar wind.

However, in the recent large SEP event of 1997 November 6, *Mazur et al.* [1999] and *Möbius et al.* [1999a] have seen pronounced increases in the mean charges of energetic ions as a function of energy. In the present paper, we examine a situation at the opposite extreme from that considered by *Ruffolo* [1997], namely, that the particles have passed through sufficient material during acceleration to come to a charge-state equilibrium that is appropriate to their speed.

Luhn and Hovestadt [1987] calculated mean charge states, $<Q>$, of energetic ions from C through Si averaging parameterized forms of the electron capture and loss cross sections over thermal electron distributions transformed to the ion rest frame. However, their calculations show sharp steps in the mean charge at ion velocities corresponding to closed electron shells. One wonders why such steps are not seen in cold matter. Observations of ions in solids and gasses [*e.g. Betz* 1972], and even in laboratory plasmas [*Dietrich et al.* 1992], are consistent with smooth monotonic variations of $<Q>$ with ion speed.

In a recent paper, *Barghouty and Mewaldt* [1999] attempt to calculate the evolution of $<Q_{Fe}>$ during stochastic acceleration. Unfortunately, these authors seem to have completely neglected the ion speed in the charge-changing

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[1] Dept. of Astronomy, Univ. of Maryland, College Park, MD

rate equations, using electron capture and loss rates that depend only upon temperature. This means that their results are not correct above ~0.1 MeV/amu, the region of greatest interest. Their paper gives the erroneous impression that highly ionized particles cannot be produced at shocks.

Ionization states have proven to be one of our most powerful tools for distinguishing the acceleration environment in shocks from that in flares. We can learn little if the acceleration site is not known. It is therefore essential that we understand the physical process of ionization as fully as possible.

Equilibrium charge states

It is extremely well known from laboratory measurements that energetic ions rapidly approach an equilibrium value of their mean charge states after traversing small amounts of matter, x_∞ [*e.g. Betz* 1972]. This equilibrium charge forms the basis of our understanding of the stopping powers and ranges of heavy ions in matter [*e.g. Pierce and Blann* 1968]. The value of x_∞ increases somewhat with energy, but is ~10^{18} molecules cm^{-2} near 1 MeV amu^{-1} for neutral H gas. Measurements of 4.8 MeV/amu ^{40}Ar stopping in a laboratory H-plasma find equilibrium $<Q>$=16.2 after traversing x_∞~2×10^{19} electrons/cm^2 [*Dietrich et al.* 1992], although sufficiently dense laboratory plasmas can yield unusually high ionization states for heavy ions such as ^{129}Xe because of the reduced time between collisions[Peter and Meyer-ter-Vehn 1991].

Rather than solve the complex web of charge-changing reactions with uncertain capture and loss cross-sections, it is common to use a semi-empirical expression for the mean charge $Q(Z,\beta)$,

$$Q(Z,\beta) = Z \times \left[1 - \exp\left(-125\beta / Z^{2/3}\right)\right] \qquad (1)$$

where Z is the atomic number of the ion and $\beta = v/c$ with an ion speed v. This form was originally suggested by *Barkas* [1963] and has since been studied extensively for ions traversing neutral solids and gasses [*Pierce and Blann* 1968; *Betz* 1972]. The exponent in Equation 1 is based on the electron speed in the Thomas-Fermi atom, $\beta_{TF} = Z^{2/3}/137$.

To extend Equation 1 to a hot plasma, we follow *Luhn and Hovestadt* [1987] in assuming that an ionizing collision between the incoming ion and an electron of the plasma will depend upon the relative speed of the two, β_{rel}, rather than upon the ion speed alone. Given the incomplete knowledge of the capture and loss cross-sections as a function of β_{rel}, we make no attempt to account for these processes in detail. Instead, we approximate β_{rel} crudely by $\beta_{ion} + \beta_{e,th}$, where $\beta_{e,th}^2 = 2kT_e/m_ec^2$, is the most-probable thermal-electron speed in the plasma. This form slightly over-weights head-on collisions relative to overtaking collisions. For a coronal plasma of ~1.5 MK, $\beta_{e,th}$ ~ 0.022. This simple approximation allows the predicted charge states to approach values that are not unreasonable for a thermal plasma when $\beta_{ion} << \beta_{e,th}$. A more sophisticated treatment seems unwarranted by the present observations. Hence, we take

$$Q(Z,\beta_{ion}) = Z \times \left[1 - \exp\left(-125(\beta_{ion} + \beta_{e,th}) / Z^{2/3}\right)\right] \qquad (2)$$

In Figure 1 we compare the simple equilibrium expression in Equation 2 with measured charge states in the large SEP event of 1997 November 6, reported by *Mazur et al.* [1999] and by *Möbius et al.* [1999a] using different measurement techniques. For O, Si, and for Fe, below 2 MeV amu^{-1}, Equation 2 reasonably describes the trend of the observed charge states, considering the current experimental uncertainties and the differences between the two sets of measurements. However, the point for Fe at ~40 MeV amu^{-1} falls below the curve, suggesting, either that these ions may have not traversed enough material to attain equilibrium, or that acceleration continues beyond the corona, or both.

The single adjustable parameter in Equation 2 is $\beta_{e,th}$, or the coronal plasma temperature, T_e. We might expect the ambient temperature of a coronal active region to lie in the range ~1-3 MK. While we might have been tempted to choose 2 MK as a more typical value, T_e=1.5 MK was chosen as the highest temperature consistent with the low-
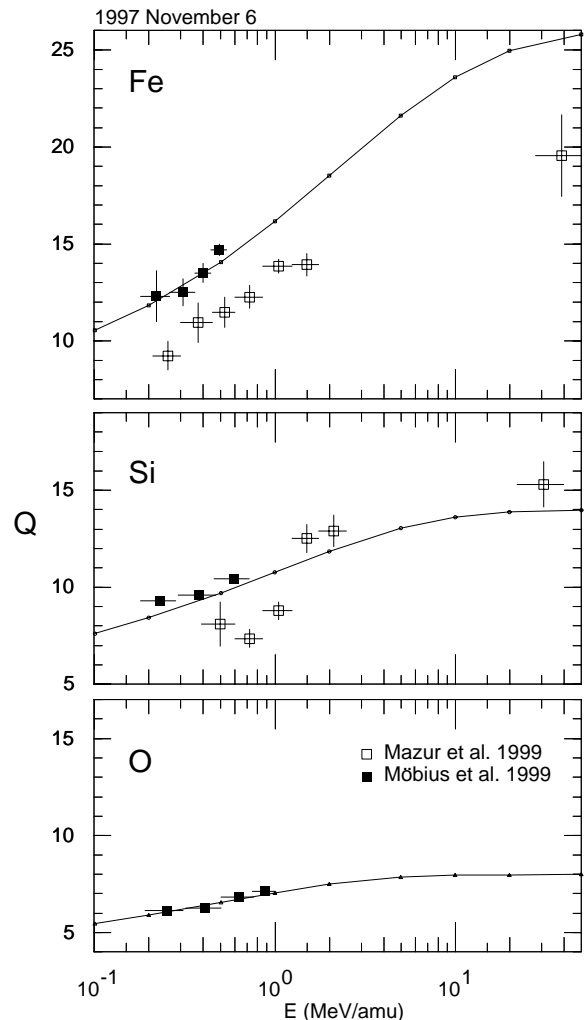

Figure 1. Measured mean ionization states of O, Si, and Fe are shown *vs.* ion energy/nucleon for the 1997 November 6 event along with equilibrium ionization states calculated from Equation 2 (see text).

energy observations of all species shown in Figure 1. However, we should point out that the value does depend on the specific form chosen for Equation 2.

Assuming that abundance enhancements follow a strict power-law dependence on Q/A, *Cohen et al.* [1999a] inferred that $Q_{Fe}=18.4\pm0.3$ in the 12-60 MeV/amu interval. While this power-law dependence is frequently not observed (see *e.g. Reames* 1999], it seems consistent with the measurement at 28-50 MeV/amu by *Mazur et al.* [1999] in this case. However, since *Cohen et al.* [1999a, b] completely neglected the possibility of ion stripping in the corona, they were forced to consider an arbitrary pattern of thermal ionization in which each element seems to be subjected to its own temperature environment. The associated abundance enhancements, in Fe/O, for example, were already observed in large gradual events at high energies during the previous solar cycle [*e.g. Tylka, Dietrich, and Boberg* 1997; *Tylka and Dietrich* 1999].

Near 1 MeV amu^{-1}, equilibrium should be established when the product of the electron density, n, and residence time, t, exceeds $nt \sim 10^{10}$ cm^{-3} s. For a coronal density $n \sim 10^{9}$ cm^{-3}, ions that scatter back and forth across the shock for an acceleration time of >10 s would reach ionization equilibrium. Above 2 solar radii where $n < 10^{5}$ cm^{-3}, equilibrium would be extremely unlikely.

Discussion

The energy variations of the ionization states observed in the 1997 November 6 event are in the energy region where changing equilibrium charge states are to be expected. The observed charges are reasonably consistent with the variations we would expect as ions approach charge equilibrium. Thus, observations in this event provide information on the height in the solar atmosphere where the strongest shock acceleration occurs, namely at or below $\sim 10^{5}$ km. We should also note that the higher values of $<Q>$ in this event reduces the magnetic rigidity of ions like Si and Fe at a given speed and increases their trapping near the shock and, hence, their acceleration efficiency [*e.g. Ng, Reames, and Tylka* 1999].

In other large gradual events, ions retain charge states typical of coronal and solar wind material, to energies of 200-600 MeV amu^{-1} [*Tylka et al.* 1995; *Ruffolo* 1997] since peak acceleration occurs at several solar radii where densities are low [*Kahler* 1994]. Observation of ions with $<Q_{Fe}> \leq 16$ and $<Q_{Si}> \leq 12$ above a few MeV amu^{-1} is strong evidence of shock acceleration occurring above ~ 2 solar radii.

At sufficiently low energies, ~ 0.1 MeV amu^{-1}, the charge states of elements still reflect the electron temperature of the source plasma where acceleration takes place. Values of $3 \leq <Q_{Fe}> \leq 16$ have been observed directly in the solar wind [*Gloeckler et al.* 1999] and could provide source plasma for the accelerated particles, although the range $9 \leq <Q_{Fe}> \leq 14$ for the solar wind is more common.

Values of $<Q_{Fe}> \geq 18$ at energies ~ 0.1 MeV amu^{-1} still seem to correspond to ions that have been heated to ≥ 10 MK in solar flares and transported across the corona without significant electron capture as found by *Luhn et al.* [1987]. In Figure 2 we plot a histogram of new observations of $<Q_{Fe}>$ at 0.58-2.3 MeV amu^{-1} in 12 different SEP events occurring in 1998 that are reported by *Möbius et al.* [1999b]. Previous low-energy values of $<Q_{Fe}>$ reported by *Luhn et al.* [1987] (12 gradual and 26 impulsive events) and by *Mason et al.* [1985] (2 events) are also shown in the figure along with the traditional identification of charge regions corresponding to gradual and impulsive events [*e.g. Luhn et al.* 1987; *Reames* 1999].

However, for impulsive flares, recent evidence [*Popecki et al.* 1999] suggests that a wide distribution, $12 \leq Q_{Fe} \leq 26$, is combined to yield a mean, $<Q_{Fe}> \sim 18$. A wide variation of temperatures with time has been suggested [*Reames et al.* 1994] as necessary to produce enhancements in elements such as Ne, Mg, and Si. These enhancements would not be possible in a ~ 10 MK environment where these ions have $Q/A \cong 0.5$, the same as that of He, C, N and O.

In the case of flares, once ions escape the turbulent acceleration region they are focused in the diverging solar magnetic fields and stream out of the corona. However, if they traverse $\sim 10^{19}$ electrons cm^{-2} in transit (10^{10} cm^{-3} with a scale height of 10^{4} km), they may indeed exhibit ionization states that have been *reduced* from those in the acceleration region. The high charge states observed for impulsive events at low energies (Figure 2) are evidence of flare heating and minimal transport through cooler material. It is entirely possible that the high corona above flares is also heated, perhaps by streaming electrons, so that the charges of 0.1 - 1.0 MeV amu^{-1} energetic ions are not appreciably diminished by electron pickup.

Ionization states are a sensitive measure of the history of accelerated particles. To apply this measure wisely in a variety of sites, we must identify and describe all of the physical processes involved.
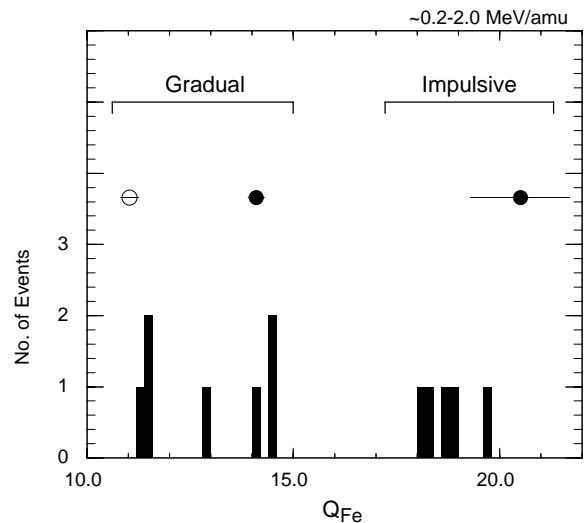

Figure 2. A histogram of the mean ionization states of Fe shows 12 events measured by *Möbius et al.* [1999b] together with mean values measured previously at low energies by *Luhn et al.* [1987] (solid circles) and by *Mason et al.* [1995] (open circle). Typical regions of Q_{Fe} are identified for gradual and impulsive events.

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D. V. Reames and C. K. Ng, Code 661, NASA/Goddard Space Flight Center, Greenbelt, MD 20771 (e-mail: reames, or cheeng@lheavx.gsfc.nasa.gov).

A. J. Tylka, Code 7654, E. O. Hulburt Center for Space Science, Naval Research Laboratory, Washington, DC 20375 (e-mail: tylka@crs2.nrl.navy.mil)

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[1]Dept. of Astronomy, University of Maryland, College Park, MD