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Ionic Charge States of Solar Energetic Particles: A Clue to the Source

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Abstract The ionic charge of solar energetic particles (SEP) as observed in interplanetary space is an important parameter for the diagnostic of the plasma conditions at the source region and provides fundamental information about the acceleration and propagation processes at the Sun and in interplanetary space. In this paper we review the new measurements of ionic charge states with advanced instrumentation onboard the SAMPEX, SOHO, and ACE spacecraft that provide for the first time ionic charge measurements over the wide energy range of $\sim$0.01 to 70 MeV/nuc (for Fe), and for many individual SEP events. These new measurements show a strong energy dependence of the mean ionic charge of heavy ions, most pronounced for iron, indicating that the previous interpretation of the mean ionic charge being solely related to the ambient plasma temperature was too simplistic. This energy dependence, in combination with models on acceleration, charge stripping, and solar and interplanetary propagation, provides constraints for the temperature, density, and acceleration time scales in the acceleration region. The comparison of the measurements with model calculations shows that for *impulsive* events with a large increase of $Q_{\mathrm{Fe}}(E)$ at energies $\leq$1 MeV/nuc the acceleration occurs low in the corona, typically at altitudes $\leq$0.2 R_S.

Keywords Sun: solar energetic particles · Ionic charge states

1 Introduction

The ionic charge of solar energetic particles (SEPs) is an important parameter for the diagnostic of the plasma conditions at the source region. Furthermore, the acceleration and transport processes depend generally on velocity and rigidity, i.e., on the mass and ionic charge of the ions. The large variations of elemental and isotopic abundances by up to several orders

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of magnitude and variations of the mean ionic charge of heavy ions, in particular of Fe, at ~1 MeV/nuc have been used for dividing SEP events into two classes, *gradual* and *impulsive* (see, e.g., Reames 1999 for an early review), following the classification of flares based on the duration of their soft X-ray emission (Pallavicini et al. 1977): (1) *Gradual* events show large interplanetary ion intensities, small electron to proton ratios, on average elemental abundances similar to coronal abundances, and ionic charge states consistent with source temperatures of (1.5–2) $\times 10^6$ K, characteristic for the solar corona. These events show long-duration soft X-ray emission and are associated with interplanetary shocks, driven by coronal mass ejections (CMEs). Particles are accelerated at the shock front over a wide range of solar longitudes, and then propagate along the interplanetary magnetic field before reaching the spacecraft. For a recent review on energetic particle observations related to CMEs and coronal and interplanetary shocks see Klecker et al. (2006a). (2) *Impulsive* events show small interplanetary ion intensities, a high electron to proton intensity ratio, enhanced abundances of heavy elements (e.g., by a factor ~10 for Fe relative to O), and enhancements of ^{3}He relative to ^{4}He by up to a factor of 10^4. Because of limited sensitivity the heavy ion ionic charge states could only be determined previously as an average over several ^{3}He-rich time periods. This event average showed high mean ionic charge states for Si ($Q \sim 14$) and Fe ($Q \sim 20$), which were interpreted as being due to a high temperature of $\sim 10^7$ K in the source region (Klecker et al. 1984; Luhn et al. 1987). These events show short-duration soft X-ray emission and the acceleration process is thought to be related to the flare. These "flare particles" can reach the spacecraft only from a narrow range of solar longitudes connecting the acceleration site with the spacecraft.

However, new measurements with improved sensitivity onboard the SAMPEX, SOHO, and ACE spacecraft demonstrate that energetic ions in coronal and interplanetary shock related (*gradual*) events, in particular at energies ≥ 10 s of MeV/nuc, often show signatures usually associated with *impulsive* events, including high ionic charge states, with $Q \sim 15$–20 for Fe (e.g., Leske et al. 1995; Mazur et al. 1999) and enrichments in heavy ions and ^{3}He (e.g., Cohen et al. 1999; Mason et al. 1999; Torsti et al. 2002; Desai et al. 2003; von Rosenvinge and Cane 2006, and references therein). Therefore, the two-class paradigm is now in question. It is, however, not questioned that SEPs originate in (at least) two different ways: (1) Coronal and interplanetary shocks related to CMEs can accelerate particles and (2) particles are accelerated in the flare process, possibly related to reconnection, and the high charge states and the large enrichments of ^{3}He and heavy ions are related to this acceleration process.

In this paper we will review recent developments on ionic charge state measurements. We first present a short summary of the different techniques to determine the ionic charge of solar energetic particles, and then discuss recent results and their implications for the acceleration processes.

2 Measurement Techniques

Over the past ~30 years basically three methods have been developed to determine or infer the ionic charge of energetic ions: (1) direct in situ determination of the particle parameters mass (M) and/or nuclear charge (Z), kinetic energy (E), and ionic charge (Q); (2) in situ measurements of particle mass and kinetic energy, and determination of Q from the rigidity-dependent cutoff of the magnetic field of the Earth; and (3) indirect methods, inferring the ionic charge from rigidity-dependent acceleration or propagation processes. For a detailed discussion of these methods see the recent reviews by Popecki (2006) and Klecker et al. (2006b).

The direct measurements are the most accurate; however, they are technically limited to energies less than a few MeV/nuc. At higher energies, novel instrumentation with large collecting power onboard the polar orbiting SAMPEX (*Solar, Anomalous and Magnetospheric Particle Explorer*) spacecraft (Baker et al. 1993) provided for the first time ionic charge measurements for many elements in the mass range C to Fe over the extended energy range of ∼0.3–70 MeV/nuc, utilizing the magnetic field of the Earth as a magnetic spectrometer (Mason et al. 1995; Leske et al. 1995; Oetliker et al. 1997). In recent years, the energy range was also extended to lower energies. At the same time sensitivity and resolution were improved with the SEPICA (Solar Energetic Particle Ionic Charge Analyzer) instrument (Möbius et al. 1998) onboard the *Advanced Composition Explorer* (ACE), and with the STOF sensor of the CELIAS experiment (Hovestadt et al. 1995) onboard the *Solar and Heliospheric Observatory* (SOHO). Over the past ∼10 years these new instruments have now extended the measurement of ionic charge states to many SEP events with low interplanetary particle intensity, in particular, also to many individual *impulsive* events.

3 Ionic Charge State Measurements: New Results

3.1 New Results in Gradual SEP Events

With the new measurements that provide for the first time ionic charge measurements in large (*gradual*) events over an extended energy range, a significant variation with energy and a large variability of the energy dependence of heavy ions have been found in many events, most notably for iron ions. At low energies ($\leq$200 keV/nuc) the mean ionic charge of Fe is usually ∼9–11 (Bogdanov et al. 2000), which is similar to solar wind charge states (Ko et al. 1999). At higher energies a large variability is observed. The mean ionic charge of Fe at energies $\leq$1 MeV/nuc is either constant or increases with energy, in a few cases by up to 4 charge units (Möbius et al. 1999; Mazur et al. 1999; Möbius et al. 2002). At energies above ∼10 MeV/nuc, however, the mean ionic charge is often observed to be significantly larger than at low energies, with $Q_{\mathrm{Fe}} \sim 15$–20 (Leske et al. 1995; Oetliker et al. 1997; Labrador et al. 2005). The variation of Q_{Fe} with energy is illustrated in Fig. 1 (left-hand side), which shows Q_{Fe} event averages in three energy ranges between 0.18 and 65 MeV/nuc for several large events. These results indicate that the previous interpretation of heavy ion charge states being solely related to the plasma temperature was too simplistic. The compilation of Fe/O ratios and heavy ion charge states in Fig. 1 (right-hand side) shows that the observed variability of Q_{Fe} at $E \geq 10$ MeV/nuc is strongly correlated with the relative abundance of Fe (Labrador et al. 2005).

3.2 New Results in Impulsive SEP Events

The high-sensitivity ionic charge measurement with the SEPICA experiment onboard ACE provided ionic charge measurements for a large number of *gradual* and *impulsive* SEP events. Figure 2 shows the distributions of the mean ionic charge of Fe at 0.18–0.25 MeV/nuc in ∼40 impulsive events compiled by DiFabio et al. (2006) and, for comparison, in ∼40 interplanetary shock-related time periods (Klecker et al. 2006c). Figure 2 shows that the distributions of the mean charge of Fe are completely different for the two classes of events: Those correlated with interplanetary shocks show in this energy range a

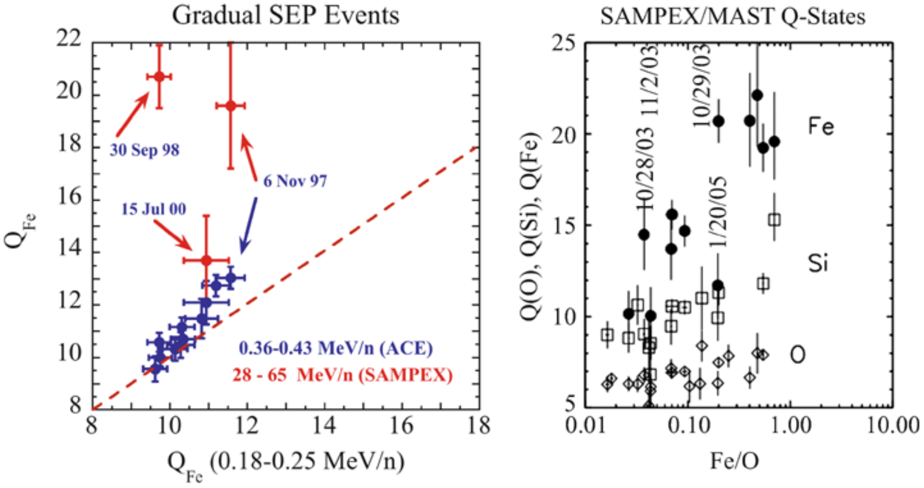
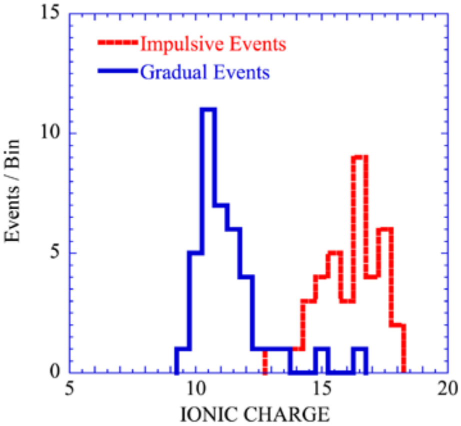


Fig. 1 *Left*: Ionic charge Q_{Fe} at 0.18–0.25 MeV/nuc versus 0.36–0.43 and 28–65 MeV/nuc (compilation from Möbius et al. 1999; Labrador et al. 2005; Popecki 2006). *Right*: Correlation of heavy ion abundances and charge states at ≥10 MeV/nuc (Labrador et al. 2005)

Fig. 2 Average ionic charge of Fe in the energy range 0.18–0.24 MeV/nuc in ~40 impulsive and ~40 gradual SEP events; for details see the text



distribution with a peak around $Q_{\mathrm{Fe}} \sim 10$, whereas the corresponding distribution of average charge states in impulsive events is considerably wider and ranges from ~14 to 18. Furthermore, all *impulsive* events observed with SEPICA onboard ACE during 1997–2000 show a strong increase of the mean ionic charge of Fe in the narrow energy range of ~0.1–0.55 MeV/nuc, on average by ~4.5 ± 1 charge units (Möbius et al. 2003; Klecker et al. 2006d; Popecki 2006; DiFabio et al. 2006).

Figure 3 illustrates this energy dependence with three typical impulsive events observed during 1998–2000. The observations show a monotonic increase of Q with energy in the measurement range of the instrument, with $Q_{\mathrm{Fe}} \sim 13$–15 at ~0.1 MeV/nuc and $Q_{\mathrm{Fe}} \sim 18$–20 at ~0.55 MeV/nuc (Popecki 2006, and references therein), at the high-energy end, consistent with the early measurements at ~1 MeV/nuc.

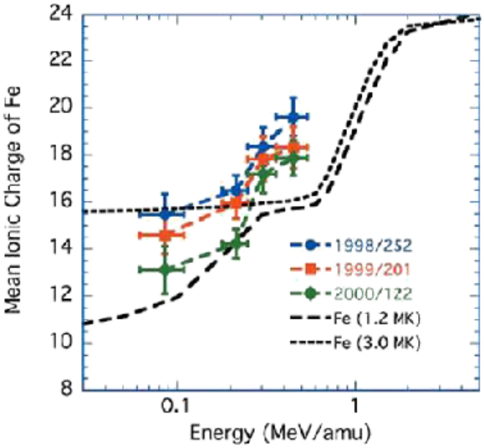


Fig. 3 The energy dependence of the ionic charge of Fe in three representative impulsive events (Klecker et al. 2006d; DiFabio et al. 2006). Also shown is the energy dependence of the equilibrium charge from ionization effects in a dense environment for 1.2×10^6 and 3×10^6 K (Klecker et al. 2006d)

4 The Energy Dependence of the Ionic Charge

Several mechanisms resulting in an increase of the mean charge states with energy have been discussed recently (for a more detailed discussion see also Popecki 2006, Klecker et al. 2006b and references therein): (1) charge changing effects resulting from ionization by thermal electrons and ions, (2) mixing of sources with different ionic charge distributions, and (3) M/Q-dependent energy spectra. However, a large increase of Q_{Fe} at energies $\leq$1.0 MeV/nuc, as systematically observed in *impulsive* events, could so far only be explained by additional ionization of more energetic ions in a dense environment. If the particles propagate in a sufficiently dense environment in the lower corona during or after the acceleration, a large increase of the mean ionic charge at energies of ~0.2–1 MeV/nuc is a natural consequence of the cross sections for ionization by thermal electrons and protons (Kocharov et al. 2000). Calculations of the equilibrium ionic charge of energetic heavy ions, including the effects of radiative and dielectronic recombination and ionization by thermal electrons and ions (p, ^{4}He), show that the mean ionic charge of an ion with speed V increases monotonically as a function of $N\tau$, where N is the plasma density and τ is the acceleration time scale. The ionic charge approaches asymptotically an upper limit, the equilibrium mean charge Q_{eq}, where $(N\tau)_{\mathrm{eq}}$ depends on ion speed and plasma temperature and is in the range of 10^{10}–10^{11} $\mathrm{s\,cm^{-3}}$ (Kocharov et al. 2000; Kovaltsov et al. 2001). Figure 3 shows as an example the equilibrium mean ionic charge of Fe as a function of energy for two temperatures (1.2×10^6 and 3×10^6 K) in the surrounding plasma, demonstrating the strong increase of Q_{eq}, for Fe at energies $\geq$0.2 MeV/nuc. The simple equilibrium model also demonstrates that the new measurements of Q_{Fe} at low energies are not compatible with a high coronal temperature of $\sim 10^7$ K, as previously inferred from the ionic charge measurements at ~1 MeV/nuc.

Figure 3 also shows that the steep increase of Q_{Fe} with energy is typically observed at somewhat lower energies than predicted by the equilibrium stripping model. It has been demonstrated recently that this difference between the observed and predicted energy dependence of Q can be explained by propagation effects (Kartavykh et al. 2005): On their way from the acceleration site at the Sun to 1 AU low-energy particles can lose a significant fraction of their energy by adiabatic deceleration. This results, for an average ionic charge $Q(E)$ at the Sun, in the same mean ionic charge at a lower energy E at 1 AU, as seen qualitatively in Fig. 3. Furthermore, the equilibrium mean charge is an upper limit that may never be reached under realistic conditions.

Therefore, a quantitative comparison of the observations with calculations requires more realistic models that include the effects of acceleration, ionization, and recombination, Coulomb energy losses at the Sun, and propagation at the Sun and in interplanetary space. Also, the details of the dependence of Q on E will depend on the type of model, i.e., whether acceleration and charge changing effects are concurrent as in the leaky-box models with stochastic or shock acceleration, or whether there is charge stripping also after acceleration, as would be the case for acceleration by a shock low in the corona with subsequent escape of the particles into interplanetary space. For a recent review on the modeling of energy-dependent charge states of SEPs see Kocharov (2006) and references therein.

5 Implications for the Source Location

5.1 Impulsive Events

The mean ionic charge of Fe and the energy spectra in impulsive events have recently been modeled by a leaky-box model including stochastic acceleration and charge changing processes. In these models, the intensity–time profiles and anisotropies of particles with different mass per charge ratio (e.g., H^+, He^{2+}, electrons) are used to infer the injection profile at the Sun and the propagation characteristics in interplanetary space. Then, the observed energy spectra and charge spectra of heavy ions are used to infer the model parameters for the acceleration and the plasma parameters of the acceleration environment. In these models stochastic acceleration is assumed with the model parameters $N\tau_A$, τ_A/τ_D, γ, and T_e, where N and T_e are plasma density and temperature, τ_A and τ_D are the time scales for acceleration and diffusion in the source region at the Sun, and γ is the power-law index of the power spectrum of the wave turbulence. The model calculations show that a steep increase of Q_{Fe} with energy at $E \leq 1$ MeV/nuc as observed in all *impulsive* events can be explained with this type of model and both the energy spectra and the observed energy dependence of the ionic charge can be reproduced satisfactorily, if interplanetary propagation is included (Kartavykh et al. 2006; Dröge et al. 2006). Typical values of the model parameters are $N\tau_A \sim 10^{10}$–10^{11} s cm^{-3}, $\tau_A/\tau_D \sim 0.1$, and $T_e \sim 10^6$ K. However, some of the charge spectra could only be reproduced by assuming two acceleration regions with different plasma parameters with significantly larger T_e ($\sim 10^7$ K) in the second region (Dröge et al. 2006). If we assume acceleration time scales in the range of ~ 1 to 10 s this corresponds to densities of $\sim 10^9$–10^{11} cm^{-3}. This is similar to the density range of $(0.6–10)\times 10^9$ cm^{-3} inferred from radio and electron measurements for the density of the acceleration region of electrons (e.g., Aschwanden 2002 and references therein); that is, it indicates acceleration in the low corona, at altitudes $\leq 0.2\ R_S$.

5.2 Gradual Events

In many gradual events the mean ionic charge is approximately constant up to energies of a few MeV/nuc. This is consistent with acceleration by a shock high in the corona or in interplanetary space, because charge stripping by the processes discussed thus far will not change the ionic charge states as a function of energy significantly for values of $N\tau_A$ $\leq 10^8$ cm^{-3} s, as shown by nonequilibrium calculations (Kovaltsov et al. 2001). These nonequilibrium models also show, for higher values of $N\tau_A$, a significant increase of Q_{Fe} at energies ≥ 10 MeV/nuc, as often observed. However, there are also alternative explanations for the increase of heavy ion charge states at high energies as discussed in the following non-equilibrium calculations.

For the cases where a significant increase of Q_{Fe} is observed below ~1 MeV/nuc, models including charge stripping and shock acceleration can qualitatively reproduce the observed energy dependence, if the acceleration starts in the low corona (e.g., Barghouty and Mewaldt 1999; Ostryakov and Stovpyuk 1999; Ostryakov and Stovpyuk 2003; Lytova and Kocharov 2005). In these models the charge state variation with energy depends on the coronal density profile $N(r)$, T_e, shock speed, compression ratio, and the absolute value and rigidity dependence of the spatial diffusion coefficients, upstream and downstream of the shock. It also depends on the type of model, i.e., whether stripping after acceleration is included. Typical forms of $Q_{\mathrm{Fe}}(E)$ are presented in Fig. 4 (Kocharov 2006), which shows the results of a numerical model for iron, including charge stripping, Coulomb losses, diffusion, convection, adiabatic deceleration, and shock acceleration, assuming an initial altitude of ~0.2 R_S for the shock, a turbulent layer with thickness 0.5 R_S, a shock speed of 600 km/s, and a coronal density profile adopted from Guhathakurta et al. (1996). Figure 4 demonstrates that there is a significant difference in Q_{Fe} for particles at the shock (plus signs), at a fixed distance from the shock (histogram), and for escaping particles with additional stripping after acceleration (diamonds).

Limits of the altitude range where the acceleration by an outward traveling shock needs to start to reproduce a large increase of Q_{Fe} at ≤1 MeV/nuc may be estimated from the requirement that the local fast magnetosonic speed V_F is sufficiently small for traveling disturbances to produce fast-mode shocks (e.g., Mann et al. 1999; Gopalswamy et al. 2001) and from the acceleration model. However, there was so far no attempt to systematically explore the altitude range compatible with the observed variation of Q_{Fe} with energy. Uncertainties in the coronal density distribution, shock geometry, and turbulence will result in large uncertainties in the altitude estimate. In a recent review an estimate of ~0.5–1 R_S (with a

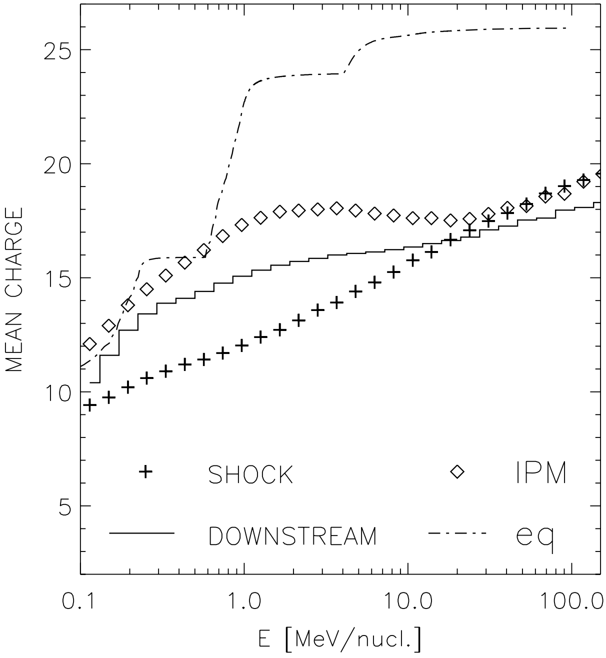


Fig. 4 Mean charge states of Fe computed with a shock acceleration model. The symbols correspond to particles at the shock front (*plus signs*), escaping particles at a fixed distance from the shock (*histogram*), escaping particles with additional stripping during escape (*diamonds*), and equilibrium charge states (*dash-dotted line*) (Kocharov 2006)

large uncertainty of ∼50%) was provided for the altitude range compatible with the energy dependence of Q_{Fe} in these events (Kocharov 2006).

A different approach, primarily intended to explain the large variability of compositional variations and spectral features of heavy ions in large interplanetary shock related SEP events, also predicts an increase of the mean ionic charge of heavy ions at high energies (Tylka et al. 2005; Tylka and Lee 2006). In this model, compositional (and ionic charge) variations are caused by the interplay of two factors: shock geometry and the mixture of two seed populations with composition and charge states similar to solar wind and flare particles, respectively. Key elements in this scenario are (1) a power-law energy spectra with an exponential rollover at high energies,

$$J(E) \sim E^{-\gamma} \exp(-E/E_0), \tag{1}$$

with E_0 depending on M/Q (Ellison and Ramaty 1985; Tylka et al. 2000) and on the angle θ_{BN} between the magnetic field and the shock normal (Lee 2005) as

$$E_0 = E_{0p}(Q/M) f(\theta_{BN}), \tag{2}$$

(2) a higher injection threshold for large θ_{BN}, and (3) averaging the energy spectra over θ_{BN} (by assuming contributions from the parallel and perpendicular regions of the evolving shock). In this scenario shock geometry determines via the injection threshold which of the two components dominate and pre-accelerated flare particles are preferentially injected at the perpendicular shock. However, whether the injection threshold at parallel and perpendicular shocks is in fact drastically different is presently disputed (Giacalone 2005) and needs further investigation.

In an alternative two-component model one assumes a direct flare component with high Fe charge states and high Fe/O ratio, which dominates at high energies, with a shock-accelerated component with charge states and heavy ion abundances similar to solar wind values dominating at low energies (e.g., Klein and Trottet 2001; Cane et al. 2003).

6 Summary

1. In all *impulsive* events observed during 1997–2000, the mean ionic charge of iron increases significantly, on average by 4.5 ± 1 charge units in the rather small energy range of ∼0.1–0.55 MeV/nuc. At ∼0.01–0.1 MeV/nuc an average value of $Q_{\mathrm{Fe}} \sim 12$ was observed for 3 events (Klecker et al. 2006d) and at ∼0.1 MeV/nuc $Q_{\mathrm{Fe}} \sim 11$–15 was observed for 14 events (DiFabio et al. 2006).
2. In *gradual* events, the mean ionic charge at low energies of ∼0.1 MeV/nuc is mostly compatible with solar wind charge states. At higher energies a large event-to-event variability is observed, with $Q_{\mathrm{Fe}} \sim 15$–20 at energies above ∼10 MeV/nuc in several events.

The energy dependence of the ionic charge in *impulsive* events can be used to infer the location of the source and acceleration region. With models including the effect of stochastic acceleration, propagation, charge stripping, and Coulomb losses at the Sun and interplanetary propagation, $Q(E)$, energy spectra, and intensity–time and anisotropy–time profiles can be reproduced. These models show that the ionic charge states are determined by a combination of the parameters temperature, density, acceleration, and propagation time scales at the Sun, and interplanetary propagation conditions, with $N\tau_A \sim 10^{10}$–10^{11} s cm^{-3}, placing the acceleration low in the corona, at altitudes $\leq 0.2\ R_S$. To further constrain the model parameters, the particle measurements need to be complemented by the measurements of, for example, X rays, electrons, and γ rays to independently determine the acceleration and propagation time scales at the Sun. Furthermore, the present stripping models do not reproduce the heavy ion abundance enhancements observed in impulsive events.

In *gradual* events, the energy dependence of the ionic charge provides information on the various sources contributing to the accelerated particle population and on the source location. A large increase of Q_{Fe} at ≤ 1 MeV/nuc can be explained by shock acceleration and impact ionization low in the corona, with a shock starting at heliocentric distances of ~ 1.5–$2\ R_S$ (Kocharov 2006). Events with $Q_{\mathrm{Fe}} \sim$ const. at low energies and with a large increase of the mean ionic charge at energies of tens of MeV/nuc, accompanied by an increase of the Fe abundance at high energies, suggest injection of ions from two sources: (1) a source with heavy ion abundances and charge states similar to solar wind or corona and (2) a flare component with heavy ion enrichment and charge states determined by charge stripping low in the corona. Whether this flare component is directly injected or further accelerated at a coronal shock is presently under debate and needs further investigation.

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