Pergamon
www.elsevier.com/locate/asr

Adv. Space Res. Vol. 30, No. 1, pp. 119–124, 2002

Printed in Great Britain
0273-1177/02 $22.00 + 0.00

PII: S0273-1177(02)00181-3

CHARGE STATES OF Mg AND Si FROM STOCHASTIC ACCELERATION IN IMPULSIVE SOLAR FLARES

Yu. Yu. Kartavykh[1, 2], S. Wannawichian[1], D. Ruffolo[1], and V. M. Ostryakov[2]

[1]*Department of Physics, Chulalongkorn University, Bangkok 10330, THAILAND*
[2]*Physical-Technical Department, St. Petersburg State Technical University, St. Petersburg, 195251, RUSSIA*

ABSTRACT

We consider the acceleration of heavy ions in impulsive solar flares. In particular, we have performed Monte Carlo simulations of stochastic acceleration by Alfvén wave turbulence, and compare new results for magnesium and silicon ions with previous results for iron. The model takes into account stripping due to collisions with ambient electrons and heavy particles (protons and He^{+2}) which becomes increasingly important for more energetic ions, as well as radiative and dielectronic recombination due to collisions with electrons. Spatial diffusion and Coulomb losses are also taken into account. For comparison, we also calculate equilibrium mean charges. We examine the effects of plasma parameters on the calculated energy-dependent charge state distributions of these elements, which can be compared with results from space-borne instruments in order to put constraints on the physical environment of the acceleration region.

INTRODUCTION

It is accepted that solar events such as flares and coronal mass ejections (CME) can be divided into two classes, "impulsive" and "gradual" (e.g., Pallavicini, Serio, and Vaiana, 1977; Kahler et al., 1984; Cane, McGuire, and von Rosenvinge, 1986). The resulting solar energetic particles (SEP) from impulsive flares are believed to originate from stochastic acceleration in hot flare plasma, whereas those from gradual flare/CME events are believed to be accelerated by a travelling, CME-driven shock. One of various differences is that SEP ions accelerated in impulsive events are stripped to higher charge states than those from gradual events (Luhn et al., 1987). Recent high-sensitivity measurements by the SEPICA instrument on board the ACE spacecraft for a variety of events have revealed mean Fe charges ranging all the way from 11.3 to 19.7 (Möbius et al., 2001; Popecki, 2001).

The ionic charge distributions can serve as unique diagnostics of the source plasma, because they are determined by ionization and recombination processes which are sensitive to the plasma temperature, density, etc. Qualitatively, the charge states can identify the plasma of origin of the particles (i.e., hot plasma, open corona, or solar wind) and help to classify SEP populations (Ruffolo, 2001). Quantitatively, they can help to elucidate the details of the acceleration site and acceleration mechanism. In addition, they can give information on the residence time of the ions in that plasma.

It is very useful to consider ionic charge states of several elements for the same event, in order to place much better constraints on parameters of the source and acceleration/propagation regions (Ruffolo, 1997), and to take advantage of the beautiful observational data from the SAMPEX and ACE spacecraft, with mean charge states obtained for up to 13 elements for a single event (Leske et al., 1995). In particular, Mg, Si, and Fe are abundant SEP species for which there is a wide range of observed charge states, providing especially good diagnostics. Therefore, this work aims to extend previous work on modeling Fe charge states resulting from stochastic acceleration in impulsive solar flares (Ostryakov et al., 2000b) to consider Mg and Si. In addition, we also consider the equilibrium mean charges in detail, and confirm the importance of ionization by collisions with p and He^{+2} for such energetic ions.

In this work, we model charge distributions under two types of conditions: a) We first consider idealized, equilibrium conditions, under which an ion is imagined to maintain a given energy while traveling through a plasma for a time sufficiently long that the charge distribution achieves a steady state (Luhn and Hovestadt, 1987; Kocharov et al., 2000). b) We then consider a realistic model of stochastic acceleration during an impulsive solar flare, as considered by Ostryakov et al. (2000a,b). Their results, including comparisons with measured spectra, indicated that even SEP ions originating in the dense plasma of an impulsive solar flare region do not follow equilibrium, energy-dependent Fe charge distributions (i.e., $\tau_a^0 N$ is not sufficiently large), in contrast with the premise of Reames et al. (1999).

Nevertheless the consideration of equilibrium mean charges is still worthwhile because they represent the extreme endpoint of stripping restricting the allowed range of charge changes. The charge distributions of heavy ions, which can be observed by means of X-ray or optical (forbidden line) spectroscopy or by direct measurements of particles, provide a means to study plasmas for thermonuclear or inertial confinement fusion. Knowledge of these distributions is also important for determining the performance of tandem accelerators (Luhn and Hovestadt, 1987). Furthermore, measurements of charge states are also widely used in solar physics and astrophysics in general; one example is the observation of optically forbidden line emission from specific Fe ions during a solar eclipse.

The importance (or necessity) of processes changing the charges of ions during their propagation through a plasma has been confirmed experimentally (Dietrich et al., 1992; Neuner et al., 1998). However, such experiments are technically difficult and do not provide us complete information about properties of equilibrium charge distributions even for a single element. Therefore numerical calculations of such distributions based on ionization and recombination cross sections available in the literature are highly desirable.

In the case of thermal (or low-energy) ions, only collisions with electrons are important in determining the equilibrium charge distribution. Ions are ionized due to collisions with electrons via direct and excitation ionization. They can also capture electrons from the surrounding plasma due to processes of radiative and dielectronic recombination. For thermal ions, almost no protons (or other heavy ions) in the ambient plasma have a high enough velocity to overcome the ionization threshold. However, additional ionization by protons becomes quite important when the ions move with a higher energy.

IONIZATION AND RECOMBINATION RATES

The ionization rates can be calculated through corresponding cross sections as (Luhn and Hovestadt, 1987; Kocharov et al., 2000):

$$\tau_{I,J}^{-1} = N_e \int \sigma_e(v_e) v_e f(v_e) dv_e + \sum_j N_j \sigma_j(v_I) v_I. \tag{1}$$

In this equation we consider collisions of the accelerated ion I with both plasma electrons (e) and various plasma ion species (j; here we consider p and He^{+2}). Then $\tau_{I,J}$ is the characteristic time of ionization from the initial ion I to ion J, and N and σ are the number density and cross section, respectively, for each plasma species. The relative speed of a plasma electron with respect to the accelerated ion I is denoted v_e, and the distribution function $f(v_e)$ is a so-called offset Maxwellian distribution:

$$f(v_e)dv_e = \sqrt{\frac{m_e}{2\pi kT}} \frac{v_e}{v_I} \left\{ \exp\left[-\frac{m_e}{2kT}(v_e - v_I)^2 \right] - \exp\left[-\frac{m_e}{2kT}(v_e + v_I)^2 \right] \right\}, \tag{2}$$

where v_I is the energetic ion speed. Note that in equation (1) we neglect the thermal velocities of plasma ion species, so that the relative speed in the final term is simply the speed of the accelerated ion I. Recombination rates are calculated in the same manner, but considering only collisions with plasma electrons.

The direct ionization cross-sections due to collisions with electrons (and corresponding rates) were calculated in accordance with Arnaud and Rothenflug (1985). To calculate the excitation ionization due to collisions with electrons, we used the formulae of Arnaud and Rothenflug (1985) and Sampson and Golden (1981). For calculating the ionization cross sections for collisions with protons (using $N_p = N_e = N$) and He^{+2} (N_{He}=0.1N) we used Bohr's formula (for details, see Kartavykh et al., 1998; Kocharov et al., 2000). Radiative recombination was accounted for according to the tables of Shull and Van Steenberg (1982a,b). Dielectronic recombination was calculated following the tables in Mazzotta et al. (1998).

Figures 1 and 2 show total ionization and recombination rate coefficients for the transitions $Si^{+9} \longleftrightarrow Si^{+10}$ and $Si^{+12} \longleftrightarrow Si^{+13}$, respectively, together with separate contributions of different processes at a plasma temperature $T = 10^6$ K. For low charges, with valence electrons in the L-shell or higher, dielectronic recombination is dominant in the energy range below $\sim$ 1 MeV/nucleon, and radiative recombination dominates at higher energies (Figure 1).

For valence electrons in the K-shell, radiative recombination is more important, with the exception of narrow energy ranges where resonant conditions for dielectronic recombination are fulfilled (Figure 2). Ionization cross sections due to collisions with He^{+2} are similar to those for protons, but with about 1/4 of their absolute magnitude.

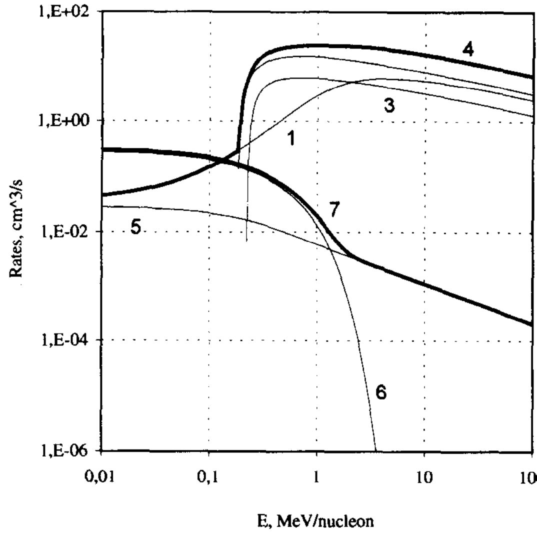

Fig. 1. Ionization rates for Si^{+9}: 1 - by electrons, 2 - by protons, 3 - by He^{+2}, 4 - sum. Recombination rates for Si^{+10}: 5 - radiative recombination, 6 - dielectronic, 7 - sum.

EQUILIBRIUM MEAN CHARGES

If an equilibrium is achieved between ionization and recombination processes, we have $n_q R_q = n_{q+1}\alpha_{q+1}$, where n_q is the relative number density of ions with charge state q, R_q is the ionization rate coefficient and α_{q+1} is the recombination rate coefficient.

Figures 3 and 6 show the mean equilibrium charges of magnesium and silicon as a function of energy, calculated at three different temperatures. For these temperatures, it is is crucial to take collisions with heavy particles (e.g., p and He^{+2}) into consideration for Mg and Si ions of $\sim$ 1-5 MeV/nucleon. Actually, additional ionization by helium ions does not lead to noticeable changes in equilibrium mean charge; nevertheless it has some influence on the mean charge of accelerated ions, as we shall see in the next section.

The curves for ionization by electrons alone, as typically used in previous research (e.g., Luhn and Hovestadt, 1987) are smoother than the more accurate curves taking into account collisions with both electrons and heavy particles. The inclusion of additional ionization by heavy particles (protons and helium) leads to occasional, sharp increases in the equilibrium mean charge, e.g., at an energy of $\sim$ 1 MeV/nucleon. This is because ionization cross sections peak shortly after a certain threshold. Taking account of additional ionization by heavy particles can increase the summed ionization rate by several orders of magnitude (for example, in the case of Si^{+12} - see Figure 2) and drastically change the relative equilibrium between ionization and recombination, leading to such sharp steps. At higher temperatures, the equilibrium charge increases more gradually with energy, because the ionization produced by electrons in the tail of the Maxwellian distribution becomes more important.

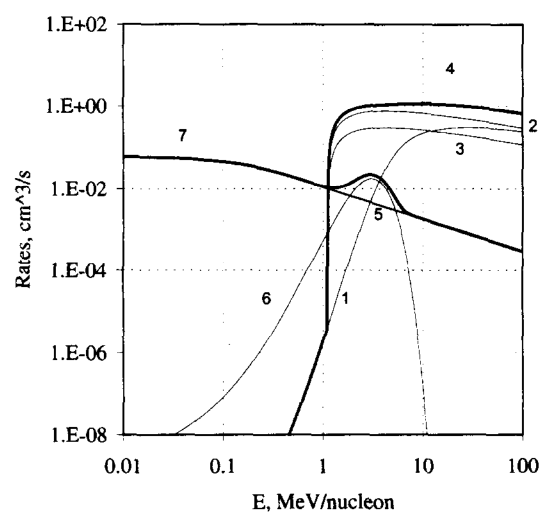

Fig. 2. Same as Fig. 1, but for Si^{+12} and Si^{+13}.

It is also seen in Figures 3 and 6 that at low energy, the equilibrium mean charge depends more strongly on temperature. Consequently ions at lower energy ($\leq$ 0.3 MeV/nucleon) are more sensitive temperature diagnostics for the acceleration region (for more details, see Kartavykh et al., 2001).

MEAN CHARGES FROM A STOCHASTIC ACCELERATION MODEL

In the present paper we use the same stochastic acceleration model as Ostryakov et al. (2000a,b). The solution of the corresponding Fokker-Planck equation is defined by the ratios of characteristic times for acceleration (τ_a), spatial diffusion (τ_d), Coulomb losses (τ_c) and ionization and recombination ($\tau_{I,J}$). A similar calculation for the case of shock acceleration has been performed by Stovpyuk and Ostryakov (2001).

New technical considerations in the present work include the selection of the injection energy, which influences the resulting spectra only through a boundary effect, yet its choice significantly influences the number of test particles required for adequate statistics, and hence the computation time. To verify this point we have performed simulations injecting particles at different initial energies, 100 eV/nucleon (thermal) and 50 - 100 keV/nucleon. After several energy steps the mean charge curves obtained for different injection energies merge into one, so in our simulations we selected an injection energy such that results in the energy range of interest are free from boundary effects while maintaining a reasonable computation time. Also, the inclusion of ionization due to collisions with He^{2+} produces small changes (at most about 0.1 charge units) at an energy of about 1 MeV/nucleon, while the inclusion of protons provides a significant increase of the mean charge, especially at low temperature and high values of $\tau_a^0 N$ (see Figure 8).

The key model parameters that affect the resulting mean charge are the plasma temperature, T, and the product of the acceleration timescale for protons and the electron number density, $\tau_a^0 N$. [Note that τ_a^0 for protons serves as a reference value, while for heavy ions we use $\tau_a = \tau_a^0 (Q/A)^{S-2}$ with an Alfvén wave spectral index S=3/2 (Ostryakov et al., 2000b).] The remaining variable parameter τ_a/τ_d has only a weak effect.

The plasma temperature mainly affects the model results for $\langle Q(E)\rangle$ (see Figures 4 and 7) in two ways: 1) by determining the initial, low energy charge distribution, and 2) by determining the final equilibrium distribution that would result if the ions remained in that plasma at a given energy for a long time (see previous section). Typically we expect $\langle Q(E)\rangle$ to be bounded by those extreme values. Note that for a high temperature and reasonable $\tau_a^0 N$ value, we see essentially no stripping beyond the thermal mean charge at low energy, even when the equilibrium mean charge has already begun to rise (see Figures 3, 4) . More precisely, even the equilibrium mean charge, $\langle Q\rangle_{eq}$, has changed less than one charge unit from the thermal value for Mg with $\langle Q\rangle \geq 10$ and $E < 0.8$ MeV/nucleon (Figure 6) and for Si with $\langle Q\rangle > 12$ and $E < 1.1$ MeV/nucleon (Figure 3). The analogous range for Fe is $\langle Q\rangle > 16$ and $E < 0.6$ MeV/nucleon (Ostryakov et al. 2000b). Thus for such ions, the mean charge directly indicates the source plasma ionization temperature. Note, however, that for O and Ne ions, whose equilibrium charges rapidly increase already at $E \sim 0.4 - 0.6$ MeV/nucleon, their observed mean charges from impulsive solar flares (at energies above ~ 0.5 MeV/nucleon) do not serve as clear

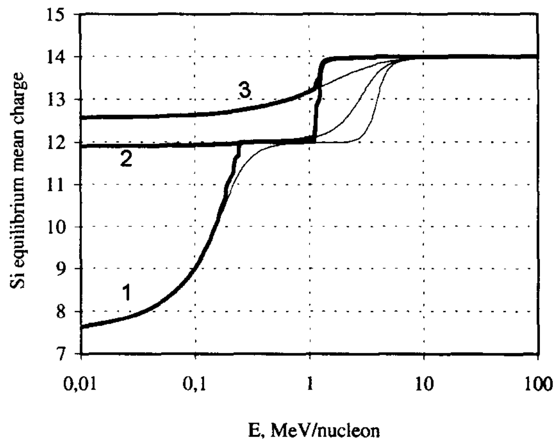

Fig. 3. Calculated $\langle Q\rangle_{eq,Si}$: 1 - $T=10^6$, 2 - $T=10^{6.5}$, 3 - $T=10^7$ K for collisions with e^- (thin curves) or e^-, p, and He^{+2} (thick curves).

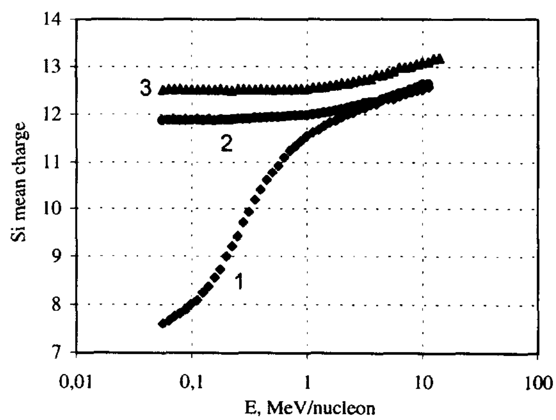

Fig. 4. Calculated $\langle Q\rangle_{Si}$ vs. E for $\tau_a^0 N = 3 \times 10^{10}$ cm^{-3} s: 1 - $T=10^6$, 2 - $T=10^{6.5}$, 3 - $T=10^7$ K.

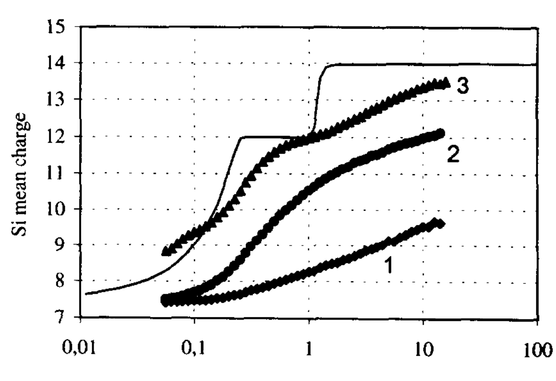

Fig. 5. Calculated $\langle Q\rangle_{Si}$ vs. E for $T=10^6$ K: 1 - $\tau_a^0 N$=0.1, 2 - $\tau_a^0 N$=1.0, 3 - $\tau_a^0 N$=10 $\times 10^{10}$ cm^{-3} s. Solid line - $\langle Q\rangle_{eq,Si}$.

indicators of the temperature. Therefore, their charge states should be calculated with a complete model of stochastic acceleration such as that presented here.

Figures 5 and 8 show that the calculated mean charges increase along with the product $\tau_a^0 N$. This can be understood in that a higher $\tau_a^0 N$ implies a greater opportunity for stripping, and the mean charge approaches the equilibrium value. Note, however, that even for the highest $\tau_a^0 N$ values considered here, the equilibrium mean charge does not provide an accurate indication of the mean charge except at extremely high energies where ions are fully stripped in the acceleration model. This justifies the need for a detailed model of acceleration rather than oversimplified approach of Reames et al. (1999).

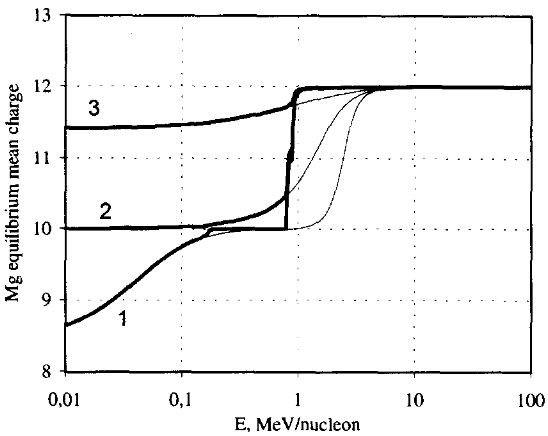

Fig. 6. Same as Fig. 3, but for Mg.

CONCLUSIONS

In this paper, we present calculations of the mean charges of energetic Mg and Si ions for both equilibrium conditions and a realistic model of stochastic acceleration during an impulsive solar flare. Our calculations indicate that it is very important to take into account ionization by collisions with both electrons and heavy particles (here, p and He^{2+}), especially for Mg and Si ions of about 1 to 5 MeV/nucleon.

The key plasma parameters that affect the calculated mean charge in the stochastic acceleration model are the plasma temperature and the product of the acceleration timescale for protons with the electron density, $\tau_a^0 N$. The plasma temperature affects $\langle Q(E) \rangle$ by determining both the initial, low-energy charge distribution and the energy-dependent equilibrium charge distribution. For low $\tau_a^0 N$, the ions undergo little stripping during acceleration. As this product increases, there is more stripping and $\langle Q \rangle$ vs. energy approaches closer to the equilibrium curve, though not yet reaching it for reasonable values of $\tau_a^0 N$ (e.g., as determined by Ostryakov et al., 2000a).

These results for the mean charges of Mg and Si ions as a function of energy, along with previous results for Fe, allow a comparison with data for these, the key abundant heavy ions that have a wide range of observed charge states. Such a comparison will be the subject of a separate paper. Note also that for a high mean charge at energies below ~ 1 MeV/nucleon, as is frequently observed for what are presumably impulsive solar flare events, we find that there is no significant stripping of the thermal charge distribution, and such ionic charge states can serve as indicators of the source plasma temperature.

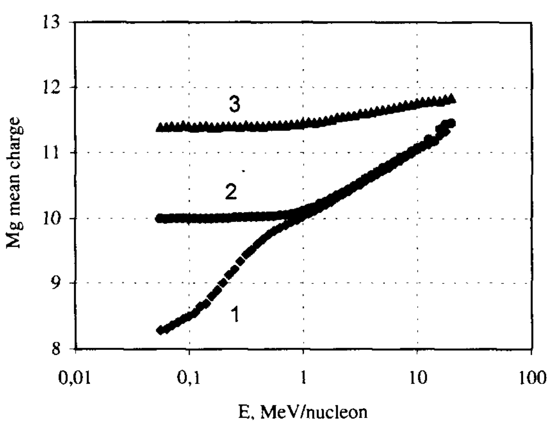

Fig. 7. Same as Fig. 4, but for Mg.

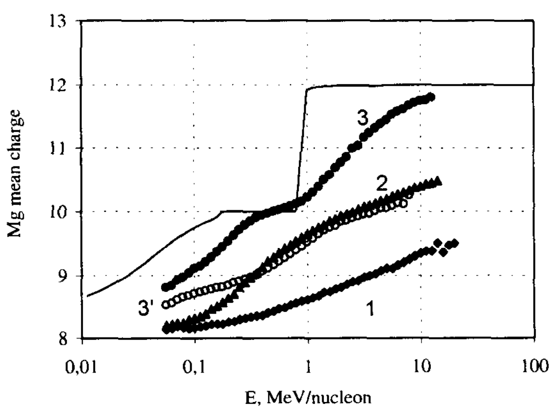

Fig. 8. Same as Fig. 5, but for Mg. Curve 3' - same as 3, but only influence of electrons is taken into account.

ACKNOWLEDGEMENTS

This work was supported by the Thailand Research Fund and the Russian Foundation of Basic Research (grant 00-02-17031). Yu.Yu.K. also thanks Chulalongkorn University for their hospitality during her extended stay there.

REFERENCES

Arnaud, M., and Raymond, J., Iron Ionization and Recombination Rates and Ionization Equilibrium, *Astrophys. J.*, **398**, 394-406, 1992.

Arnaud, M., and Rothenflug, R., An Updated Evaluation of Recombination and Ionization Rates, *Astron. Astrophys. Suppl.*, **60**, 425-457, 1985.

Cane, H. V., R. E. McGuire, and T. T. von Rosenvinge, Two Classes of Solar Energetic Particles Events Associated with Impulsive and Long-duration Soft X-ray Flares, *Astrophys. J.*, **301**, 448-459, 1986.

Dietrich, K.-G., D. H. H. Hoffmann, E. Boggasch, J. Jacoby, H. Wahl, et al., Charge State of Fast Ions in a Hydrogen Plasma, *Phys. Rev. Letters*, **69**, 3623-3626, 1992.

Kahler, S. W., N. R., Sheeley, Jr., R. A. Howard, D. J. Michels, M. J. Koomen, et al., Association between Coronal Mass Ejections and Solar Energetic Proton Events, *J. Geophys. Res.*, **89**, 9683-9693, 1984.

Kartavykh, Yu. Yu., V. M. Ostryakov, I. Yu. Stepanov, and M. Yoshimori, Stochastic Acceleration and Charge Change of Helium Ions in the Solar Flare Plasma, *Cosmic Research., Engl. Transl.*, **36**, 437-445, 1998.

Kartavykh, Yu. Yu., S. Wannawichian, D. Ruffolo, and V. M. Ostryakov, Equilibrium Charge Distributions of Energetic Heavy Ions in a Plasma, *Proc. of Regional Conference of Plasma Research in the 21st Century*, 49-53, 2001.

Kocharov, L., G. A. Kovaltsov, J. Torsti, and V. M. Ostryakov, Evaluation of Solar Energetic Fe Charge States: Effect of Proton-Impact Ionization, *Astron. Astrophys.*, **357**, 716-724, 2000.

Leske, R. A., J. R. Cummings, R. A. Mewaldt, E. C. Stone, and T. T. von Rosenvinge, Measurements of the Ionic Charge States of Solar Energetic Particles Using the Geomagnetic Field, *Astrophys. J. Lett.*, **452**, L149-152, 1995.

Luhn, A., and Hovestadt, D., Calculation of the Mean Equilibrium Charges of Energetic Ions after Passing through a Hot Plasma, *Astrophys. J.*, **317**, 852-857, 1987.

Mazzotta, P., G. Mazzitelli, S. Colafrancesco, and N. Vittorio, Ionization Balance for Optically Thin Plasmas: Rate Coefficients for All Atoms and Ions of the Elements H to Ni, *Astron. Astrophys. Suppl.*, **133**, 403-409, 1998.

Möbius, E., M. Popecki, B. Klecker, L. M. Kistler, A. Bogdanov, et al., Energy Dependence of the Ionic Charge State Distribution during the November 1997 Solar Energetic Particle Event, *Geophys. Res. Lett.*, **26**, 145-148, 1999.

Möbius, E., B. Klecker, M. A. Popecki, D. Morris, G. M. Mason, et al., Survey of Ionic Charge States of Solar Energetic Particle Events During the First Year of ACE, in ACE 2000 Symposium (AIP Conf. Proc. 528), eds. R. A. Mewaldt et al., AIP, College Park, MD, 2000.

Neuner, U., M. Ogawa, H. Kobayashi, M. Takizawa, K. Nishigori, et al., Interaction Experiments of MeV Heavy Ions with a Laser Plasma and a z-Pinch Helium Plasma, *Nucl. Instr. Meth. A*, **415**, 586-590, 1998.

Ostryakov, V. M., Yu. Yu. Kartavykh, and G. A. Kovaltsov, Energetic Spectra Formation for SCRs at the Stochastic Acceleration with Account of Coulomb Losses, *Astron. Lett., Transl. Pis'ma Astron. Zh.*, **26**, 122-128, 2000a.

Ostryakov, V. M., Yu. Yu. Kartavykh, D. Ruffolo, G. A. Kovaltsov, and L. Kocharov, Charge State Distributions of Iron in Impulsive Solar Flares: Importance of Stripping Effects, *J. Geophys. Res.*, **105**, 27315-27322, 2000b.

Pallavicini, R., S. Serio, and G. S. Vaiana, A Survey of Soft X-ray Limb Flare Images: the Relation between their Structure in the Corona and Other Physical Parameters, *Astrophys. J.*, **216**, 108-122, 1977.

Popecki, M. A., T. H. Zurbuchen, R. M. Skoug, C. W. Smith, A. B. Galvin, et al., Simultaneous High Fe Charge State Measurements by Solar Energetic Particle and Solar Wind Instruments, in ACE 2000 Symposium (AIP Conf. Proc. 528), eds. R. A. Mewaldt et al., AIP, College Park, MD, 2000.

Reames, D., C. K. Ng, and A. J. Tylka, Energy-Dependent Ionization States of Shock-Accelerated Particles in the Solar Corona, *Geophys. Res. Lett.*, **26**, 3585-3588, 1999.

Ruffolo, D., Charge States of Solar Cosmic Rays and Constraints on Acceleration Times and Coronal Transport, *Astrophys. J.*, **481**, L119-L122, 1997.

Ruffolo, D., Classification of Solar Energetic Particles, *This issue*, 2001.

Sampson, D. H., and Golden, L. B., Ionization Cross Sections with the Inclusion of Excitation-Autoionization Contributions for Ions with Five or Fewer Bound Electrons, *J. Phys. B: At. Mol. Phys.*, **14**, 903-913, 1981.

Shull, J. M., and Van Steenberg, M., The Ionization Equilibrium of Astrophysically Abundant Elements, *Astrophys. J. Suppl.*, **48**, 95-107, 1982a.

Shull, J. M., and Van Steenberg, M., Errata, *Astrophys. J. Suppl.*, **49**, 351, 1982b.

Stovpyuk, M.F., and Ostryakov, V.M., Heavy Ions from the 6 November 1997 Event: A Charge-Consistent Acceleration Model, *Sol. Phys.*, **198**, 163-167, 2001.