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Energetic Solar Particle Charge Behavior During Source Acceleration

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Abstract: To explain data of solar ions charge states, two main kind of models have been developed: (1) definition of the charge state during the acceleration process, on basis to high energy cross-sections for electron loss and capture: charge interchange occurs between a population which is being accelerated getting very rapidly a power low typ 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, on basis to thermal cross-sections for ionization and recombination. We analyze and discuss differences and implications.

Introduction

Charge states of energetic ions and their evolution during their passage 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_{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. All those expressions do not consider the temperature of the medium (T). For astrophysical applications, these 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 charge as a function of energy must be derived taking into account the kind of energy change processes. Since there is not available data of particle charge evolution of ions moving through plasmas, either during stopping or acceleration, a big amount of theoretical

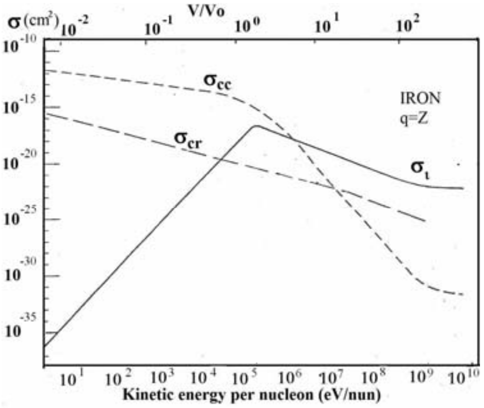

Figure 1: HECS in atomic matter

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. It was found that depending on the kind of acceleration mechanism and its efficiency, on the temperature and density of the medium, then, 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 α is the acceleration efficiency and α_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 λ compared with that of the atomic processes 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 to the neutral state and to be lost from the accelerated flux. Since $t_a \sim 1/\alpha$, then if α 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 ions in plasmas, as it exist in atomic matter. One is obliged to do some approximations: 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. 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 non-thermal spectrum. Then, it is not clear why such thermal cross-sections may be extrapolated when high energy population is involved. 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 the cse of 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 σ_l, σ_{cc} and σ_{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 ref. [4]).

Models of Charge Evolution

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 ions 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 the 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] uses 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. Now, let us call (THCSM) those models that use thermal cross-sections, to differentiate of the HECSM models. The pioneer THCSM is [14], which assumes charge-changing processes after the acceleration, during particle transport in the hot coronal plasma. A subsequent series of works have appeared [15, 16, 17, 18, 19] and so on] with all kind of refinements (acceleration of different types, p-p impact ionization, photoionization, kappa velocity distributions, etc), most of them of numerical nature.

The HECSM-Escape Model

The HECSM developed in [1, 3, 4, 11, 12, 13], (strangely named "Escape" by one of us, DRF), is not a numerical code but a simple analytical expression for q_{eff}. - *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-*. Our q_{eff} expression 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 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 and for evaluations of the acceleration rates, (2) for the development of the electron pick-up spectroscopy, as a tool in the field of plasma diagnosis [2], (3) to study the charge evolution of solar energetic ions and (4) by probing several sets of HECS (as can be found in the literature [e.g. 20]), we pretend to infer (from the best fitting of our analytical q_{eff} expression to data of solar charge states) about the nature of charge changing cross sections of high energy ions in cold and hot plasmas. One of the kindness of our HECSM is the possibility to test its predictions, when data on charge state of very low energy ions will be available: as can be seen in Fig. 1, the capture cross-section 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_{eff}, up to a given energy where both electron capture and loss become comparable, and then q_{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, since no other model predict this trend toward neutralization at the beginning of the acceleration. Given above the status and goals of the HECSM model, it is convenient to discuss papers [21, 22]**:** the authors remark that our results do not fit the results in [7] at 0.3 Mev/n! and overestimates ionic charge at E > O.1 Mev/n! - Obviously, there was a total misunderstanding of the HECSM ("*Escape"*)**:** the HECSM has not at all as goal to be consistent with thermal approaches. **The physical conception of the phenomenon is just the opposite to the thermal one.** 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 did not dispose of charge state data, our runs had been of pure predictive nature, on basis of a given set of HECS [3, 4]. However, with the appearance of valuable data [23], such remarks made in [21, 22] are not relevant any more: in fact, according [23], data of 3 of the 4 events studied with SEPICA onboard ACE **are systematically above** the equilibrium charge states obtained with a thermal model [8], and conclude that a more complete model including non-equilibrium conditions may perhaps be consistent with their data. At this regard, curves (4) and (5) of Fig. 2 **reproduce exactly** data of events 1 and 2 of [23] (results will be reported elsewhere). Such curves are of the type of curve (1) growing faster than thermal model predictions. Our q_{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) the original one (curve 1). With such arbitrary change of HECS, curves (2 and 3) grow quite slow, as thermal model predictions (against observations in [23]) and tend toward the completely stripped state at very high energies (70-90 MeV/n). So, curve (1), penalized in [21] is within the frame of the trend of data in [23].

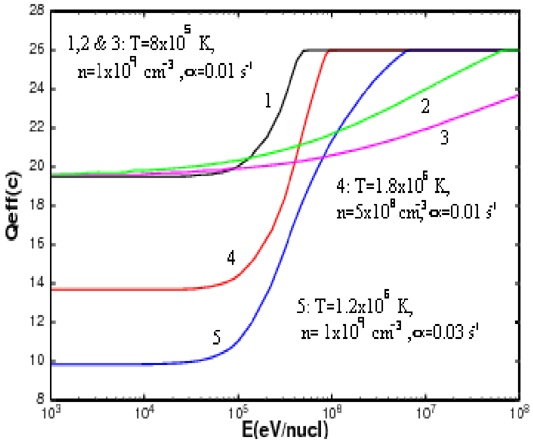

Figure 2: Predictions of the HECSM.

Conclusions

In order to predict the charge evolution of solar energetic ions, different models have been developed. 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 representatives of local matter, there exist some inferences indicating that this cannot be a systematic situation. The kindness of the HECSM that we have developed, 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 when 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, γ and X-rays, neutrons, etc). We conclude that a stricter study of HECS is needed now that valuable data of solar ions charge states is appearing.

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