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Study of charge behavior during solar particle acceleration

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Resumen

Con objeto de reproducir la evolución con energía de los estados de carga observacionales de los iones energéticos solares, hemos desarrollado un modelo en el que los estados de carga se definen en la fuente durante el proceso de aceleración de los iones solares. El intercambio de carga entre iones y la materia local se estudia en base a secciones eficaces de alta energía para pérdida y captura electrónica. El modelo se desarrolla bajo dos enfoques diferentes. Aplicamos el modelo a datos observacionales de estados de carga para la mayor parte los eventos publicados en la literatura. Analizamos y discutimos nuestros resultados e implicaciones dentro del contexto de otros modelos: concluimos que nuestro modelo analítico da mayor información de la física involucrada que las simulaciones numéricas desarrollada por otros autores.

Palabras clave: PES, evolución de estados de carga, aceleración.

Abstract

In order to explain the evolution with energy of the charge state of solar par-ticles we have developed a model where charge states are defined at the source during the particle acceleration process. Charge-interchange processes between the accelerated ions and local matter are considered on basis of electron loss and capture cross-sections at high energies. The model is worked out under two different approaches. We apply the model to observational data of charge states of most of particle events published in the literature. We discuss our results and implications within the frame of other existing models: we conclude that our analytical model gives more information of the underlying physics than the nu-merical simulations developed by other authors.

Key words: SEP, charge states evolution, ecceleration.

Introduction

It is well known in several branches of physics that the knowledge of charge states of energetic ions, and their evolution with energy during the passage of ions through matter is a very important factor for the study of particle interaction with matter and E.M. fields. The scope of applications was described in Pérez-Peraza and Alvarez (1990). As stated recently by Kaganovich *et al*. (2006) charge interchange collisions play an important role in many applications such as heavy ion inertial fusion, collisional and radiative processes in the Earth´s upper atmosphere, ion-beam lifetimes in accelerators, atomic spectroscopy, ion stopping matter and a wide range of problems in atomic physics. The behavior of charge states in connection with the energy and charge spectra is of particular interest: chemical and isotopic abundances of the accelerated ions are highly dependent on the charge states during their acceleration, escape from the source and propagation at the Sun and in interplanetary space, and so is the emitted radiation when the accelerated ions capture electrons of the medium (Pérez-Peraza *et al*., 1989; Pérez-Peraza and Gallegos-Cruz.,1998). The present knowledge of Effective Charge, qeff (or mean equilibrium charge state) is associated with experimental results of Stopping Power of ions in atomic matter, which can be adequately described by several semi-empirical smooth functions of ion velocity and nuclear charge (Z). These kinds of relations refer to experiments of ion deceleration toward stopping in atomic matter. All those expres-sions do not consider the temperature of the medium (T). Therefore, for astrophysical applications, these kinds of ex-pressions are usually extrapolated by introducing T, commonly by means of a thermal velocity. All those semi-empirical relations, though useful for some purposes, do not give enough information about the underlying physics. Strictly, these kinds of expressions are not valid when ions instead of being stopped are undergoing an acceleration process while interacting with the local matter, as is the case in Cosmic Ray sources. In fact, because the energy gain rate is of a different nature (electromagnetic) from the Stopping Power rate (atomic), the evolution of particle charge as a function of energy must be derived taking into account the kind of energy change process involved. Since there are no data of particle charge evolution of ions moving through plasmas, either during stopping or acceleration, a big amount of theoretical work has been done in relation with the charge state evolution of solar flare particles. We analyze here one of the models developed at this regard, namely hereafter the High Energy Cross-Sections model (HECSM), and discuss it within the frame of other models.

The Model of Charge Evolution

It is widely believed that the simplest description of a physical phenomenon is usually the best approach to understand the underlying physics involved in the phenomenon. With this aim, we have developed an analytical expression for the effective charge qeff of the accelerated particles which gives us information about the acceleration mechanism and its efficiency, the acceleration time, the source parameters, and indirectly the nature of the charge interchange cross-sections.

In the model presented here, it is assumed that resonant ions with MHD turbulence are accelerated from the thermal background, and while being accelerated they interact with local matter, such that under specific conditions, they undergo charge interchange with the electrons, ions and atoms of the source. Once particles escape from the acceleration volume, no important charge transfer is established out of the source. The model is analyzed from two different approaches:

The simplified approach

Derivation of this simplified approach was given in Pérez-Peraza and Alvarez-Madrigal (1990a, 1990b). It is assumed an ion (A, Z) of velocity v(E) which is being accelerated while interacting with a flux of targets nv_R which are moving with a relative velocity v_R among them. For T > 2.7 x 10^4 K we use electrons as targets. By simple physical arguments it was obtained the following expression for the effective charge:

$$q^*eff = q_0 + n\, v_R t_a\, [\sigma_l(v_R) - \sigma_c(v_R)] \qquad (1)$$

With q_0 as the local thermal charge of the ion in consideration, determined by the local temperature of the medium of density (n) at the source; t_a is the acceleration time of mechanism of efficiency α (s^{-1}) (here we use Fermi-type acceleration); σ_l and σ_c are the electron loss and electron capture (Coulomb plus radiative) cross-sections respectively (which depend majorly on the ion projectile parameters).

The general approach

This is in principle the global approach to the problem, which assumes that two populations are interacting: on one hand, a population which is not in thermodynamic equilibrium (TE), namely the accelerated projectile ions, with a typical solar particle spectrum (either an inverse potential law, or an exponential one), and on the other hand a population in TE, namely the thermal targets, with a Maxwell type velocity. The evolution with energy of the ions charge during acceleration under this approach is expressed in the frame of the plasma. In order to take into account all the projectiles, one takes the integral of the solar energetic particles spectrum which gives the number of particles in a relative velocity interval [j, j+1], that is:

$$N_j(v_R) = \int_{v_{R_{th}}+j\Delta v_R}^{v_{R_{th}}+(j+1)\Delta v_R} J_j(v_R)\,dv_R \qquad (2)$$

Δv_R is a velocity increase that is defined as follows:

$$\Delta v_R = \frac{v_{R_{max}} - v_{R_{th}}}{i}$$

i is the desired number of velocity intervals, $v_{R_{th}}$ is the ion's thermal relative velocity and $v_{R_{max}}$ is the maximum relative velocity that corresponds to the high energy cutoff of the accelerated ions (Heristchi *et al.*, 1976), that we are arbitrarily taking as 100 MeV/n.

The relative velocity is the one defined by Einstein's special relativity, therefore:

$$v_{R_{th}} = \frac{v_{th/elec} + v_{th/ion}}{1+\frac{(v_{th/elec})(v_{th/ion})}{c^2}} \quad \text{and} \quad v_{R_{max}} = \frac{v_{th/elec} + v_{cutoff/ion}}{1+\frac{(v_{th/elec})(v_{tcutoff/ion})}{c^2}}$$

Where $v_{th/elec}$ is the electron's thermal velocity, $v_{th/ion}$ is the ion's thermal velocity and $v_{cutoff/ion}$ is the ion's velocity that corresponds in this work to 100 MeV/n.

Next, we proceed to calculate (using the simplified approach) the total charge state for the particles within the interval [j, j+1]

$$N_j q_j = \left[\int_{\nu_{R_{th}}+j\Delta\nu_R}^{\nu_{R_{th}}+(j+1)\Delta\nu_R} J(\nu_R)d\nu_R\right]\left[q_0 + n\nu_{R_j} t\left(\sigma_l\left(\nu_{R_j}\right)-\left(\sigma_c\left(\nu_{R_j}\right)\right)\right)\right] \quad (3)$$

Where $\nu_{R_j} = \nu_{R_{th}} + \frac{(2j+1)\Delta\nu}{2}$ is the ion's average relative velocity at the [j, j+1] interval. We now have the total charge state of that velocity interval. In order to have an average charge, one requires at least 2 values, so we will take the total charge state of the next velocity band [j+1, j+2], this is

$$N_{j+1}q_{j+1} = \left[\int_{\nu_{R_{th}}+(j+1)\Delta\nu_R}^{\nu_{R_{th}}+(j+2)\Delta\nu_R} J(\nu_R)d\nu_R\right]\left[q_0 + n\nu_{R_{j+1}} t\left(\sigma_l\left(\nu_{R_{j+1}}\right) - \left(\sigma_c\left(\nu_{R_{j+1}}\right)\right)\right)\right] \quad (4)$$

We have now the average charge state of the ions in the interval of velocities [j, j+2]. Our final charge state equation in the velocity interval [j, j+2] is expressed as follows:

$$q_{eff_{j,j+2}} = \frac{N_j q_j + N_{j+1}q_{j+1}}{N_j + N_{j+1}} = \left\{\left[\int_{\nu_{R_{th}}+j\Delta\nu_R}^{\nu_{R_{th}}+(j+1)\Delta\nu_R} J(\nu_R)d\nu_R\right]\left[q_0 + n\nu_{R_j} t\left(\sigma_l\left(\nu_{R_j}\right) - \sigma_c\left(\nu_{R_j}\right)\right)\right] + \left[\int_{\nu_{R_{th}}+(j+1)\Delta\nu_R}^{\nu_{R_{th}}+(j+2)\Delta\nu_R} J(\nu_R)d\nu_R\right]\left[q_0 + n\nu_{R_{j+1}} t\left(\sigma_l\left(\nu_{R_{j+1}}\right) - \sigma_c\left(\nu_{R_{j+1}}\right)\right)\right]\right\} \Big/ \int_{\nu_{R_{th}}+j\Delta\nu_R}^{\nu_{R_{th}}+(j+2)\Delta\nu_R} J(\nu_R)d\nu_R \quad (5)$$

This expression only estimates the average charge value in one interval of velocities. To obtain the average charge state per velocity interval we make the succession:

$$<q_{eff}(\nu)> = <q_{eff_{0,2}}>, <q_{eff_{2,4}}>, <q_{eff_{4,6}}>, \ldots, <q_{eff_{j,j+2}}>, \ldots, <q_{eff_{i-4,i-2}}> \quad (6)$$

Where j = 0, 1, 2, …, i-2. It can be seen from (5) that for j = 0, our starting velocity is $\nu_{R_{th}}$ whereas for j = (i - 2), our final velocity is $\nu_{R_{max}}$. Each one of these values, allows us to construct the graphic that expresses the evolution of the aver-age charge state as the energy increases. Also, it is well known that as the number of intervals increases, so does the precision of our results. The charge state value $<q_{eff_{0,2}}>$ is retro-fed when calculating $<q_{eff_{2,4}}>$ and so on in order to preserve the evolving nature of the equation 1.

It should be noted that we avoid in equation 4 the Maxwellian distribution, since it is well known that this distribution does not correspond to the nature of the high energy ions that are being accelerated. Besides, it is well known (e.g. Savéliev, 1982) that 70.7% of particles have a velocity in the range 0.5-1.5 times the most probable velocity, ν_{mp}; those with v > 3 vmp, and v > 5 ν_{mp} represent only the 0.04% and 8 x 10^{-9}% respectively, and since our integrals are limited to the range ($\nu_{th/ion} \rightarrow \nu_{cutoff/ion}$) the number of particles with $v_{targets} \approx \nu_{mp}$ is still much higher.

$J(V_R)$ is the energy spectrum of the accelerated ions: we examine here 3 possibilities: (i) $J(\nu_R) = N_0E^{-\gamma}$,

(ii) $J(\nu_R) = N_0E^{-\gamma}\exp(-E/E_0)$ and

(iii) $J(\nu_R) = N_0\exp(-E/E_0)$.

It can be appreciated that (1) is a completely analytic expression. In particular, this approach has the advantage that given a temperature (T) and a density (n), the only free parameter is the acceleration efficiency (α) which appears in the acceleration time (t_a), whereas equation 5 has an extra free parameter, either the index γ or the characteristic value E_0 of the spectrum. It can be appreciated that the evolution of ion charge depends basically from the balance between the cross-sections σ_l and σ_c. Results derived from equation 1 were published in Pérez-Peraza and Alvarez-Madrigal (1990); Pérez-Peraza *et al.* (1999); Rodríguez-Frías *et al.* (2000, 2001a, 2001b, 2002) y Peral et al. (2002).

Charge interchange cross-sections

Intensive studies of electron capture and loss cross-sections of high energy ions in atomic matter date from the 1940's: the status is periodically reviewed, among which, some of the more interesting are Betz (1972) and Kaganovich (2006).

On the basis of such cross-sections (Pérez-Peraza *et al.*,1983, 1985) the criteria for the establishment of charge changing process of heavy ions with the local matter was developed, when ions are undergoing acceleration and coulomb energy losses at the source. That was done for several acceleration mechanisms, and it was found that depending on the mechanism, and its acceleration efficiency, as well as the temperature and density of the medium, either both processes electron capture and loss occur, or one of them may be inhibited: electron capture at high energies, or electron loss at low energies, or even there can be situations where ions do not undergo any charge interchange in the source, as for instance when acceleration is very fast in a relatively diluted medium with an open field lines topology in the acceleration volume.

Given the condition $\alpha > \alpha_c$ (where α is the acceleration efficiency and αc is related to the Coulomb barrier), such establishment depends on the relation between their mean flight times for acceleration and for charge-changing processes, i.e. the mean free path for acceleration λ compared with that of the atomic process λ_c, λ_p: it may occur that $\lambda > \lambda_c$ while $\lambda << \lambda_p$ or vice versa, in such a way that in the case that only electron capture is established, ions in a cold plasma may eventually become neutral and get lost from the accelerated flux. Since $t_a \sim 1/\alpha$, then if α is small t_a is long enough for charge changing processes to be established, but if the efficiency is very high, t_a is quite short for such establishment, and then one or two of the atomic processes could be inhibited. -Therefore, the establishment of charge changing processes is very sensitive to the corresponding cross-sections.-

Unfortunately, there is not, to the best of our knowledge, experimental cross-sections of high energy ions in plasmas, as in atomic matter. Due to the lack of experimental data one is obliged to make some assumptions: because the high energy ions interact with the coronal thermal plasma, people usually recur to the cross-sections of equilibrium ionization fractions in the coronal plasma (e.g. Jordan, 1969; Jain and Narain, 1978; Arnaud and Raymond, 1992). However, such cross-sections are developed for plasma components that are in thermodynamic equilibrium (TE) with a well defined Maxwellian type spectrum, whereas the energetic ions projectiles interacting with the thermal targets are out of TE, with a non-thermal spectrum. Then, it is not clear why such thermal cross-sections may be extrapolated to a high energy population (Luhn and Hovestadt, 1987; Kocharov *et al.*, 2000, 2001). Besides, it is well known that the measured distribution of charge states of solar ions is not representative of the equilibrium charge distribution of thermal plasma, defined by the temperature, but rather of the amount of traversed matter in the source and its environment.

Another option was developed in Pérez-Peraza *et al.* (1983, 1985) by applying the cross-sections of high energy particles in atomic matter to plasmas, even at energies lower than the thermal energy of electrons, provided the ions are undergoing an electromagnetic acceleration process. Therefore, finite-temperature cross-sections were derived in those works by introducing, a relative velocity v_R between the projectile and the thermal targets (electrons, protons and atoms of Hydrogen) (see Figs. in Pérez-Peraza *et al.*, 1985 where σ_l, σ_{cc} and σ_{cr} are the electron loss, coulomb capture and radiative capture cross-sections, corresponding respectively to ionization, recombination and radiative recombination in thermal jargon).

Analysis and results

Values of the local thermal charge states $q_0(T)$ for each ion species at the beginning of the acceleration were taken from Arnaud and Raymond (1992). Ecuations 1-6 are coupled to the criteria of charge interchange: at each energy value it is tested if both processes capture and loss are occurring, or only one of them, or even none of them. In the later case $q^*_{eff} = q_0$.

For testing our model predictions, we proceeded here to fit the three approaches of the model equations 1-6 to data of mean charge state of ions (mostly iron) that has been published since 1995.

Regarding data on mean ionic charge states, according to Klecker *et al.* (2006), up to the decade of the 80's it was conventional accepted that mean ionic charge of heavy ions was compatible with coronal temperatures in the range $1–2\times10^6$ K. Later the large ionic charge of heavy ions in impulsive SEP events was interpreted as being due to high temperatures of $\sim10^7$ K at the flare site, whereas the ionic charge states in gradual SEP events were assumed to be similar to those of the solar wind. However, new results with advanced instrumentation from several missions (e.g. Wind, SAMPEX, SOHO, SEPICA onboard ACE) have shown that this picture was oversimplified. One of the key accomplishments with the new generation of instruments was the extension of ionic charge measurements over a wide energy range and the much improved sensitivity of the instrumentation (Klecker *et al.*, 2006).

It is worth noting here, that such oversimplification was pointed out long ago as a natural implication of the criteria for the establishment of charge interchange developed in Pérez-Peraza *et al.*(1983, 1985): as mentioned before it was found that depending on several factors during ion acceleration, charge equilibrium could be established, while in other circunstances electron capture can be inhibited, so that ions acquire faster a high mean charge than it is expected from charge equilibrium, or a lower mean charge at a given energy when the conditions during acceleration are such that electron loss is inhibited; additionally, under some conditions charge interchange does not occur at all, and ions keep their local charge q_0(T) from the corona ~10^6 K), or from the flare region (~10^7 K) as it is sometimes seen in some SEP. Concretely, in those previous papers we had advanced the thesis that the ionic charges are most frequently not defined uniquely by ionization equilibrium of a collisionally dominated plasma at the source matter temperature, as used to be claimed in the literature. This is supported by the fact than in many SEP events an energy dependence of the ionic charge states is observed with a large event-to-event variability (Oetliker *et al.*, 1997; Mazur *et al.*, 1999).

Furthermore, if one rejects our primitive hypothesis that charge states are defined by the amount of traversed matter in the source and its close environment, and it were assumed that it is only determined by ionization equilibrium at the source temperature, hence since flares occur in a wide range of heliolongitudes an heliolatitudes from event to event, it is natural to assume also a high variability in coronal and chromospheric depths. So, there is no reason to assume that charge states are systematically a kind of samples of the coronal matter at an altitude where T~ 1–2×10^6 K or the flare site (T~ 10^7 K), or even to recur to multi-sources at different altitudes in a single event to explain high charge state values and the energy dependence of charge states. It should be mentioned, however, that acceleration of particle flare remnants by CME driven coronal and interplanetary shocks could lead to observe high energy ions with charge states which correspond to lower energy ions. A very interesting model was given by Mullan and Waldron (1986), where photoionization in the solar corona due to a flux of X-rays from the parent solar flares determines the charge states of the energetic ions. When the parent flare reaches ~ 10^7 K, the ionization equilibrium turns a collisionally dominated plasma into a radiatively dominated plasma, in which case a single coronal temperature allows them to describe charge states from C up to S of some events reported by Luhn *et al.* (1984). Such data is given at a fixed energy range, so that this model does not lead to evaluate the charge evolution with velocity q(v). The model predicts then, that charge state is defined before the acceleration step, which takes place out of the flare volume. Once the acceleration occurs, ions represent a sample of the temporally radiation dominated coronal plasma. Another interesting approach is given by Sollit *et al.* (2008), who give an expression to describe charge states as a function of a decay time, the SEP's power law, the ion's atomic number and a reference element. Though, they derive a nice analytical expression for the ion's charge, there is no explicit dependence on charge interchange cross-sections, so, that it can be seen as a semi-empirical analytical expression.

We thus remain within the frame of our primordial hypothesis, and only in those events where the source conditions and the acceleration process do not allow charge interchange to occur, the observed ionic charge states are real samples of those of the local source matter, where ionization equilibrium is collisional and/ or radiative dominated.

For our analysis we have chosen data of 17 events among the many published in the literature, some of which correspond to the same series of solar events. Event 1, 2, 3 (Fe), from series of 1998 to May 2000 (Möbius *et al.*, 2003), events 4, 5, 6 (Fe), from series of 1997-2000 events (Klecker *et al.*, 2000), event 7 (Fe), from the May 1, 1998 (Klecker *et al.*, 2005), events 8 (Si) from October-November 1992 (Mazur *et al.*, 1999), events 9,10, (Fe, Si respectively) event 11 November 6th 1997 (Tylka *et al.*, 2001, event 12 (Fe) from November 1st, 1992 event (Leske *et al.*, 1995; Mason *et al.*, 1995, Oetliker *et al.*, 1997), events 13-17 (Fe) from November 6th, 1997, September 30th 1998, November 6th, 1998, June 26th, 1999, July 15th 2000 respectively (Popecki, 2006).

Results of fittings are shown through Figs. 1-17 where the curves in blue correspond to approach (a) and other colors to approach (b) respectively. It can be appreciated that fits are in general quite correct for typical values of n, T and α in chromospheric and coronal associated flare conditions, though results deviate from the lowest energy point in events 14 and 15. Also it should be noted in events 13, 14, 15 that, if data of ACE/SEPICA and SOHO/STOF are fitted, then data of SAMPEX/LEICA, MAST cannot be fitted with the same set of parameters.

The best fits are obtained with both, the one-free parameter (α) approach (a), and approach (b) in the option (ii), as is illustrated in events 1, 2, 4, 13, 14, 15, 16. 17. Relatively good fittings are obtained with approach (b) in option (i), though results deviate from data in events 9 and 11 at low and high energies respectively. The worst fit is systematically obtained with approach (b) in the option (iii) as can be seen in events 1, 2, 4, 13, 14, 15, 16. 17. We have failed, however, to fit events 10 and 12, where even under extreme values of the parameters, low energy and high energy data can-not be fitted simultaneously, so, we

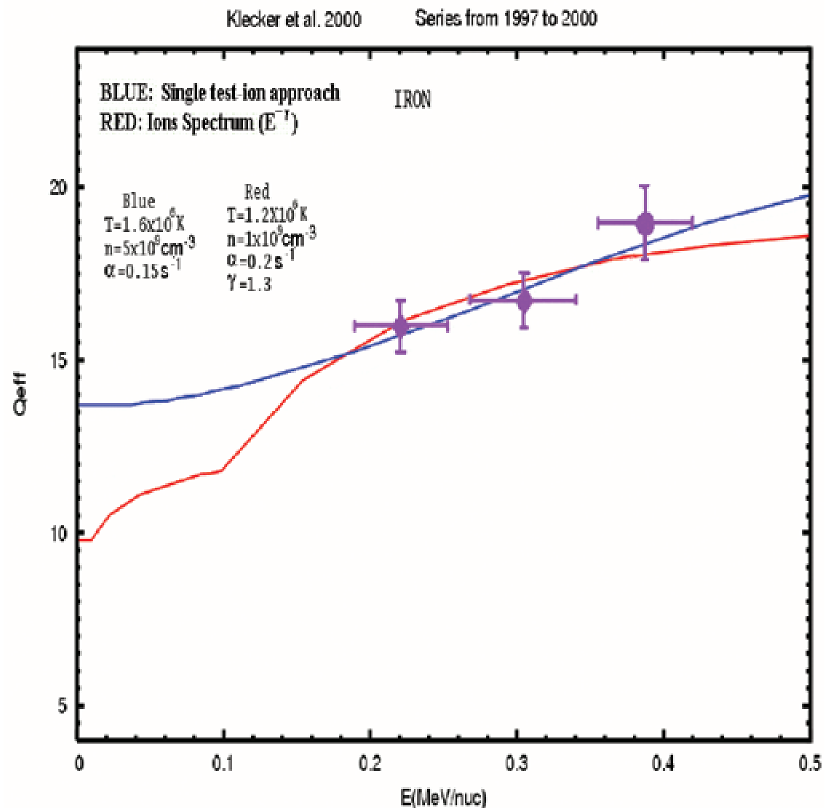

Fig. 1. Event 1: Fittings to data of (Fe) from the series of 1998 to May, 2000 events (Möbius *et al*., 2003) (event 3 of the authors).

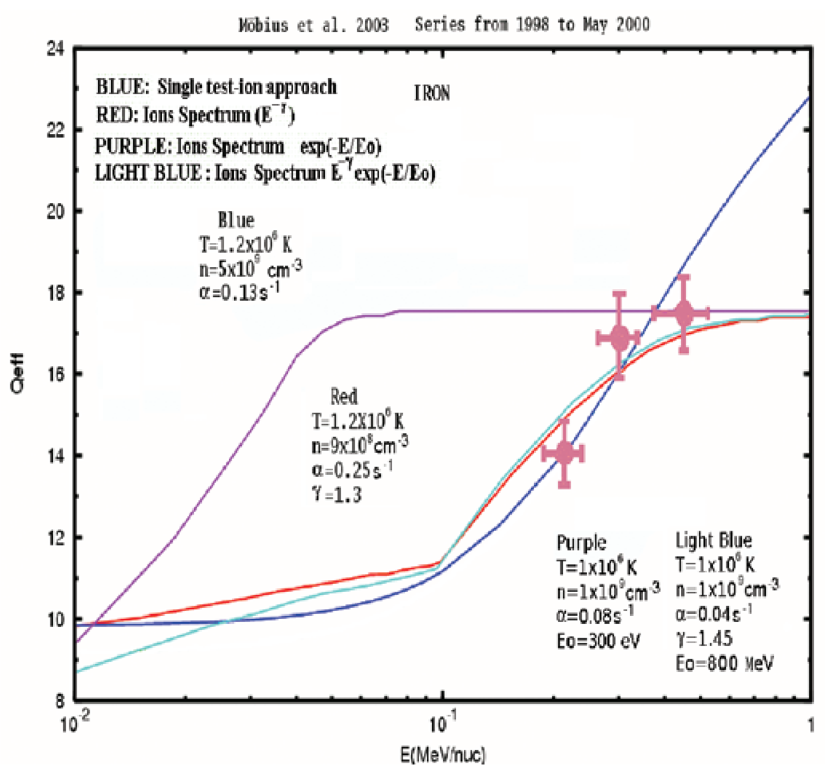

Fig. 2. Event 2: Fittings to data of (Fe) from the series of 1998 to May, 2000 events (Möbius *et al*., 2003) (event 4 of the authors).

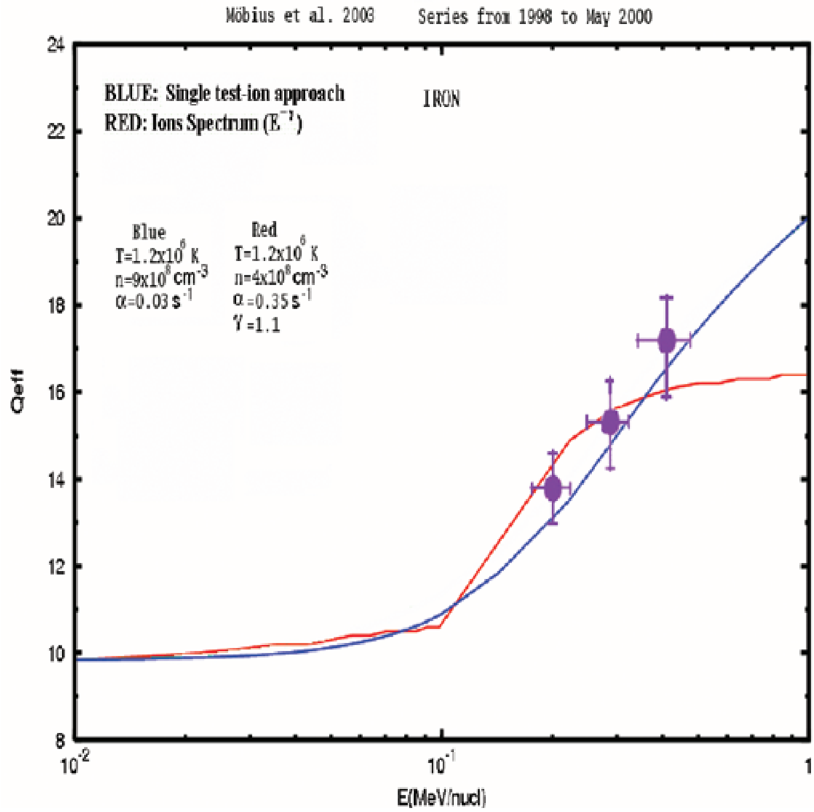

Fig. 3. Event 3: Fittings to data of (Fe) from the series of 1998 to May, 2000 events(Möbius *et al*., 2003) (event 2 of the authors).

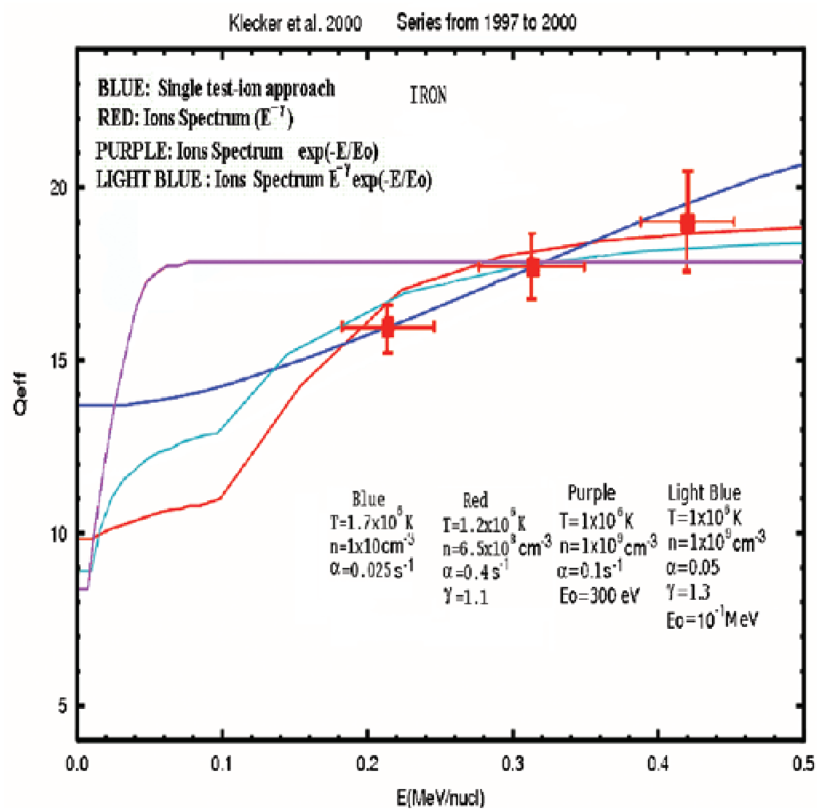

Fig. 4. Event 4: Fittings to data of (Fe) from the series of 1997 to 2000 events (Klecker *et al*., 2000) (event 27 of the authors).

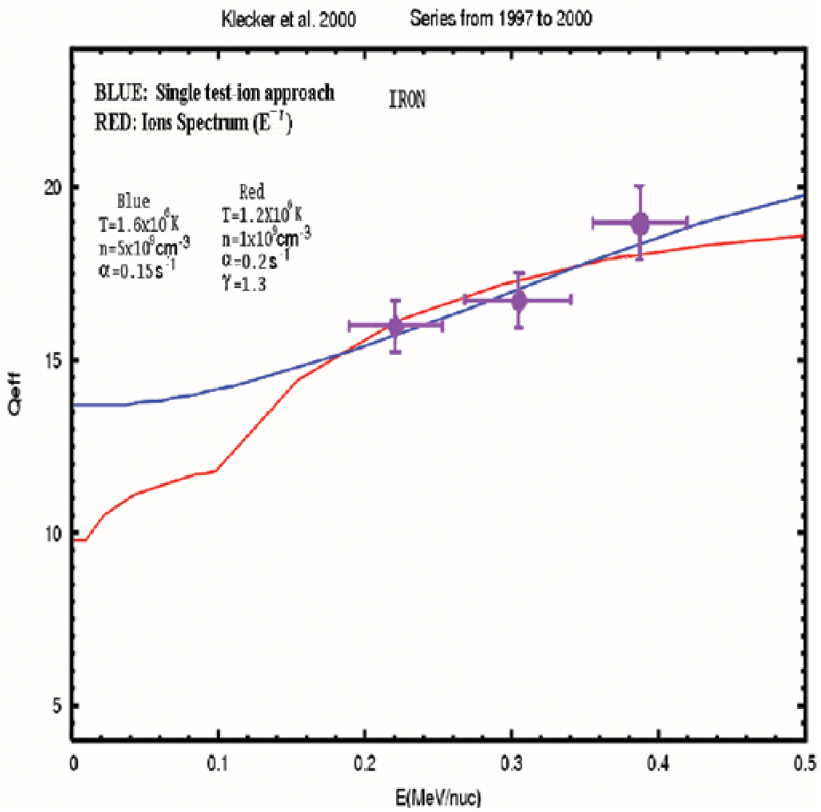

Fig. 5. Event 5: Fittings to data of (Fe) from the series of 1997 to 2000 events (Klecker *et al*., 2000) (event 31of the authors).

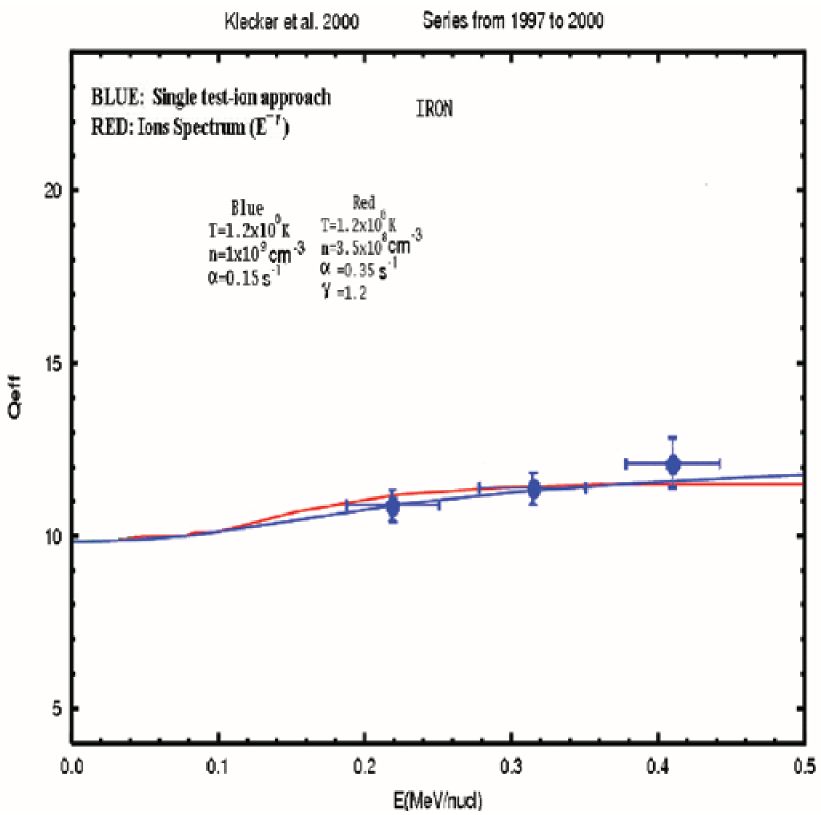

Fig. 6. Event 6: Fittings to data of (Fe) from the series of 1997 to 2000 events (Klecker *et al*., 2000) (event 18 of the authors).

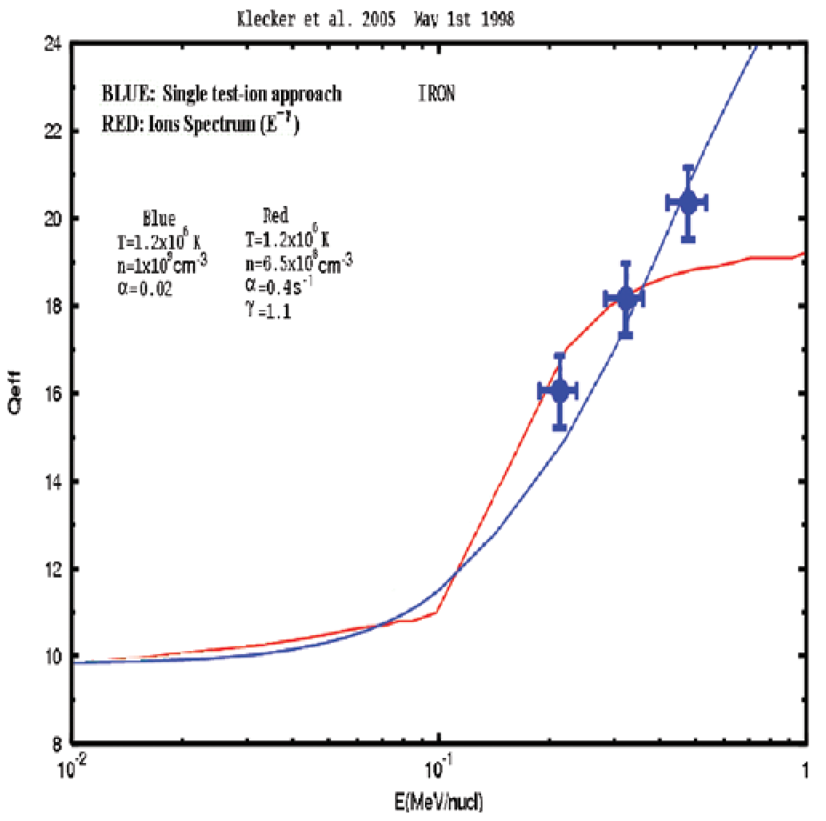

Fig. 7. Event 7: Fittings to data of (Fe) of the impulsive event of May 1st, 1998 (Klecker *et al*., 2005). (event 1 of the authors).

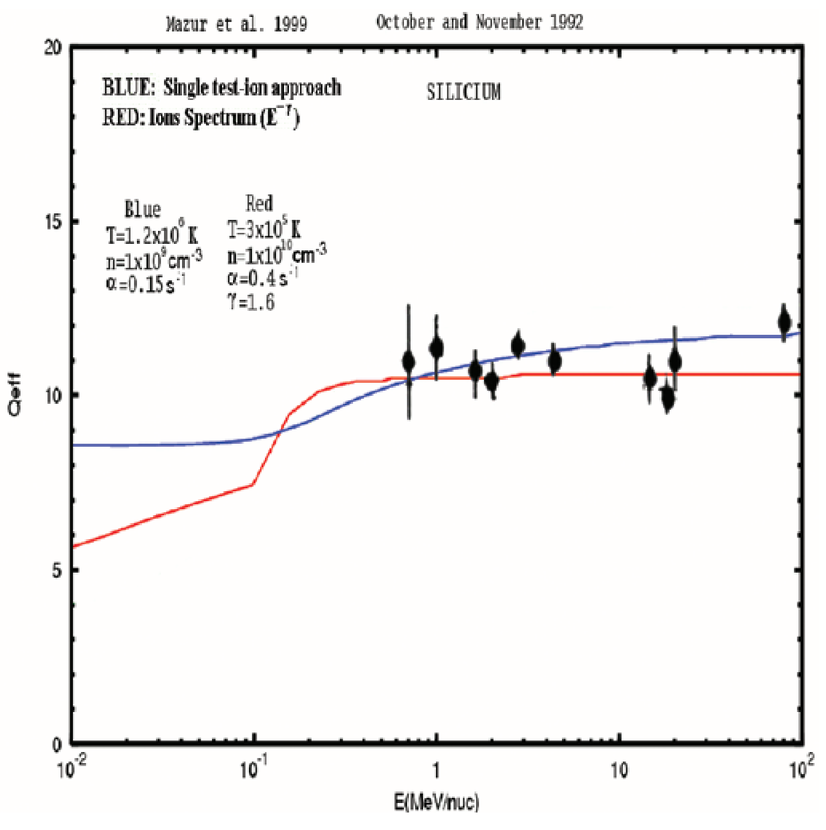

Fig. 8. Event 8: Fittings to data of (Si) from the series of October-November, 1992 events (Mazur *et al*., 1999).

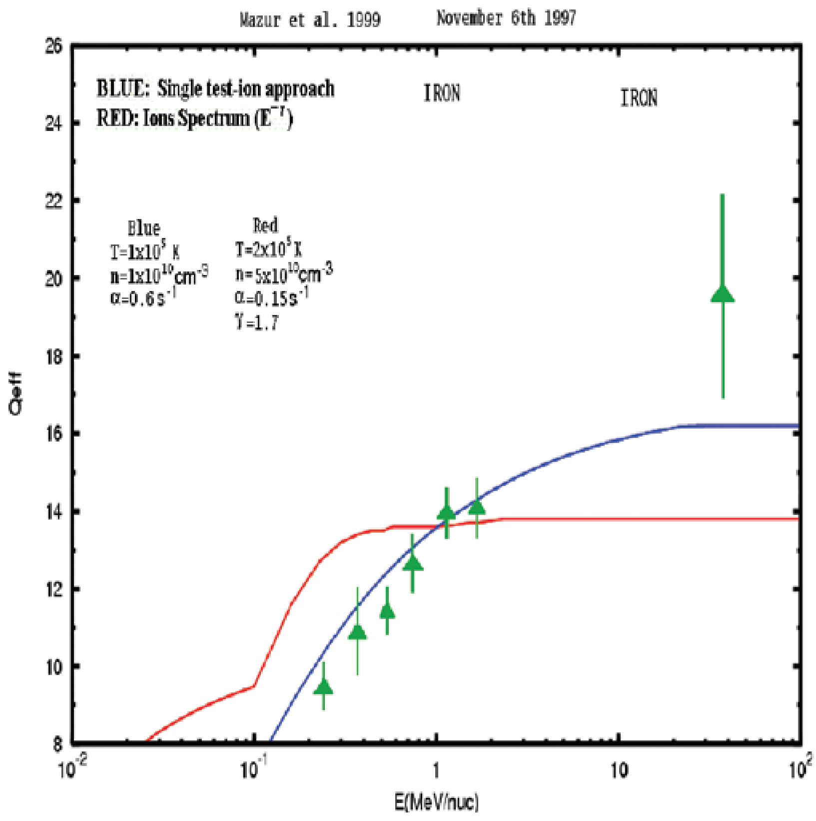

Fig. 9. Event 9: Fittings to data of (Fe) of the November 6th, 1997 event (Mazur *et al.*, 1999).

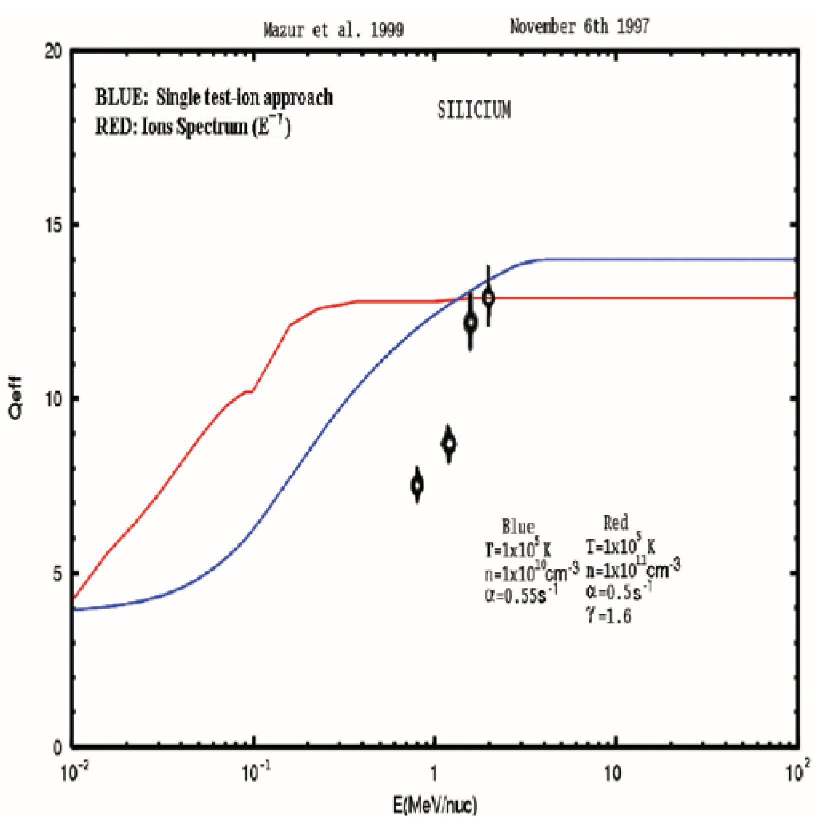

Fig. 10. Event 10: Fittings to data of (Si) of the November 6th, 1997 event (Mazur *et al.*, 1999).

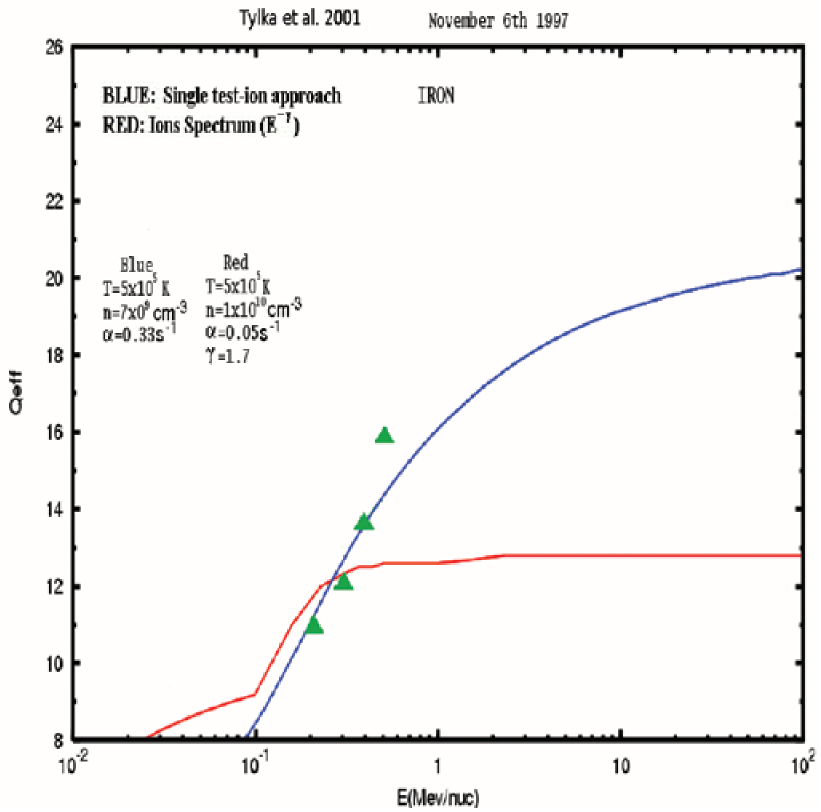

Fig. 11. Event 11: Fittings to data of (Fe) of the November 6th, 1997event (Tylka *et al*., 2001).

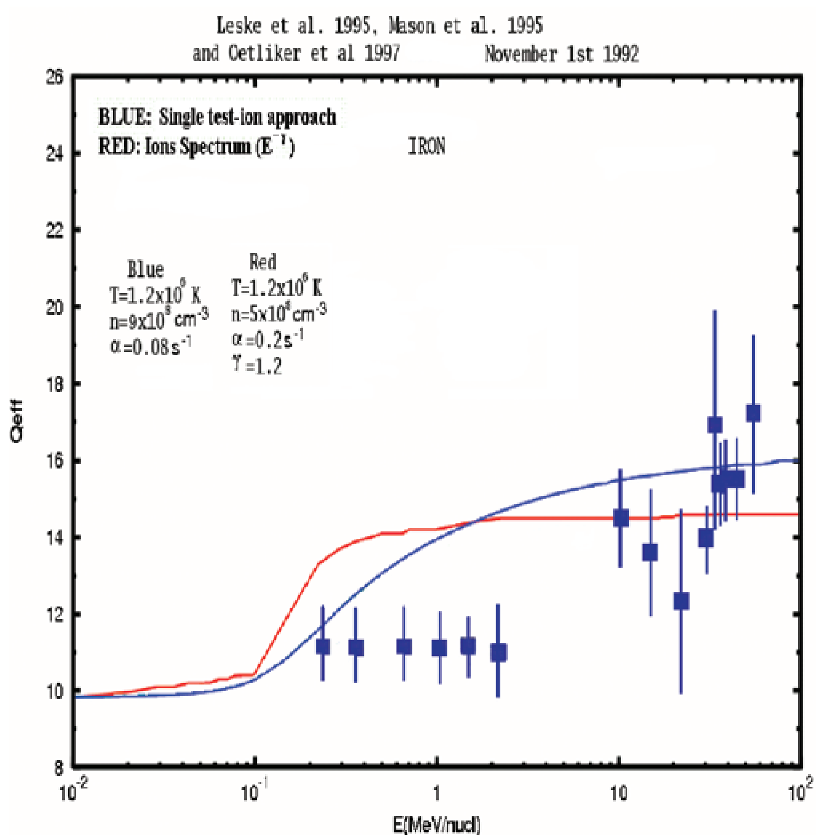

Fig. 12. Event 12: Fittings to data of (Fe) of the November 1st, 1992 event (Leske *et al*., 1995; Mason *et al*., 1995; Oetliker *et al*., 1997).

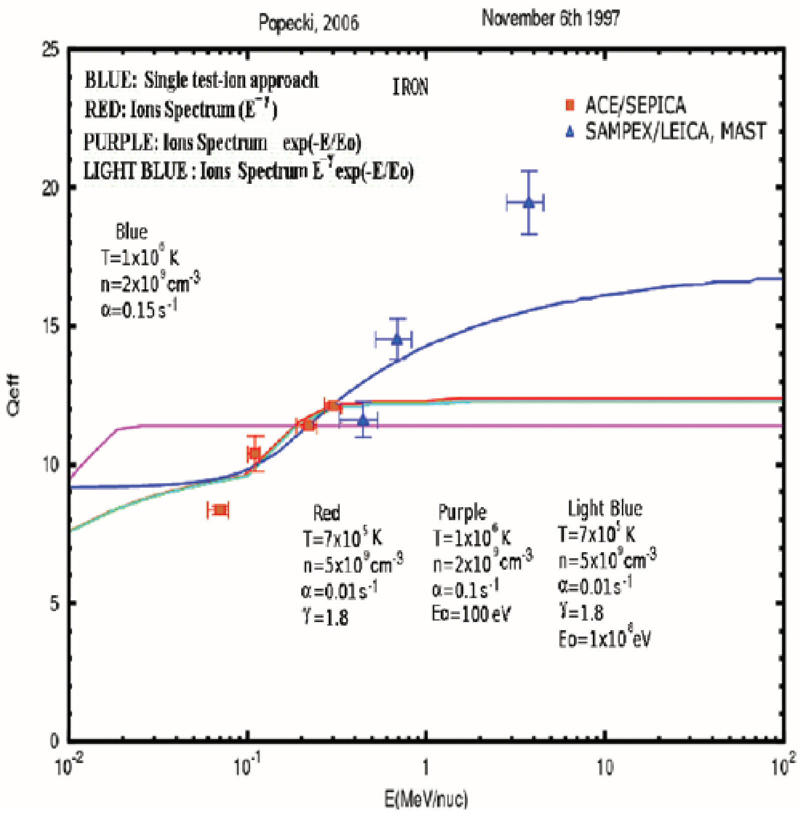

Fig. 13. Event 13: Fittings to data of (Fe) of the November 6th, 1997 gradual event (Popecki, 2006).

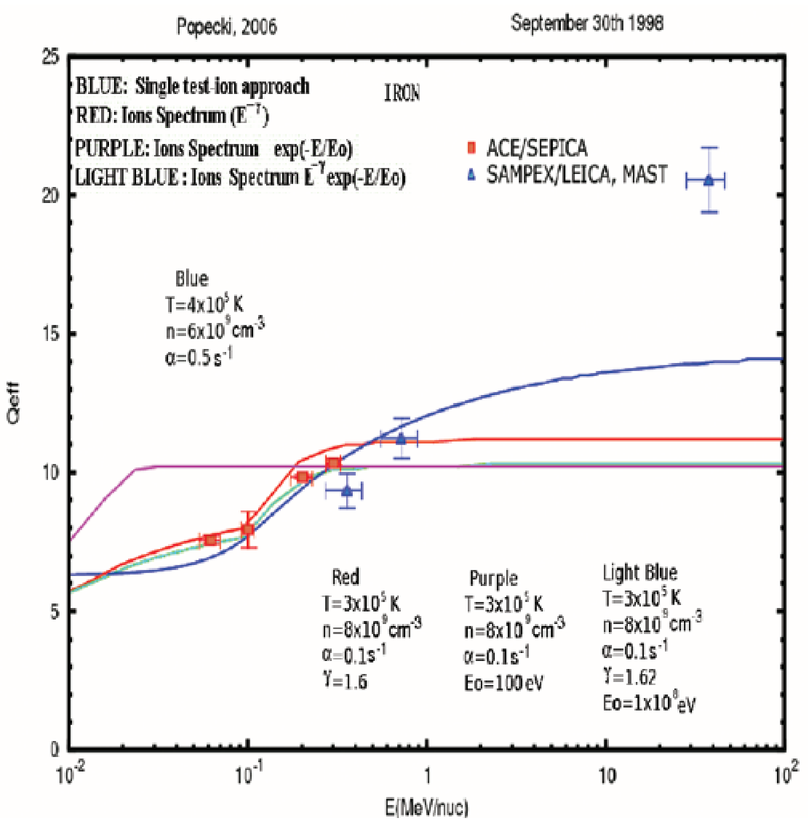

Fig. 14. Event 14: Fittings to data of (Fe) of the September 30th, 1998 gradual event (Popecki, 2006).

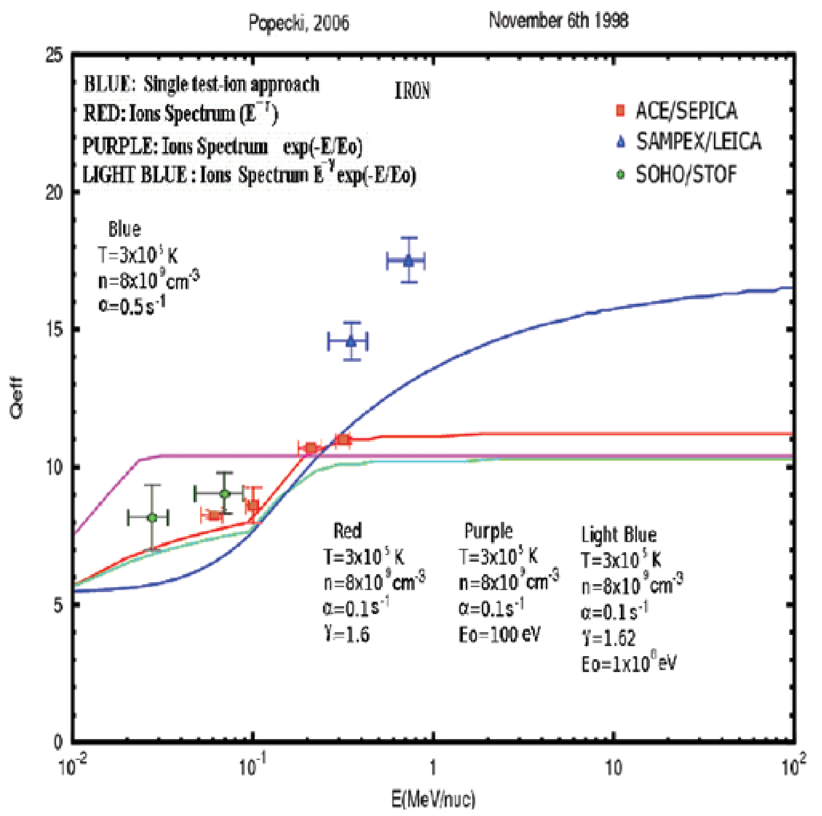

Fig. 15. Event 15: Fittings to data of (Fe) of the November 6th, 1998 event (Popecki, 2006).

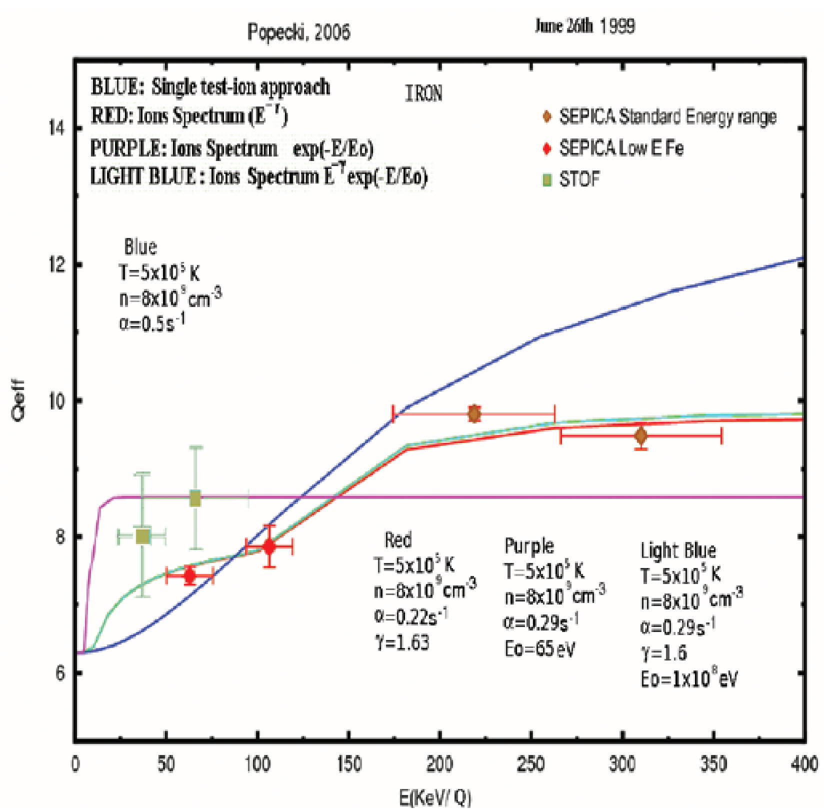

Fig. 16. Event 16: Fittings to data of (Fe) of the June 26th, 1999 event (Popecki, 2006).

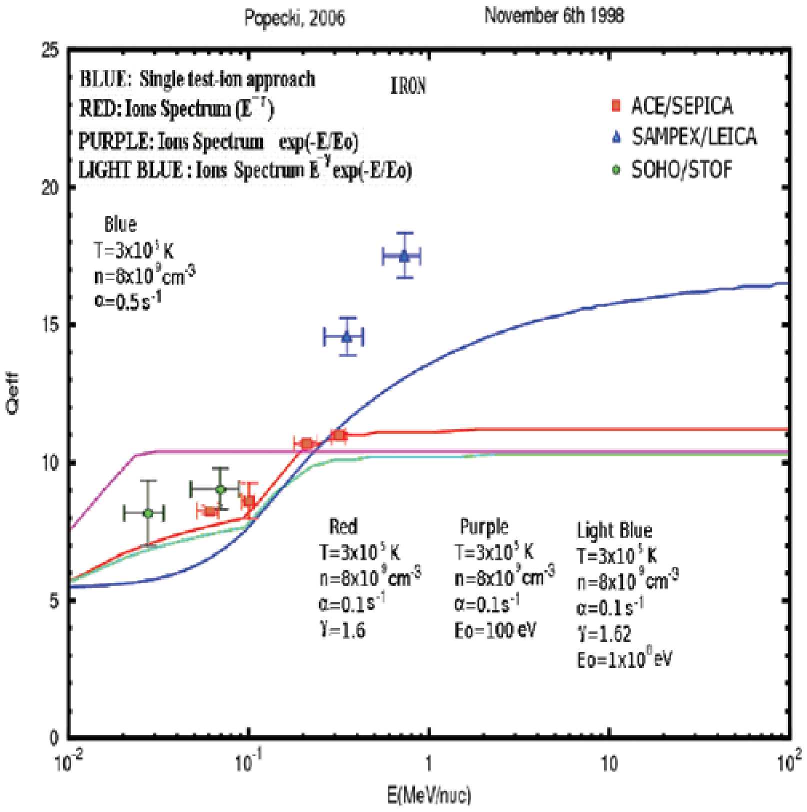

Fig. 17. Event 17: Fittings to data of (Fe) of the July 15th, 2000 event (Popecki, 2006).

have arbitrarily chosen to fit the high energy data; if low energy data in these two events would correspond to still lower energies, by a factor of $\sim 10^3$ times, we could fit data quite correctly, as was shown in Fig. 2 of Rodríguez-Frias *et al.* (2000). Besides, we cannot attribute our fail with these events to the gradual behavior of them, because most of the events that have been correctly fitted in this work, have been also classed as of gradual nature, as is the case of events 8, 9 and 11, 13-17. Nevertheless, it should be emphasized, as pointed out by Popecki (2006), that the distinction of SEP into two classes as distinguished by charge state values is not a strict categorization as comes out from observations (Oetliker *et al.*, 1997). Perhaps the involved acceleration process in these cases is not of the stochastic Fermi-type nature, or, the involved energy spectra were not of the kind used in this work. A more refined analysis is needed in these cases.

It is worth to mention that our previous results with the approach (a), in Rodríguez-Frías, *et al.* (2000, 2001), were criticized by Kovaltsov *et al.* (2002) and Kocharov *et al.* (2002), because our predictions increase with energy steeper than their numerical code (based on thermal cross-sections). This was an unfortunate criticism because data also grow steeper than their model predictions, as was emphasized by Klecker *et al.* (2005), who have shown that data of 3 of the 4 events studied with SEPICA onboard ACE are systematically above the equilibrium charge states obtained with the numerical model by Kocharov *et al.* (2000), and conclude that a more complete model including non-equilibrium conditions may perhaps be consistent with their data. At this regard, such data is quite well reproduced here, as it is illustrated for events 1 and 4 from the work of Klecker *et al.* (2005), with our the analytical approaches (curves blue of our events 7 and 3), and even event 3 is well reproduced by the approach (a) in the option (i) (the red curve). Obviously, Kovaltsov *et al.* and Kocharov *et al.* did not understand at all our model, which is based on high energy cross-sections of charge interchange (because we are dealing with high energy ions) and not on thermal cross-sections as they do. Neither have they under-stood that, according to our criteria there are situations where electron capture does not occur but only electron loss, in which case ions strip off faster than in equilibrium, or that ions can gain charge at the beginning of the acceleration, in the very low energy range when electron capture does not occur yet. They seem to ignore that, in general, an analytical approach is not only more economic to manage, but gives much more physical information than highly complex numerical codes.

Conclusions

In order to predict the charge evolution of solar energetic ions, three main kinds of models have been developed, our analytical model, the radiation dominated from X-rays model (Mullan and Waldron, 1986) and numerical codes (e.g. Kocharov *et al.*, 2000, 2001). The many advantages of our analytical model presented in this work were extensively discussed in Pérez-Peraza *et al.*, 2007, and will not be repeated here. Instead we want to emphasize that this is our first attempt to fit data, since previous works were limited to present predictions of the charge evolution behavior. We have shown that our analytical model reproduces quite well data, at least better than previous efforts with numerical simulations.

Since the model is based on pre-established criteria for particle charge interchange during acceleration (Pérez-Peraza *et al.*, 1983, 1985, 1989), we are able to obtain a relatively steep increase of charge when both electron capture and loss are established, as is seen in some SEP events, or even a steeper increase when electron capture has been inhibited, and on the other hand, a flat increase of charge when electron loss is inhibited at low energies. In such a situation, it may even occur that charge decreases at low energies up to an energy where electron loss is established and then the charge begins to grow. The level of steepness is of course determined by the acceleration efficiency in its competition with the mean free path for electron loss and capture. These features are not contemplated in any other model. Therefore, we have presented here the best fittings that have been published up to now. Nevertheless, the model is in continuous optimization, and one of the next steps will be the evaluation in our equations (1) and (5) of the effect of the cross-section of photoionization from X-rays, not for thermal matter, but for high energy particles during the stage of ion acceleration.

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