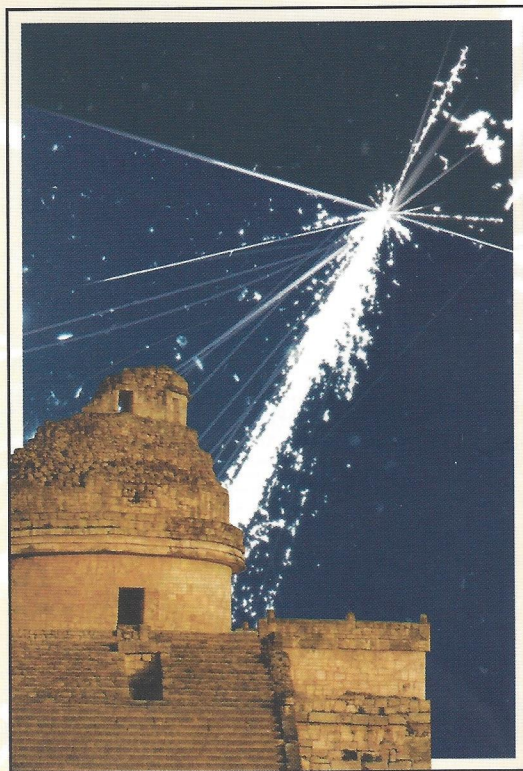


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## Energetic Solar Particle Charge Behavior During Source Acceleration

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**Abstract:** In order to explain data of solar particle charge states, two kind of models have been developed : (1) definition of the charge state during the source acceleration process, on basis to high energy electron loss and capture cross-sections. It is assumed the atomic interactions between a population which is being accelerated getting very rapidly an exponential (or inverse power law) spectrum namely the ions projectiles, and another population which is in thermodynamic equilibrium , with a Maxwellian spectrum, namely the targets. (2) Definition of the charge state during or after acceleration in the source environment, on basis to thermal ionization and recombination cross-sections. We analyze and discuss differences their implication.

### INTRODUCTION

Charge states of energetic ions and their evolution 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 [1]. It is of particular interest the behavior of charge states in connection with the energy and charge spectra: chemical abundances of the accelerated ions are highly dependent on the charge states during their acceleration and escape from the source, and so it is the emitted radiation when the accelerated ions capture electrons of the medium [2]. The present knowledge of Effective Charge,  $q_{\text{eff}}$  (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, and in principle could be applied to the transport of cosmic rays in the interstellar space. However, such expressions do not consider the temperature of the medium ( $T$ ). Therefore, for astrophysical applications, these kinds of expressions 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 different nature (E.M.) to the Stopping Power rate (atomic), the evolution of particle

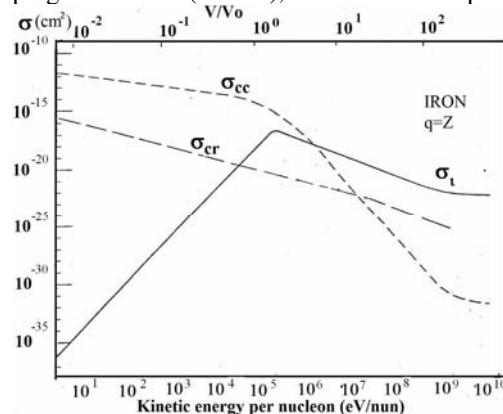


Figure 1: HECS in atomic matter

charge as a function of energy must be derived

taking into account the kind of energy change process. Since there is not data of particle charge evolution of ions moving through plasmas, either during stopping or acceleration, a big amount of theoretical work has been done, mainly 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.

### CHARGE CHANGING CROSS-SECTIONS

Long ago, in works [3,4] it was studied the criteria for the establishment of charge changing process of heavy ions with the local matter, 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, the temperature and density of the medium, either both processes electron capture and loss are established, or one of them may be inhibited, electron capture at high energies, or electron loss at low energies, or even do not undergo any charge interchange. Given the condition  $\alpha > \alpha_c$  (where  $\alpha$  is the acceleration efficiency and  $\alpha_c$  is related to the Coulomb barrier), such establishment depends on the relation between their mean flight time for acceleration and charge-changing processes, i.e. the mean free path for acceleration  $\lambda$  compared with that of the atomic process  $\lambda_c, \lambda_p$ : it may occur that  $\lambda > \lambda_c$  while  $\lambda \ll \lambda_p$  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 to the neutral state and to be lost from the accelerated flux. Since  $t_a \sim 1/\alpha$ , then if  $\alpha$  is small  $t_a$  is enough long 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 atomic processes could be inhibited. -Therefore, the establishment of charge changing processes is very sensitive to the corresponding cross-sections. - Unfortunately, there is not, at our knowledge, experimental cross-sections of high energy particles in plasmas, as it exist in atomic matter. One is obliged to do some approximations: because the high energy particles interact with the coronal thermal plasma, people usually recur to the cross-sections of equilibrium ionization fractions in the

coronal plasma [e.g. 5, 6,7]. However, such cross-sections are developed for plasma components that are in thermodynamical equilibrium (TE) with a well defined Maxwellian type spectrum, whereas the energetic ions projectiles interacting with the thermal targets are out of the TE, with a power law or exponential spectrum. Then, it is not clear why such thermal cross-sections may be extrapolated to a high energy population. 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. However, as emphasized in [8] due to the lack of experimental data several assumptions can be made: one of them, followed in [8], is precisely the use of thermal cross-sections. Another option was developed in [3,4], based also on a kind of "extrapolation", i.e. to apply 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 under an electromagnetic acceleration process. Figure 1 shows the cross-sections built as explained in [3,4] for completely stripped iron ( $q = Z$ ) in atomic hydrogen, where  $\sigma_i, \sigma_{cc}$  and  $\sigma_{cr}$  are the electron loss, coulomb capture and radiative capture respectively (ionization, recombination and radiative recombination in thermal jargon). Then, to "extrapolate" to finite temperature matter, a relative velocity between the projectile and the thermal targets (electrons and protons) was introduced (see Figs. in [4]).

### MODELS OF CHARGE EVOLUTION

Let us call (THCSM) those models that use thermal cross-sections, to differentiate of the HECSM models. As stated in [9] the problem was for the first time raised in [3], that is, historically, the HECSM have been the first to study charge evolution: either during acceleration [3,4,9] or after acceleration [10] in the source environment. In [10] it is assumed that the acceleration is so fast that any charge-changing process in a cold plasma is out of the acceleration region. This assumption confirms what we said in the previous section that depending on the acceleration efficiency and the mean free path of the atomic processes, there may be some situations where parti-

cles undergo free-flight, with no atomic interactions. While it is recognized in [10] the correct approach in [4] to the study of the charge-changing processes, however, the main difference between [10] and [3,4] is that, in these later works it is claimed that, if there are not atomic interactions during acceleration, most probably there will not be during transport in the more diluted coronal plasma while escaping through the open magnetic field lines. Both models [9, 10] are numerically solved, whereas the HECSM [3,4,11,12,13,] are analytically solved. The first models [3,4,10] use the temperature-dependent equilibrium charge states given in [6] and then move to those of [7]. The analytical model uses them only within the frame of the initial charge of ions  $q_0(T)$  at the beginning of the acceleration.

Regarding the THCSM, the pioneer work is [14], which assumes a charge-changing process after the acceleration, during particle transport in the hot coronal plasma. This work has inspired a subsequent series of works with all kind of refinements (acceleration of different types, p-impact ionization, photoionization, kappa velocity distributions, etc) [15,16,17,18,19 and so on] all of them of numerical nature.

#### THE HECSM-ESCAPE MODEL

The HECSM developed in [1,3,4] was baptized by one of us (DRF) as "Escape" [11-13], though if seems somewhat a high-flown and pompous name, it simply refers to particles escaping to the interplanetary space, without any other connotation. In fact, this is not a numerical code because our expression for  $q_{\text{eff}}$  is an analytical one. It is assumed that the simplest description of a physical phenomenon is usually the best approach to understand the underlying physics involved in the phenomenon. This is the case of our  $q_{\text{eff}}$  analytical expression which gives us information about the acceleration mechanism and its efficiency, the acceleration time, the source parameters, and indirectly the qualitative nature of the charge interchange cross-sections. In deriving such an analytical and simplified expression we had in mind several goals (1) to have a manageable expression for calculation of coulomb losses while particles are being accelerated, for evaluations of the acceleration rates and for the development of the electron pick-up spectroscopy, as a

tool in the field of plasma diagnosis [2], (2) to study the charge distribution of solar ions and (3) by probing several sets of HECS (as can be found in the literature [e.g. 24]), we pretend to infer about the nature of charge changing cross sections of high energy ions in cold and hot plasmas, from the best fitting of our analytical  $q_{\text{eff}}$  expression to data of solar charge states. We expect a qualitative approach in the very low energy domain where thermal ions have very low energy at the initial acceleration moment. Unfortunately, we have not found data on the energy-dependence of charges states for a given time in individual solar proton events, for several ions; since average through several events are not suitable for our goal. So, up to now we only had published predictions for a given set of HECS, as given in [3,4], without probing yet other HECS. One of the kindness of our HECSM is the possibility to be tested when data on charge state of very low energy ions will be available: as can be seen in Fig. 1, the capture cross-sections ions at very low energy are several orders of magnitude higher than the electron loss cross-section, such that at the beginning of the acceleration in cold plasmas electron loss can be inhibited, as explained before, so that some ions will present a fall in  $q_{\text{eff}}$ , up to a given energy where both electron capture and loss become comparable, and then  $q_{\text{eff}}$ , begins to increase toward the  $Z$  value, as can be seen in several figures in [11-13]. This kind of test is unique to this model, no other model predict this trend toward neutralization at the beginning of the acceleration. Given above the status and goals of the "escape" model, it is so futile to discuss one paper [21,22] (published twice! and may be also in some Russian reviews) whose goal is not at all clear. Authors, followers of work [14], are apparently extremely worried about the "escape" model, to invest time in a "deep" analysis, reason why we are very obliged: they are quite right when in their conclusions they discover the "escape tragedy": it does not fit the results in [7] at 0.3 Mev/n and overestimates ionic charge at  $E > 0.1$  Mev/n! Obviously, there was a total misunderstanding of the escape model, so that in turn we also want to spend space, a little one, to comment about such worries: escape has not at all as goal to be consistent with thermal approaches. The physical conception of the phenomenon is just the opposite. As explained above,

once local particles are being accelerated (becoming an out of TE population), acquiring an spectrum different from the Maxwellian, there is no reasonable need to fit thermal equilibrium charge distributions (typically in TE). Our goal is completely different, we are interested to know the behaviour of HECS in plasmas. In the measure that we do not dispose of data, our runs have been of pure predictive nature, on basis of a given set of HECS [3, 4]. Nevertheless, we show in Fig. 2 that our  $q_{\text{eff}}$  is very sensitive to the cross-sections, so that even a slight change in one of them using [20], may lead to underestimate (curves 2, 3, 4) or to overestimate (curve 5) the original one (curve 1) so severely penalized in [21,22]. With such arbitrary change of HECS, curves (3 and 4) that rise slower than curve (1), tend toward the completely stripped state at very high energies (70-90 MeV/n). So that the best one by the moment is still curve (1). Obviously, a stricter study of HECS is needed, when the required data on charge distribution of solar ions will be available.

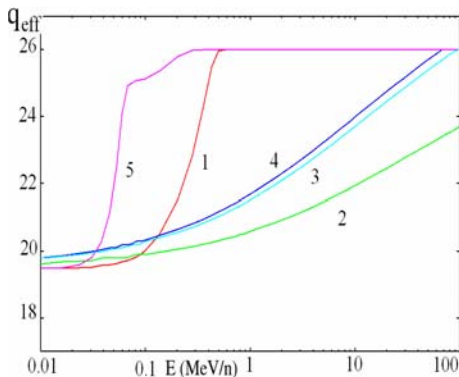


Figure 2:  $q_{\text{eff}}$  with different HECS sets

## CONCLUSIONS

Due to the lack of data of charge changing cross-sections of high energy particles in plasma, and on charge state distribution of solar ions in a solar event at a given time, different models have been developed to predict the charge evolution of solar energetic ions. Main differences among models are the kind of cross sections employed, and whether charge interchange, if occurs, takes place, during or after acceleration. Though, in some events the observed charges can be repre-

sentatives of local matter, there exist some inferences indicating that this cannot be a systematic situation. The kindness of the HECSM that we have developed, namely "escape" are: (1) it is an analytical model with the subsequent computational economy and direct physics content, and (2) it provides a test of the model that could be done data at very low energies will be available, that is, charge state should be lower than the local thermal one of the presumably source (determined by other means,  $\beta$ , X-rays, etc).

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