Pergamon

Adv. Space Res. Vol. 21, No. 4, pp. 629–632, 1998
©1998 COSPAR. Published by Elsevier Science Ltd. All rights reserved
Printed in Great Britain
0273-1177/98 $19.00 + 0.00

PII: S0273-1177(97)00973-3

DIAGNOSTICS OF SOLAR PARTICLE ACCELERATION PROCESSES

J. Pérez-Peraza* and A. Gallegos-Cruz**

**Instituto de Geofísica, U.N.A.M., 04510-C.U., México D.F., Mexico*
***Ciencias Básicas, UPIICSA, IPA, Té 950, Iztacalco 08400, México D.F., Mexico*

Abstract

Atomic interactions of accelerated ions with the local matter of the acceleration volume produce radiation from the capture of free or bounded electrons. These emissions present very peculiar signatures and may be employed for the goal of plasma diagnosis in a wide range of circumstances. This diagnostic method, namely *Electron Pick-up Spectroscopy* allows for the identification of acceleration mechanisms, the mass, velocity, abundances and charge state evolution of the accelerated ions, the composition and density of target particles of the source matter, the temperature of the medium and topology of the acceleration volume. It is emphasized the sensibility of this diagnostic method to the temperature-dependent charge interchange cross-sections between the two interacting particle populations.

Introduction

In works /1,2/ we pointed out the importance of charge interchange of energetic particles (during their acceleration) with the local matter of their sources: this process takes place provided the amount of traversed matter (~ density x flight time) is high enough for the establishment of charge interchange between the accelerated ions and the thermal particles of the background medium: either because the matter density is high enough or because particles expend enough time in the source due to restricted escape conditions from a closed topology of high magnetic field strength. Besides, Isler /3/ has developed a diagnosis technique for controlled fusion experiments, which is also based on the produced emission following electron capture and has proved to be highly efficient in fusion experiments. Similarly, we claim that the proposed diagnostic method may become a useful tool, in space physics and astrophysics as well as at laboratory scale.

Charge Interchange Establishment

The criteria to determine whether energetic ions keep their local thermal charge state of the source or not, during their acceleration has been previously discussed in /1,2,4/ on basis to the competition of atomic characteristic lengths associated with the passage of charged particles through matter: the amount of traversed matter $L = \rho v t_f$ (where t is the flight time in acceleration volume, v is the particle velocity and ρ is the density), the mean free path for Coulomb collisional losses $\lambda_{coul} = \rho v t_{coul}$, the mean free path for electron capture or loss $\lambda_{c,l} \sim 1/N_t\sigma_{c,l}$ (where N_t is the target concentration and σ_c, σ_l are the cross-sections for electron capture and loss) and the characteristic hydromagnetic acceleration step $l_a = l_a(\alpha_{acc})$, where the acceleration efficiency $\alpha_{acc} = \alpha_{acc}(v, q^*_{eff}; \mathcal{E}, B, W)$ of the specific acceleration mechanism, depends on particle parameters and on hydromagnetic parameters, such as electric ($\mathcal{E}$) and magnetic (B) fields and the spectrum of turbulence (W). Basically, a given charge interchange process (capture or loss) is established during ion acceleration when the conditions of the source are such that $\lambda_{c,l} \leq l_a < L$ and $l_a < \lambda_{coul}$, otherwise, particles undergo free fly keeping their local thermal charge up to relativistic energies, in which case such a charge state gives a diagnostic of the source temperature. The relevant criteria for charge interchange establishment are described by several inequalities according the specific acceleration mechanism and the physical conditions of the source. In fact, Coulomb collisional losses are considered through a parameter $\alpha_{thr} = \alpha_{thr}(v, q^*_{eff}, A, Z; T, N)$ defined as the threshold value of the acceleration efficiency where both the acceleration and deceleration rates equate. The rate of acceleration at non-relativistic energies (where charge interchange may be established, $E < 50\ MeV/n$) can be described as $(dE/dt)_{acc} = \alpha_{acc}E^{\eta}$, where E is the ion kinetic energy and η depends on the specific acceleration mechanism (e.g. $\eta = 0.5$ for stochastic Fermi type acceleration and electric field acceleration and $\eta = 1$ for Betatron type acceleration), and on the other hand $\lambda_{c,l}$ and q^*_{eff} depend on the capture and loss cross-sections which in turns depend on whether the matter is predominantly in atomic state or in the plasma state, the velocity of the ions projectiles, their charge state (hydrogenids or highly charged) and so on; thus it turns out that the mentioned criteria for charge interchange during acceleration in astrophysical sources is much more complex than in fusion experiments, depending on a high number of parameters, including an specific value of the ion velocity (v_{cross}) where $\sigma_c = \sigma_l$, below which electron capture is dominant and above which electron loss becomes dominant, in such a way that the referred criteria become of a very assorted nature according to specific situations. The relevant cross-sections are thus functions of several parameters of the ion projectils and targets: $\sigma = \sigma[A, Z, v_r(T), q^*_{eff}, v_{cross}, A_t, Z_t]$, where $v_r(T)$ is the relative velocity between projectils v and targets v_t. The later is taken as the most probable thermal velocity at the temperature T of the medium. Since from our spectroscopy we pretend to infer about the acceleration process, our free-parameter is the acceleration efficiency (α_{acc}), so that the lacking information states on the cross-sections, and therefore, a reliable knowledge of both σ_c and σ_l is required to develop such an spectroscopical method.

Temperature-Dependent Cross-Sections (CICS)

Experimental cross-sections of electron capture and loss of energetic ions interacting with thermal targets are limited to some ions (mostly hydrogenids or fully stripped), some atomic targets and very delimited velocity ranges of the projectile ions. Consequently, the theoretical analytical formalisms are correspondingly of partial nature, with no consideration of the temperature of the target medium. However, in astrophysical sources the finite-temperature nature of matter is a crucial factor. Therefore, in order to overcome such a partial status of the existing CICS we proceeded as described in /1/ by adapting the CICS given in the literature [e.g. /5,6/] to fit a continuous description through the entire energy range of solar energetic ions and introducing instead of the ion velocity a relative velocity between that of the ions and the temperature-dependent velocity of the thermal targets /2/. Hence, according to the CICS found in the literature we obtained in this way a global description of the CICS for any kind and charge state of projectiles, for any target, any temperature and any ion velocity; Coulomb-capture cross-section is dominant below v_{cross} in atomic media relative to the radiative-capture cross-section, whereas in ionized matter radiative capture is dominant over Coulomb-capture through the entire velocity range. Electron loss becomes the dominant process at $v > v_{cross}$. The major uncertainties of the obtained CICS concern electron capture at quasi-thermal velocities (at the beginning of the ion acceleration) where a kind of compromise between the employed cross-sections and thermal cross-sections (for conditions of thermodynamical equilibrium) must be done, and the sharp jump in the capture cross-section at a certain temperature for which the relative velocity considers instead of the bounded electron velocity of a major atomic matter state, the velocity of free electrons of a major ionized state. On the other hand, the strong dependence of the CICS on the ion effective charge q^*_{eff} introduces an important uncertainty due to the limited present status of our knowledge on this parameter.

Self-Consistent Effective Charge formulation

The present status of q^*_{eff} is associated with experimental results of stopping power in atomic media, and it is described by semi-empirical relations /6/ ; some extrapolations to astrophysical contexts are done by introducing a parameterized temperature-dependent factor in those relations. However, particle acceleration cannot be seen as only the opposite process to power stopping, since this depends on the medium parameters such as density and temperature, whereas acceleration is of different nature, depending on hydromagnetic parameters such as the turbulence spectrum and the electromagnetic fields. In power stopping experiments ions of high energy (mostly stripped of their electrons) lose energy to the medium while gradually picking-up electrons of the medium till an eventual thermalization in a highly charged state or even in a neutral state. Particle acceleration in atomic sources begins from the thermal background with the charge state defined by the ionization equilibrium at the temperature of the medium. If the conditions for charge interchange are fulfilled, ions may capture some electrons while their velocity is still lower than v_{cross} , but as soon as $v > v_{cross}$ they rapidly lose electrons to end completely stripped at some MeV/n. Hence, we realize that in order to have a self-consistent description of q^*_{eff} in a medium of any ionization degree and valid for situations of acceleration, deceleration or no energy changes during particle passage through matter, the effective charge of ions must be derived on the basis of the relevant temperature-dependent CICS /7/ according to the following analytical expression

$$q^*_{eff}(E, Z) = q_0(E, Z) + N_t v_r(E) t[\mathcal{F}\sigma_l(\Lambda/\lambda_l) - \sigma_c(\Lambda/\lambda_c)] \tag{1}$$

where it has been assumed that the relative velocity v_r ,σ_l and σ_c do not depend on the elapsed time, $q_0 = q(t_0)$ is the initial charge state of the energetic ions at each interaction with the medium, and for the beginning of the acceleration process has been taken as the local thermal charge state $q_0 = Q_L(T, Z)$ from ionization equilibrium results /7/. The average number of electrons that are pulled out from the energetic ion per interaction with each target particle fits ($1 \leq \mathcal{F} \leq Z$). It can be seen that expression (1) is of general nature whatever the kind of process that ion may undergo while traversing matter: when ions undergo acceleration, t, is related with the acceleration time $t_a = l_a/v_r$ for particles to gain energy from E to $E + \Delta E$, and Λ is related to the acceleration step l_a ; when ions suffer deceleration Λ is related to the so called Range (R) and t to the time $t_d = R/v_r$ for particles to be decelerated from E to $E - \Delta E$; when ions do not undergo any energy change , hence t is related to $t_f = L/v_r$, where t_f is the mean flight time in a region of thickness L.

Photon Emission from Electron-Capture

The emitted radiation from electron pick- up during ion acceleration is evaluated on the assumption that each electron capture produces one photon: the number of capture interactions in the interval dE (i.e. at a given energy E) and interval dt (i.e. at a given time t) of a flux of ion projectils interacting with the source matter is,

$$\mathcal{I} = N_t(Z)\mathcal{N}(E,t,Z)v_r\sigma_c \qquad (photons/sec^2\ energy) \tag{2}$$

where $\mathcal{N}(E,t,Z) = N_o f(E,Z,t)$ $(ions/sec\ energy)$ is the differential spectrum of acceleration at the source level, widely discussed in /9,10/, and $N_t(Z)$ $(targets/cm^{-3})$ is the concentration of targets of the thermal background. It follows then that the the total number of captures (and so, the total number of photons) I from the beginning of the acceleration (at $t = 0$) up to a time t, from an initial threshold energy E_o up to an energy E is,

$$I(E,t) = N_t \int_{E_0}^{E} [\sigma_c v_r \int_o^t \mathcal{N}\ dt]\ dE' \qquad (Photons/sec) \tag{3}$$

since each emitted photon has an energy $\mathcal{E}_\nu(\mathcal{E})$ the corresponding energy flux is,

$$F(E,\mathcal{E}_\nu,t) = N_t \int_{E_0}^{E} [\sigma_c v_r \int_o^t \mathcal{N}\ \mathcal{E}_\nu\ dt]\ dE' \qquad (energy/sec) \tag{4}$$

$F(E,\mathcal{E}_\nu,t)/4\pi(1A.U.)^2$ $(energy/cm^2\,sec\,sr)$ and $I(E,t)/4\pi(1A.U.)^2$ $(photons/cm^2\,sec\,sr)$ give respectively the energy flux and photon intensity at the earth level. The energy of the emitted photon is,

$$\mathcal{E}_\nu = (q^*_{eff}e^2/r_n) - (q^*_{eff}e^2/r_c) \tag{5}$$

where $r = n^2h^2/Ze^2m_e$ is the orbital radius of the n-level (free or bound), $r_c = q^{*2}_{eff}e^2/m_eV_r^2$ is the electron capture radius, with m_e the electron mass. The emissions predicted by this diagnostic method were illustrated in /2,4/ for several acceleration mechanisms, for both atomic and ionized matter in the source. Here we illustrate the method for another example of a coronal source of ionized matter with $T = 10^6$ K and $N_t = 10^{10}$ cm^{-3} for the concentration of target electrons. We assume a Fermi-type aacceleration process /9,10/ with acceleration efficiency $\alpha_f = 10^{-1}$ sec^{-1}. The considered projectiles are the accelerated ions of O^6, Si^9 and Fe^9 that rapidly become fully stripped during their acceleration. The threshold value for resonant interaction of the ions with the accelerating stochastic turbulence has been fixed to the Alfven velocity with $B = 10$ Gauss. According to /10/ the steady state status of the acceleration process in solar particle sources is reached after 20-50 sec, so that we have integrated eq. (3) up to t = 30 sec. We have considered conservative values for N_o of the source differential spectra, at $E \geq 50\ eV/nuc$: 10^{33} $(eV/nuc)^{-1}$ for Oxygen ions and 10^{32} $(eV/nuc)^{-1}$ for Si and Fe ions, corresponding to gradual coronal events, however, for impulsive events the value for Fe must be chosen about an order of magnitud higher.

Fig. 1 shows the produced photon fuxes by electron pick-up as ions are being accelerated. It can be appreciated that for a given temperature and density in the source and the same acceleration parameters for the different ions, the emission flux associated to each one is discernible from each other. **The calculated flux intensity is a lower limit because we have only considered the capture of free electrons, ignoring bounded electrons, in which case the capture cross section is $\propto Z^5Z_t^5$, so that the contribution of heavy ions interacting with haevy targets increases the flux intensity**. Since the emitted flux is sensitive to the temperature of the source, through the v_r value in σ_c and q^*_{eff}, to the acceleration parameters $\alpha\tau$ and time, to the threshold energy for acceleration, E_o which is related to the local hydrmagnetic velocity, to the N_o and N_t values, it can be realized that a fine structure of the emissions, as described in /2,4/, leads to a diagnosis method of the acceleration phenomenon. **In this paper, we only want to emphasize that the lower limit of the flux intensity is in the range $\sim (10^{-1} - 10^8)$ $(photons/cm^2\,sec\,sr)$ depending strongly on N_t and mainly on the N_o values.**

Discussion

We claim to have developed a new diagnostic method that differentiates from the method described in /3/. The Isler's method is based on: (a) the projectiles are monoenergetic beams of neutral hydrogen of low energy (< 150 KeV/n). (b) the targets are fully ionized or hydrogenids ions of C, O, N. (c) the beam projectiles do not change their energy during their interaction with the plasma. (d) projectiles undergo one charge state change. (e) partial cross sections are numerically simulated for delimited particle velocity ranges, considering mainly monoenergetic projectiles of one kind and three different targets, and both with only two possible charge states. (f) the emitted radiation is

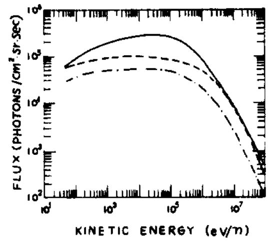

Figure 1: *Evolution of the flux intensity of electron pick-up emissions as the capturing ions are being accelerated, [eq. (3)], from their Alfven velocity up to some tens of MeV/nuc, where they become fully stripped.* **Intensity may varies several orders of magnitud depending on the amount of accelerated particles $\propto N_o$, as well as on the density of targets***: Fe (solid linc), O (dashed line) Si (point-dashed line). Even that N_o of Si is about ten times higher than that for Fe, the flux from Fe is higher because its σ_c is higher*

well defined in the visible and UV lines. (g) the pursued goals are the determination of densities of fully ionized low-Z ions, ionic temperatures and plasma rotation. In contrast, our method is based on the following precepts: (a) projectiles are ions of any (A,Z), any charge state ($q = 1...Z$) and with a well structured energy spectrum from $\sim$ 10 eV/n up to $\sim 10^2$ MeV/n. (b) targets are ions or atoms of any (A,Z) and any charge state defined by the temperature and pressure of the source matter. (c) projectiles undergo energy changes during their interaction with the medium due to acceleration (either of stochastic or secular nature) and/or deceleration by collisional losses. (d) as projectiles are accelerated (or decelerated) their charge state is evolving according to their velocity, i.e., their effective charge $q^*_{ef}(v)$ varies with the particle energy changes, so that at energies of $\sim$ MeV/n during their acceleration $q \rightarrow Z$ and during deceleration toward an eventual thermalization $q \rightarrow 0$. (e) our cross-sections are analytically derived to fit the entire energy range of cosmic particles, for any (A,Z), any initial local charge state, evolving in terms of $q^*_{ef}(v)$ and with explicit dependence on the matter temperature, since cosmic sources display a wide temperature range ($T \sim 10^3 - 10^8$ K). (f) the emission spectrum is highly complex since the energy spectrum of the accelerated ions is very wide and initial local ionization states are very assorted, so that a given projectile (A, Z, v, q^*_{ef}) interacting with a given kind of target (A_t, Z_t, q_{ef}, T, N) produces emissions which drift in frequency as the projectile effective charge $q^*_{ef}(v)$ evolves during acceleration (or deceleration), sweeping a wide range of the electromagnetic spectrum. Consequently, in the extreme cases of $T \leq 10^4$ K when most of targets are in atomic state, a continuum is obtained, whereas at $T > 10^6$ K very sharp X-rays lines are produced. (g) the main goal of this spectroscopy is the identification of: - the involved acceleration mechanism and its corresponding efficiency to infer about the prevailing electric and magnetic field strengths and turbulence spectrum - the projectile parameters (A, Z, v) - the evolution of the projectile charge state - the target parameters - density and temperature of the source - the topology of the magnetic field - and the contribution of any decelerating effect. However, the fundamental difference between our spectroscopical proposal and that developed in /3/ states on the employed cross-sections. The lack of experimental data on finite-temperature dependent cross-sections for charge interchange between a particle population that does satisfy the SAHA law and another one that does not, gives to our method a double-folding importance: the diagnostic goals delineated above, and on the other hand to use the confrontations of our predictions with eventual observational corroborations as a "*calibration technique*" for determining the accuracy level of the derived temperature-dependent cross-sections.

References

[1] Pérez-Peraza, J., Martinell, J. and Villareal, A., Adv. Space Res. 2, 197-200 (1983).

[2] Pérez-Peraza, J., Alvarez-M., M. and Gallegos-C., A., Proc. 19th Int. Cosmic Ray Conf. 4, 18-30 (1985).

[3] Isler, R.C., Plasma Phys. Control. Fusion 36, 171-208 (1994).

[4] Pérez-Peraza, J., Alvarez-Madrigal, M. and Gallegos-Cruz, A., Adv. Space Res. 9-12, 97-101 (1989).

[5] Nikolaev, V.S., Soviet Phys. Uspekhi 8, 269-294 (1965).

[6] Betz, H. D., Rev. Modern Phys. 44, 465-539 (1972).

[7] Pérez-Peraza, J. and Alvarez-Madrigal, M., Proc. 21st Int. Cosmic Ray Conf. 5, 382-385 (1990).

[8] Arnaud, M. and Rothenflug, R., Astrom. Astrophys. Suppl. Ser. 60, 425-457 (1985).

[9] Pérez-Peraza, J. and Gallegos-Cruz, A., ApJ Suppl. 90, 669-682 (1994).

[10] Gallegos-Cruz, A. and Pérez-Peraza, J., ApJ 446, 400-420 (1995).