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PARTICLE ACCELERATION IN COMETARY PROCESSES OF MAGNETIC RECONNECTION

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RESUMEN. Haces de partículas energéticas ($\sim$ 1 MeV/n) provenientes de los cometas Giacobini-Zinner y Halley han sido observados. La fuente de estas partículas energéticas puede encontrarse en el proceso de reconexión impulsiva asociado a los eventos de desconexión de las colas cometarias, cuando el cometa cruza una frontera sectorial de campo magnético interplanetario, o en procesos de larga duración asociados con la activación de la lámina de corriente neutra de la cola por ondas de choque interplanetarias, o provenientes de las fulguraciones solares. Con el objeto de investigar la naturaleza del proceso de reconexión, se procede a estudiar el espectro de energía de las partículas aceleradas y los procesos de interacción de las mismas con la materia local. Se formulan predicciones acerca de las características de los flujos de emisiones fotónicas producidas por la captura electrónica de los iones energéticos durante el proceso de aceleración, debido a su interacción con los gases atómicos y plasmas cometarios.

ABSTRACT. Highly collimated burst of energetic ions up to $\sim$ 1 MeV/n have been observed from Comet Giacobini-Zinner and Comet Halley. The source of high energy charged particles in comets may be found in the impulsive reconnection process associated to disconnection events of comet tails, when it crosses through an interplanetary sector boundary, or in a long lived process associated with the activation of the tail current sheet by interplanetary or flare shock waves. In order to probe the nature of the reconnection process we investigate the energy spectrum of the accelerated particles and we make predictions about the characteristics of photon emission fluxes produced by electron capture of the energetic ions during their interaction with cometary plasmas and neutral matter.

Key words: COMETS — PARTICLE ACCELERATION

INTRODUCTION

Recent observations of energetic particles near comet Giacobini-Zinner on the ICE spacecraft (Wenzel et. al., 1985) show energetic particle populations, up to around 500 KeV. Also, highly collimated bursts of heavy ions lasting typically 10-20 minutes were observed. Observations of energetic ions near Halley's Comet aboard the Vega 1 spacecraft (Somogyi et.al. 1986) show energetic ions up to 700 KeV, while measurements aboard the Giotto spacecraft indicate energetic water-group ions (O^+, OH^+, H_3O^+) up to at least 270 KeV (Mc Kenna-Lawlor et. al., 1986). It is conventionally believed that these energetic cometary ions are created in the following form: atoms and molecules sublimate from the cometary nucleus because of its low gravity, escaping into space with an average velocity $\sim$1 Km. sec^{-1} . These neutral particles undergo first several chemical reactions in the inner coma and later, farther out, they become subjected to various processes of ionization, being the main processes the photoionization and the charge-exchange of an electron of neutrals to solar wind protons. Once the neutral particles become ionized they are subjected to the solar-wind electric field, $\vec{E}$ and the interplanetary magnetic field, $\vec{B}$,. These new created cometary ions, that are practically at rest, become accelerated by the solar-wind electric field in the $\vec{E} \times \vec{B}$ direction and convected

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away in the antisunward direction, while drifting parallely to $\vec{B}$; it is usually said that cometary ions are picked up by the solar wind. The energy gain is proportional to the ions mass so that for typical solar wind conditions, the maximum energy increase is a few KeV per nucleon ($\sim$ 3 KeV nuc^{-1}). In fact the maximum velocity acquired is given as $2V_{sw}$ sen Θ, where V_{sn} = solar wind velocity and Θ is the angle between the interplanetary magnetic field and the solar wind velocity. Therefore for $\Theta \sim 90°$, the maximum energy for protons is $\sim$1 KeV; 70 KeV for water-group ions and 140 KeV for CO_2 ions. Therefore the pick-up process is not sufficient to account for the observed fluxes of high-energy ions, and so, an additional process is usually postulated (Cravens, 1986; Ip and Axford, 1986) such as Fermi acceleration near or at the bow shock, or by adiabatic compression in the bow-wave region and the magnetic barrier close to the nucleus, or by secondary acceleration in the plasma turbulence surrounding the comet, or by magnetic reconnection. In relation with magnetic reconnection several posibilities are open, as for instance, reconnection with the subsequent magnetic merging during disconnexion events, or by activation of the tail neutral sheet by the passage of an interplanetary or a flare shock wave, or during the crossing of sector boundaries, etc. Such an activation of the cometary neutral sheet may lead to electric field acceleration of cometary ions to high energies, as was shown by Mullan et. al., (1984) in the case of solar proton delayed events produced in latent coronal neutral sheets, when magnetic field line diffusion is activated by a flare shock wave.

Concerning the magnetic field configuration of comets, this is inferred from the ultraviolet fluorescence radiation emitted by ions (mainly CO^+) trapped in field lines. The global structures seems to fit the Alvén, (1975) model, with a tail consisting of two oppositely polarized magnetic lobes separated by a neutral sheet. This configuration is the consecuence of the folding of the interplanetary magnetic field as a comet sweeps through the interplanetary medium. This folding of magnetic flux tubes also results in a cross tail current passing through the neutral sheet; according to Maxwell equations an electric field is generated, that may accelerate particles up to 10 KeV. When the drift velocity of the electron is higher than the ion sound velocity, ion-sound current instabilities are created. The result is such a large turbulence that an anomalous resistivity may be generated, such that the cross-tail current is practically disrupted. A significant fraction of the current flowing along the field lines is discharged through the sheet in a similar process of a geomagnetic substorm. Dessler (1971) has discussed conditions under which there might even be magnetic merging in this kind of neutral sheets.

The aim of this work is to study in which extent the observed energetic ions is a result of magnetic merging in a cometary reconnection process associated to the neutral sheet. To do so, one way is by analyzing the predicted and the observational features of particle fluxes (the energy spectrum, for instance) but another way may be by the analysis of the electromagnetic emission produced by the interaction of those accelerated particles with the local matter. Here we derive the acceleration energy spectrum from neutral sheet acceleration and the fluxes of protons which are emitted during acceleration by electron capture of the accelerated ions interacting with the local atomic and ionized matter.

To derive the energy of particles accelerated in the electric field which is generated by magnetic merging, in a magnetic neutral current sheet topology, we follow the procedure given in Pérez-Peraza et. al., (1977) and Pérez-Peraza and Gálvez (1978). The method consist in deriving particle trajectories within the magnetic field topology of the neutral sheet. The knowledge of these trajectories allows for the determination of the time that particles undergo such acceleration before leaving that configuration, and therefore to know the energy reached by particles according to their motion within the acceleration region: given a magnetic field topology of the form B=(Bx,By, Bz), with $B_x=(2B_i/L)$, $B_y=(B_o/L)$ and $B_z= 0$, where L is the lenght scale of the neutral sheet, B_i and B_o are the incoming and the local magnetic field into the diffusion region It was shown that the energy distribution of the accelerated particles is of the form

$$N(E)=9.1\times10^{-2}NV_d\ (E/E_o)^{-1/4}\ \exp\ (-1.12\ (E/Eo)^{3/4})\quad \text{(part/eVcms)} \qquad (1)$$

where N is the density of the concerned particles in the plasma, V_d is the incoming diffusion velocity of plasma into the sheet ; and the characteristic energy value E_o is given as

$$E_o=(qcm^{0.5}\ E^2/B_x)^{2/3} \qquad \text{(c.g.s)}$$

where q and m are the change and mass of particles, c is the light velocity and $E=(1/c)\ V_d B_o$ is the generated electric field.

$$E_o=(2.338 \times 10^{17} m^{0.5}\ qLV_d E)^{2/3} \quad \text{eV} \qquad (2)$$

The calculated energy spectra for carbon and oxygen ions are illustrated in Fig. 1.

I.- Photon fluxes emitted from electron capture

The conditions for electron capture and charge equilibrium during acceleration of local ions in astrophysical sources were given by Pérez-Peraza et. al., (1982,1983,1985b) The electron capture cross section in atomic and ionized matter were taken from Pérez-Peraza et. al. (1985a). The procedure to estimate the corresponding photon fluxes from electron capture was given by Pérez-Peraza et. al. (1985c): the latter may be summarized as follows. First it must be tested whether electron capture is established or not, at a given energy, while particles are being accelerated. When an electron is captured, the number N_e=Z-q* of retained electrons by the ions is evaluated, where Z is the atomic number and q* is the effective charge state of the ion at a given energy during acceleration. After, we compare N_e with the degeneracy restriction $2n^2$ (where n here is the principal quantum number). From here we test at which orbital level ($r_n=n^2\ h^2/Ze^2 m_e$) the configuration is filled, where h=Planck constant, m_e and e are the electron mass and charge respectively and so, by an interative method we test ($r_{n+i} < r_c < r_{n+i+1}$), at which energy level the electron has been captured ($r_c=q_c^* e^2/m_e V_R$), where V_R is the relative velocity between the projectil and thermal targets. Two different emissions were analyzed:

(1) Coulomb capture: When the photon (hν) appears from free-bound transitions.

(2) Radiative capture.- When the photon (hν) appears from bound-bound transitions.

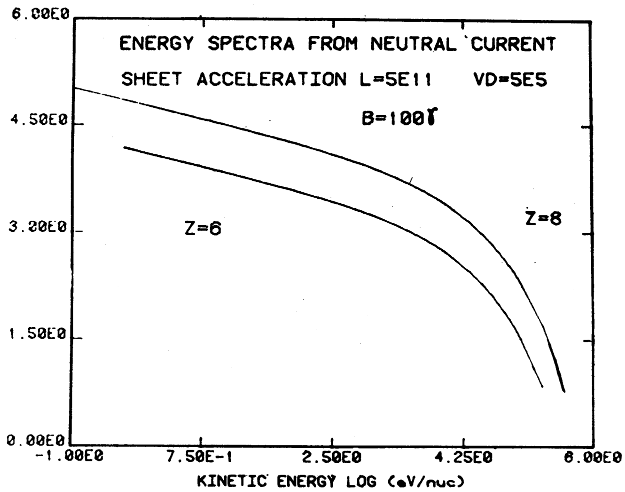

Fig. 1. Energy spectra from neutral current sheet acceleration.

For calculations we have evaluated photon fluxes F, as they should be observed at 1 A.U. from the comet, under the assumption of isotropic emission. Two main situations have been worked out, first that the matter of the source is essentially the plasma tail, with electron density of 5000 cm^{-3} and temperature of 10^4 °k, and on the other hand, that the source is predominatly at the atomic state (the atomic tail) where the hydrogen density is n=135 protons/cm³ and T=5×10^3°K. In both cases the interaction volume was taken to be $10^{34}cm^3$.
On Fig. 2 it is illustrated the behavior of the expected radiation as particle is increasing energy by the accelerating process, and so, the electron capture takes place at deeper and deeper energy levels. In this case the capture electrons are the bounded electrons of local atomic hydrogen, at a temperature of 5000°K and density of 3000 cm^{-3}. Fig.3 shows the corresponding energy spectrum, for the same projectil ions, carbon and oxygen, integrated through an assumed acceleration time. Fig. 4 is the corresponding time-profile, for an arbitrary time scale (with no physical meanning). Figs. 5-7 show the emission drift, the energy spectrum and the time profile for the same projectil ions interacting with the cometary plasma matter of electronic density 5000 cm^{-3} and temperature of 10^4 °K. In both cases, interaction with atomic and with ionized matter, the density of projectil ions was taken 400 cm^{-3} for oxygen, 2000 cm^{-3} for carbon, and of course, the considered acceleration process in neutral current sheet acceleration. As can be seen the emitted radiation covers a wide range of the electromagnetic spectrum, from micro-waves to X-rays.

II. Spectroscopic observations revised in the light of search for observational corroboration.

A variety of spectroscopic observations and technics may be done in order to detect

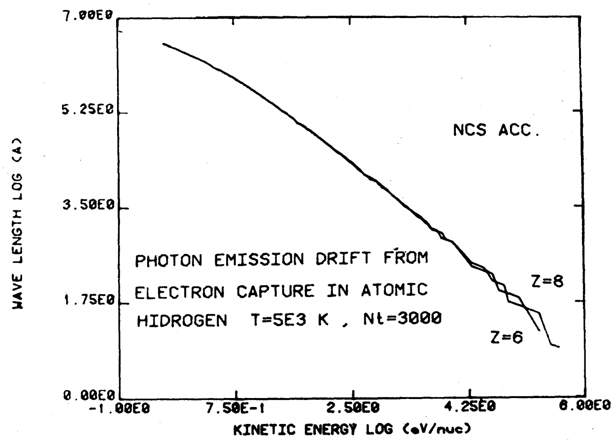

Fig. 2. Photon emission drift from electron capture in atomic hydrogen.

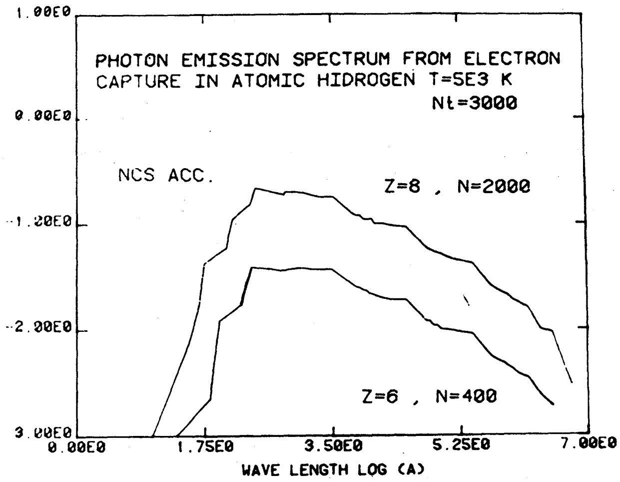

Fig. 3. Photon emission spectrum from electron capture in atomic hydrogen.

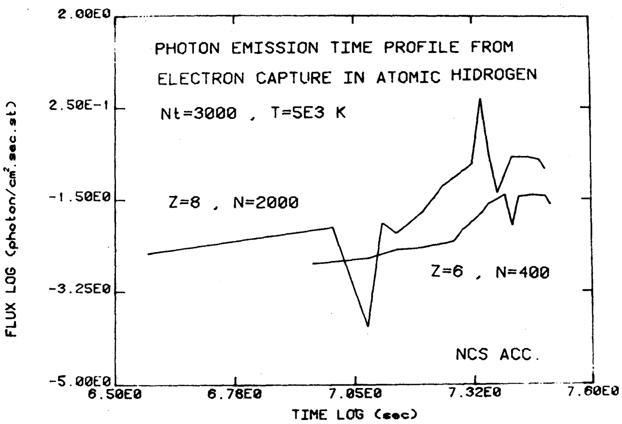

Fig. 4. Photon emission time profile from electron capture in atomic hydrogen.

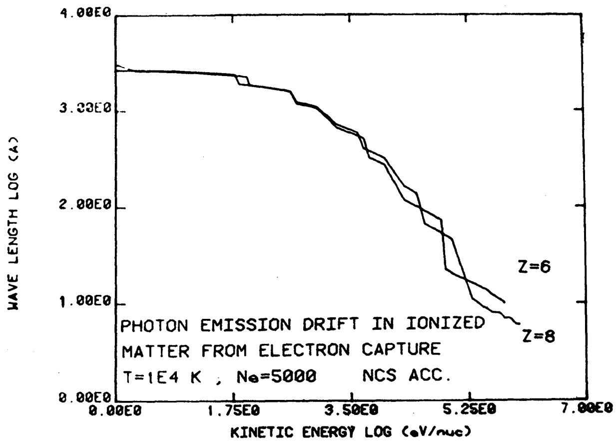

Fig. 5. Photon emission drift in ionized matter from electron capture.

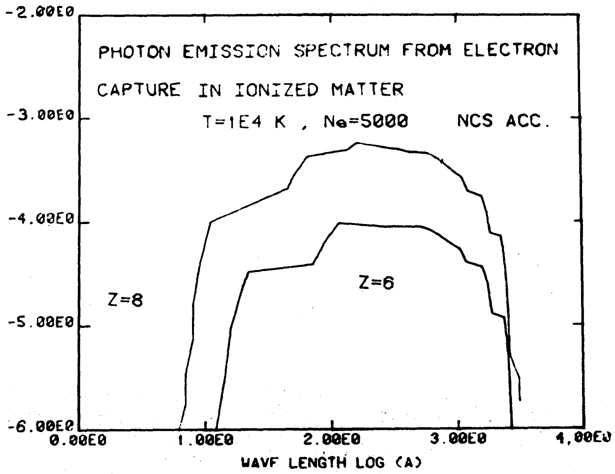

Fig. 6. Photon emission spectrum from electron capture in ionized matter.

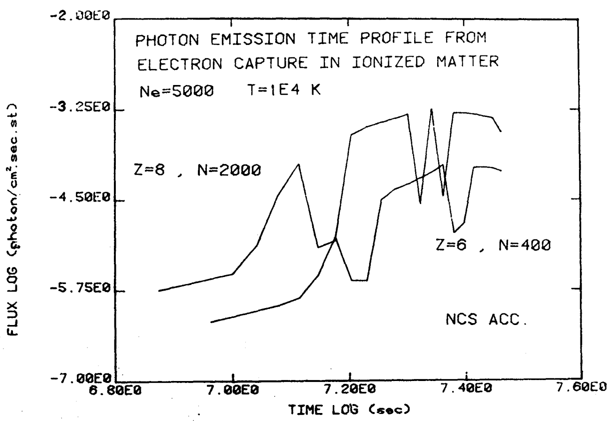

Fig. 7. Photon emission time profile from electron capture in ionized matter.

some photon emission from electron capture. It should be pointed out that the present theorical prediction of photon emission is strongest in the UV range of the spectrum. The emission decreases as we go to longer wavelengths. Therefore, careful analysis of UV spectroscopic observations from satellites could be useful for this detection.

Theoretical predictions were made for a heliocentric distance of r=1 A.U. Most of the comets are small and faint at this distance, being a hard problem for spectroscopic observations. However, an observational technic (Degewij, 1980) using image-tube spectrograph and photographic plate-holder, led to spectra of comets with $M_V \sim 15$-8 at $r < 2.9$ U.A. Weak cometary activity can be searched by substracting the sky spectra from the object spectra with a microdensitometer. A revision of these spectra showed that, although weak cometary activity is detected, the spectra does not present lines for evidence of photon emission. The spectra covered the range from 3500 to 6000 Å.

Spectroscopic observations of comets with CCD (Johnson et. al., 1984) extended from 5600 to 10400 Å, show remarkable features from 7500 to 8000 Å, (Fig. 8) This is important because a peak of the theoretical emission spectra is located at $\sim$7830 Å. Unfortunatly the strong emission of C_2(3-0) and CN A-X (2-0) and a low resolution ($\sim$25 Å) do not permit for a good resolution in this range. The advantage of this method is that permits the analysis in near infrared and spectroscopic observations of faint comets ($M_V < 16$).

In relation with UV spectroscopic observations, the International ultraviolet explorer (IUE) got spectra in the range of 2200 to 3400 Å from comet Bradfield (1979X) (Feston et. al., 1982). Nevertheless with a low resolution ($\sim$30A), and instrumental noise, interesting features appear at 3250 A and in the region of 3330 to 3360 Å (Fig. 9) A careful analysis of the peaks of the predicted emission spectra could lead to the discovery of a relationship.

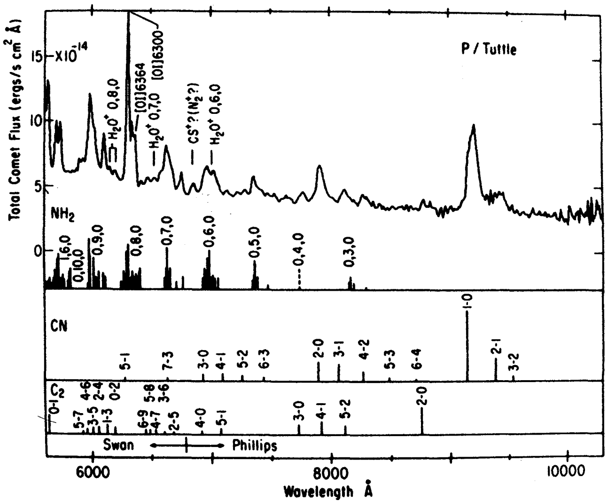

Fig. 8. Spectrum after Johnson et al. 1984, *Icarus*, 60, 351.

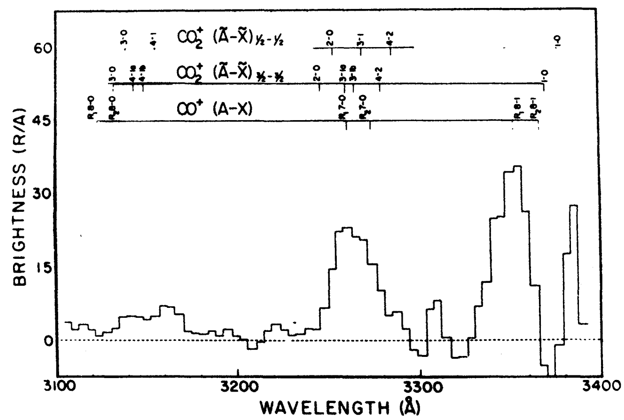

Fig. 9. Spectrum after Festou et al. 1982, *Ap. J.*, 256, 331.

III. A proposal of observational program to corroborate theoretical predictions.

Two ways to confirm theoretical predictions are as follows:

-Spectroscopic observations of future comets. Faint comets could be observed spectroscopically by CCD or spectrographically with analysis by a microdensitometer. In both cases it should be considered:

a) To work with a resolution of 8-16 Å seems reasonable, although it would be ideal to reach a 0.3 Å resolution (Lamber and Danks, 1983) in order to resolve flux peaks form narrow bands.

b) Analysis should be centered mainly in the 3100 and 7830 Å wavelenghts where there are flux peaks from the theoretical prediction.

A good sample to make spectroscopic observations is Comet Wilson (1986 ℓ) which is predicted to have $M_V \sim 3.3$ at $r \simeq 1.2$ A.U. and $\Delta = .624$ A.U. in 1987 05 02 U.T. Unfortunatly, at Dec. -74°; out of sight for almost all the telescopes in northen hemisphere.

-Analysis of Halley's Comet spectroscopic observations. The highest collection of spectroscopic observations in cometary studies was obtained during Halley's Comet last return. Also many new observational technics were developed during this study. The observations of far UV wavelenghts from space could provide some evidence for photon emission of the kind we are looking for.

IV. Conclusions

We have evaluated particle energy spectra of two of the more abundant ions in cometary matter, as well as the photon fluxes emitted by the electron capture process from the interaction of these ions with the local cometary matter. We claim that the developed theory is a useful tool to sounding acceleration processes (in this case, magnetic merging and reconnection), particle charge evolution, source magnetic topologies and physical parameters of sources of energetic cometary ions; this may be done by the analysis of the confrontation between the predicted emissions and plausible observational data. It should be pointed out that the magnitude of the flux intensity scale is somewhat arbitrary and may be moved depending on the assumptions concerning the emission cone (isotropic or collimated fluxes), the comet-observator distance and the assumed target and projectil densities. This must be taken into account for any confrontation with observational data, such that an eventual fitting should lead to delimitate the range of source parameters.

In order to test the present theoretical work we believe that a first attempt must be performed in the following directions:

-High resolution spectroscopic observations of comets centered in 3100 and 7830 Å could provide elements to corroborate predictions on photon emission from electron capture.

-Analysis of spectroscopic observations from space in far ultraviolet wavelengths could show some of the searched features of pothon emission.

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