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The influence of non-thermal electrons on the charge states of heavy ions

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Abstract. We investigate the influence of non-thermal electrons on the formation of ionic states of heavy elements in SEP events. The equilibrium mean charge of Mg, Si and Fe for several samples of non-Maxwellian populations (power law electron beam and bi-Maxwellian distribution) were calculated. According to our estimates the anomalously high density of non-thermal electrons is required to obtain substantial difference in the mean charge of heavy ions as compared with 'pure' thermal dstribution.

1 Introduction

It is well known that impulsive and gradual events (apart from their other properties) are distinguished by the mean charge of accelerated heavy ions. For example, the mean charge of Fe in impulsive events is about 20, while in gradual it is 11-14 (Luhn et al., 1985; Luhn et al., 1987; Möbius et al., 1999; Möbius et al., 2000). Other elements (for example, Si) reveal the same tendency. Additionally, impulsive events are often accompanied by microwave type III radio bursts (Kahler, 1982; Cane and Reames, 1988a,b; Krucker et al., 1999). Such an emission is supposed to be produced by energetic non-thermal electrons moving in the solar atmosphere. As was qualitatively proposed by Miller and Vinas (1993), this non-thermal population might in turn result in the additional ionization of Fe ions up to Fe^{+20}. The present paper is devoted to the quantitative study of this problem.

The upper limit for the energetic ion mean charge is the so-called equilibrium charge attained when ion of a certain energy moves through a rather dense plasma for a long time (Luhn and Hovestadt, 1987; Kocharov et al., 2000; Ostryakov et al., 2000). This implies the balance between ionization and recombination processes. Actual mean charge of the ion lies between its thermal and equilibrium values because the acceleration and propagation times are not enough for such equilibrium to be reached. Ions are mainly ionized due to collisions with thermal electrons and protons and decrease their charge via radiative and dielectronic recombinations. In our previous papers only thermal electrons and protons were considered as an ionizing agent for a projectile (Kharchenko and Ostryakov, 1987; Kartavykh et al., 1998; Kocharov et al., 2000; Ostryakov et al., 2000). In the present paper we also take into account the existence of non-thermal electron populations and calculate in this case the equilibrium mean charge of Mg, Si and Fe ions. Bi-Maxwellian distribution and power law electron beam have been considered as examples.

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2 Equilibrium mean charge in the presence of non-thermal electrons

As processes changing the ion charge we include its stripping due to collisions with surrounding electrons and heavy particles (protons and helium), as well as recombination with background electrons. Most generally, the ionization rate can be written as:

$$S = N\int_0^\infty \upsilon\sigma f(\upsilon)d\upsilon \quad , \ \mathrm{s}^{-1}, \tag{1}$$

where υ - the relative collision velocity, σ - the corresponding cross section, N - the number density and $f(\upsilon)$ - the distribution function of ionizing particles over υ.

The electron velocity giving the main contribution to (1) (i.e., to particle ionization) can be estimated by varying the upper limit of integration in (1) over υ (the corresponding energy E_m). The energy of sharp changes in S, at which the saturation of ionization rates occurs, is just the energy under duscussion. The behaviour of these rates (based on the atomic reactions mentioned above) as a function of E_m qualitatively depends on the ratio of ionization potential (which defines the ionization cross section threshold) to a plasma temperature. Again, the integral determining the stripping rate attains its saturation just after the ionization threshold provided that the ionization potential is much higher then thermal energy (as for Fe^{+17}). On the contrary, if this threshold energy is of the order of temperature (in energy units) the ionization rate approaches its maximum value more gradually (as for Fe^{+5}). Figure 1 demonstrates that the electrons of energies ≥ 1 keV are the most important for the electron-induced ionization of highly charged thermal Fe (as well as of Mg and/or Si). Clearly, for high energy ions (more than several MeV/nucleon) the collision energy, $\sim E_i m_e/m_p$, is greater than any ionization potential (for Fe) and thermal electrons being considered at rest are able to ionize them.

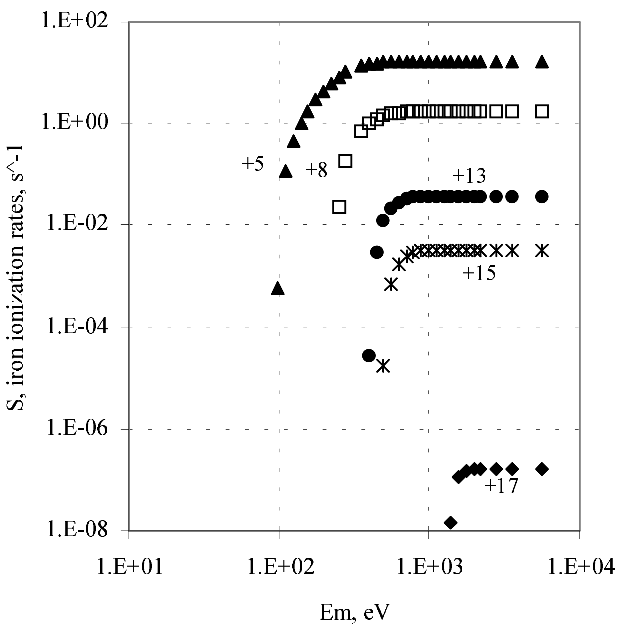

Fig. 1. The ionization rates S as a function of E_m (see text) for different iron charge states (labels at curves). The calculations were performed for thermal ions (υ_i=0).

Electrons and ions in the solar corona are assumed to obey Maxwellian distribution. However, at certain conditions (in the presence of density and/or temperature gradients) the considerable deviations from that are possible (see, e.g., Dzifcakova (1992) and references therein). Moreover, different kinds of non-thermal (non-Maxwellain) distributions are invoked to reconcile some observations (for example, solar wind ionic composition does not well agree with the measured coronal temperature). Electron distribution which consists of two Maxwellians (actually observed in the solar wind) was used by Esser and Edgar (2000) to calculate there the ionic fraction of several heavy elements. Such distribution is a composition of the core and halo electrons with different temperatures (T_c and T_h) and different concentrations (N_c and N_h). In our study we assume similar distribution for the background electrons within the acceleration region:

$$f(\upsilon) = N_c\left(\frac{m_e}{2\pi T_c}\right)^{3/2}\exp(-m_e\upsilon^2/2T_c) + N_h\left(\frac{m_e}{2\pi T_h}\right)^{3/2}\exp(-m_e\upsilon^2/2T_h)\ . \tag{2}$$

The temperature of core electrons was supposed to be 10^6 K, while for halo electrons it was chosen as 2.32×10^7 K (2 keV). The ratio of halo to core electron number densities ($\delta\equiv N_h/N_c$) was changed in our simulations at fixed temperatures of those populations. Here the ionization rates were calculated in the frame of moving ion because in this case it is possible to integrate Eq. (1) analytically over the angular variables. The subsequent integration over υ can be performed numerically making use the distribution function

$$\begin{aligned} f(\upsilon) = {} & N_c\sqrt{\frac{m_e}{2\pi T_c}}\frac{\upsilon}{\upsilon_i}\left\{\exp\left(-\frac{m_e}{2T_c}(\upsilon-\upsilon_i)^2\right) - \exp\left(-\frac{m_e}{2T_c}(\upsilon+\upsilon_i)^2\right)\right\} + \\ & N_h\sqrt{\frac{m_e}{2\pi T_h}}\frac{\upsilon}{\upsilon_i}\left\{\exp\left(-\frac{m_e}{2T_h}(\upsilon-\upsilon_i)^2\right) - \exp\left(-\frac{m_e}{2T_h}(\upsilon+\upsilon_i)^2\right)\right\} \end{aligned} \tag{3}$$

(Luhn and Hovestadt, 1987). Figure 2 and 3 show the equilibrium mean charge of energetic Mg and Fe ions for δ=0.01 and δ=0.1. For comparison, Q_{eq} for 'pure' Maxwellian distribution (it corresponds to δ=0) is also depicted. It is seen that the changes in Q_{eq} are significant (about several charge units) when the admixture of non-thermal electrons is high enough (δ=0.1). It is worth noting that the variation in halo electron temperatures (up to 5 keV) does not result in the considerable alterations in Q_{eq}.

As another kind of non-thermal electrons admixture we have considered their power law distribution (see, e.g., Fleishman and Yastrebov, 1994). It is widely accepted that the energetic electrons distributed in accordance with this law generate microwave type III radio bursts and/or hard X-ray bursts which are observed in impulsive SEP events. Similar to (2) the combined distribution function for this case can be written in the rest frame:

$$f(\upsilon) = N_0\left(\frac{m_e}{2\pi T_0}\right)^{3/2}\exp(-m_e\upsilon^2/2T_0) + N_b\frac{\xi-3}{2\pi\upsilon_0^3}\left(\frac{\upsilon_0}{\upsilon}\right)^{\xi}F(\mu)\ , \tag{4}$$

where $F(\mu)$ is a pitch-angle distribution, ξ being apparently varied from 3.3 to 6.0. In the present work we consider mean value ξ=4 supposing the existence of such energetic electrons in the energy range from 2 keV up to 20 keV, υ_0 being the lower edge of the distribution function (which corresponds to 2 keV). As to the pitch-angle distribution,

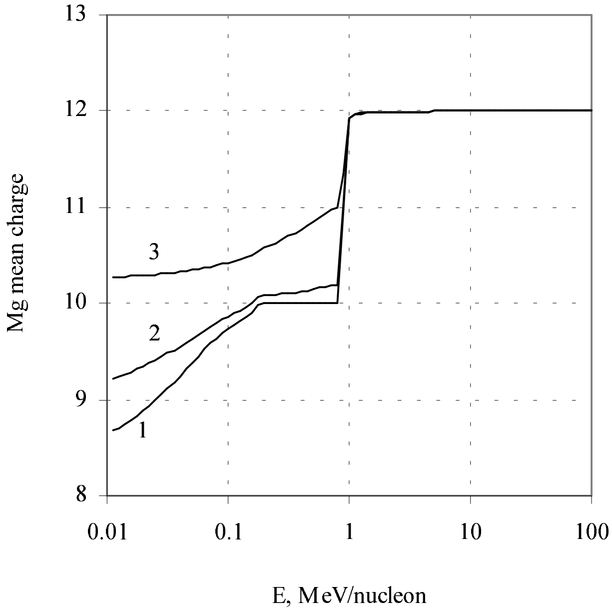

Fig. 2. Equilibrium mean charge of Mg in the case of 1 - “pure” Maxwellian plasma, δ=0; 2 - bi-Maxwellian plasma, δ=0.01; 3 – same as 2 but for δ=0.1.

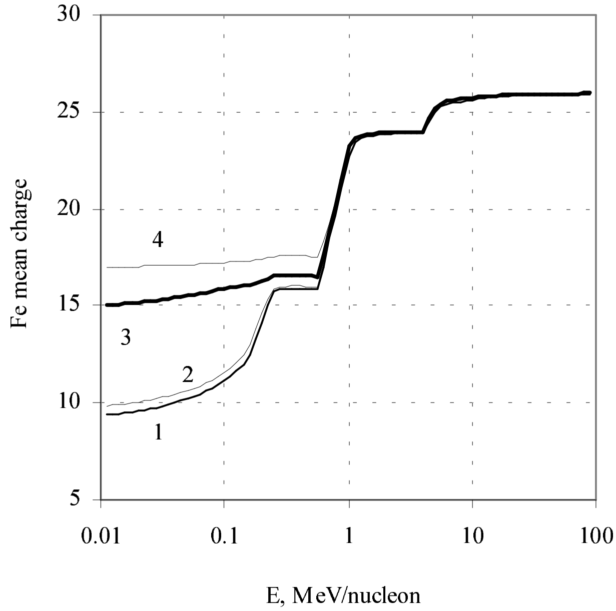

Fig. 3. Equilibrium mean charge of Fe in the case of 1 - “pure” Maxwellian plasma, δ=0; 2 – power law admixture to Maxwellian plasma, δ=0.01; 3 – bi-Maxwellian plasma, δ=0.1, 4 - same as 2 but for δ=0.1.

the characteristic time of isotropization of beamed electrons is likely much less than the characteristic time of particle acceleration in impulsive SEP events. Hence, one should consider such beamed electrons as isotropically distributed. Similar to previous case, we denote the fraction of non-thermal energetic electrons equal to $\delta = N_b/N_0$. Note also that for beamed electrons the calculations of integral (1) were performed numerically over the relative collision velocity both in angular and energy spaces. Figure 3 shows the equilibrium mean charge of Fe for several values of δ. It is clearly seen that the same inference can be made regarding the influence of this kind of non-Maxwellian electron admixture. Namely, it becomes significant if the number density of non-thermal electrons is high enough (δ ~ 0.1).

3 Discussion and conclusion

As was shown in previous Section, the equilibrium mean charge of ions moving through non-thermal plasma differs noticeably from that of ‘pure’ Maxwellian case if the admixture of energetic electrons is high enough (δ ~ 0.1). Let us briefly discuss the possibility of the presence of such non-thermal particle populations in solar flare plasmas.

There are numerous papers evaluating the number density of non-thermal electrons based on the observed microwave type III radio bursts and/or hard X-ray emission. For instance, in the paper of Huang (2000) the generation of type III radio bursts was analysed. Author’s estimates yield the ratio of non-thermal electrons producing this kind of emission to thermal ones to be about 10^{-6}. Even smaller magnitude has been obtained in the paper of Mel’nik et al. (1999).

Slightly more “optimistic” estimates can be derived on the basis of hard X-ray emissions observed in solar flares. For example, according to Aschwanden et al. (1995) the total number of electrons in beams was shown to be 4×10^{28} – 10^{33}. If we assume that impulsive events occupy the plasma volume about 10^{26} – 10^{27} cm^3 (Pallavicini et al., 1977) with the number density 10^9 cm^{-3} or higher, then the maximum ratio of energetic to thermal electrons is to be 10^{-2} (δ~10^{-6} – 10^{-2}). The same conclusion on the value of δ can apparently be drawn from direct measurements of beamed electrons in the interplanetary space.

At the same time Miller and Vinas (1993) have estimated the number density of non-thermal electrons based on the observed ^{3}He fluxes escaping from the sun. The obtained ratio δ was shown to be very high, about 0.1. This in turn would require nonlinear approaches in plasma dynamics.

Finally, if solar flare plasma has low or moderate admixture to a Maxwellian background this has a minor effect on the charge states of heavy ions. As a result, it is not enough to explain the observed high charge states of heavy elements. To our mind, the photoionization in most powerful solar flares is more favourable.

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