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Stochastic Fermi acceleration of ions in the pre-shock region of comet P/Halley

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Summary. Energetic cometary ion fluxes measured between $2.5\,10^6$ km and 10^6 km from the cometary nucleus along the inbound trajectory of s/c VEGA-1 are used to derive the temperatures of the ion distributions in the solar wind frame. The increase of the temperature is modelled by the temperature change derived from a Fokker-Planck type equation with a source term and a stochastic acceleration term. The temperature increase predicted by theory is about 3 keV, higher than the observed one ($\simeq 1.4$ keV). The difference may be due to the approximations applied. The second order Fermi mechanism is thus capable of producing the temperature increase observed.

Key words: comets – ion-acceleration mechanisms

1. Introduction

The TUNDE-M instrument on board the spacecraft VEGA-1 recorded ions of cometary origin in the energy range of 40 to 630 keV (nominal values, Somogyi et al., 1986). Upstream of the bow shock the lowest four energy channels were effective, while in the region inside the shock, up to the phase of closest approach all the 52 channels were operational. As discussed in Kecskeméty et al. (1986), most of the ions observed in the upstream region belong most probably to the water group and are mainly O^+ and OH^+. Considering this the energies of the ions detected in the lowest four channels are between 78 and 132 keV. Time profiles of the ion fluxes as measured in the region $r = 12\,10^6$ km to 10^6 km from the cometary nucleus along the inbound leg of the s/c trajectory (this part of the trajectory will be referred to as the pre-bow-shock (PBSh) region in what follows, since the bow shock crossing in the inbound leg occurred at about $r = 10^6$ km) are shown in Fig. 2 of Kecskeméty et al. (1986).

More instrumental details (including observational geometry) have also been given in Kecskeméty et al. (1986) in which correlations with magnetic field directions and energy distributions of ions in the solar wind reference frame (SWRF) were discussed.

The purpose of this paper is to study the effectiveness of the stochastic second order Fermi acceleration in the PBSh region. Large, quasi-periodic enhancements of the ionic intensities were observed between $r = 12\,10^6$ and $2.5\,10^6$ km in the PBSh region (see Fig. 2 in Somogyi et al., 1986) which must be of very complex origin. We thus confine our investigations to the relatively quiet region between 2.5 million km to 1 million km from the nucleus.

The possibility of stochastic Fermi acceleration in the solar wind- cometary interaction have been considered previously by Amata and Formisano (1985) and by Ip and Axford (1986). In the latter paper, various other mechanisms for particle acceleration (adiabatic compression, magnetic field reconnection, first order Fermi acceleration in a diffuse shock) have also been taken into account and the conclusion was reached that second order Fermi acceleration was "likely to be of particularly importance" in cometary environments such as P/Giacaboni-Zinner and P/Halley. The time evolution of a $\delta(t)\ \delta(T - T_0)$ injection of the density of ions with kinetic energy T_0 at the time t was also given in that paper. Here we use a different approach: instead of solving the first momentum equation (for ionic density) we derive and solve an equation for the time dependence of the ionic temperature (Sect 2 of this paper) for subsequent comparison with experiment (Sect 3).

2. Time-dependence of ionic temperature in a second order Fermi acceleration

2.1. Injection mechanism

It is well known that cometary neutral molecules moving away of the cometary nucleus with relative velocities $1\,\mathrm{km\,s^{-1}}$ get ionized by the UV radiation of the sun and also by charge-exchange with solar wind ions. The freshly born cometary ions are picked up by the solar wind in which they gyrate around a centre moving parallel to the magnetic field with a velocity $u\cos\theta$ (where u is the solar wind velocity and θ is the angle with the magnetic field direction, Ip and Axford, 1986). The resulting ion

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Send offprint requests to: A.J. Somogyi cyclotron instability gives rise to Alfvén waves and makes the magnetic field turbulent. The solar wind loses speed as a consequence of getting loaded with the pick-up ions. Scattering in the turbulent field makes the ion distribution isotropic, this process ends up after several gyration periods with a uniformly distributed $|u|$ in the SWRF. Essential features of this injection mechanism are: a) the ionization process and b) the scattering on the MHD turbulence excited by the cometary ions moving parallel to the magnetic field.

The processes of ionization were dealt in many papers (cf. Ip and Axford, 1982), while the theory of the build-up of magnetic turbulence was first given recently (Galeev et al., 1985; Sagdeev et al., 1986). Comparison with the values of the level of magnetic turbulence as measured near P/G–Z (Tsurutani and Smith, 1986) and P/Halley (Riedler et al., 1986) showed an overall agreement with values predicted by the theory (Galeev et al., 1986).

2.2. *The basic equation for resonant stochastic acceleration*

As it is known, this acceleration can be described by the equation

$$u\frac{\partial f}{\partial x}=\frac{Q\delta(v-u)}{4\pi r^2\lambda v^2}\exp(-r/\lambda)+\frac{1}{v^2}\frac{\partial}{\partial v}\left(v^2 D\frac{\partial f}{\partial v}\right) \qquad (1)$$

where

$$D=\frac{e^2v_{\mathrm{A}}^2\cdot 1}{4m_{\mathrm{i}}^2c^2\,v}\int_0^{\pi/2}\frac{d\theta\sin^3\theta}{\cos\theta}\,[B_k^2]_{k=\omega_{B\mathrm{i}}/v\cos\theta} \qquad (2)$$

with the following notations: the x axis is directed along the solar wind flow; f is the six dimensional density function (assumed to be independent of y and z); Q is the total cometary gas flow per second ($\simeq 1.2\,10^{30}$ molecules/s for P/Halley); r is the radial distance from the nucleus; λ is the characteristic length of ionization for cometary neutral molecules ($\simeq 2\,10^6$ km, see Gringauz et al., 1986); v is the particle velocity, v_{A} the Alfvén velocity of solar wind flow, $\omega_{B\mathrm{i}}=eB/m_{\mathrm{i}}c$ is the ion cyclotron frequency (m_{i} being the ionic mass) and B_k^2 is the spectral density of magnetic fluctuations i.e. energy density contained at the wave number interval of $(k, k+dk)$. Values of B measured in the interval selected for this study ($2.5\,10^6\,\mathrm{km} > r > 10^6$ km in the PBSh region) show that with a reasonable approximation,

$$B_k^2=\tilde{B}^2/k \qquad (3)$$

Figure 1 shows an example of the magnetic field power spectra as measured in the region envisaged.

The second term on the r.h.s. of Eq. (1) is the quasi-linear term describing the diffusive acceleration of particles by MHD turbulence, while the first term on the r.h.s. is the source term which describes the production of new ions due to photoionization and their subsequent isotropization by Alfvén turbulence. If we neglect the diffusion term, the solution of the Eq. (1) has the form

$$f_0(v,x)=\frac{3}{8\pi m_{\mathrm{i}}}\frac{\rho_\infty u_\infty}{uv^3}\left(1-\frac{u_\infty^{1/2}}{2v^{1/2}}\right)\sigma(v-u)\sigma(u_\infty-v)\,, \qquad (4)$$

where ρ_∞ and u_∞ are the density and the bulk velocity of the undisturbed solar wind, respectively; $\sigma(x)$ is the step function: $\sigma=1$ for $x>0$, $\sigma=0$ for $x<0$. Due to the second term on the r.h.s. of Eq. (1), a high energy tail of the distribution appears. For the case under consideration, when $\tilde{B}^2 \sim 1/k$, the high energy tail has the form

$$f(v)\propto\exp(-m_{\mathrm{i}}v^2/2T),\ \text{for}\ v>u_\infty\,. \qquad (5)$$

2.3. *The temperature variation of ions during the 2nd order Fermi process*

The value of T, the ionic temperature, can be obtained from Eq. (1) by multiplying it by $m_{\mathrm{i}}v^2$ and integrating over the three components of v. Taking into account Eqs. (2) and (3) this procedure yields

$$u\frac{dT}{dx}=\frac{1}{3}m_{\mathrm{i}}v_{\mathrm{A}}^2\omega_{B\mathrm{i}}\frac{\tilde{B}^2}{B^2} \qquad (6)$$

In the case of $\Lambda/R=2$ (Λ is the scattering mean free path, R is the ion gyroradius) Eq. (6) coincides with the result obtained by Ip and Axford (1986) under the assumption of approaching the strong turbulence limit:

$$\frac{dT}{dt}=\frac{3R}{4\Lambda}ZeBv_{\mathrm{A}}^2 \qquad (7)$$

On the r.h.s. of Eq. (6), v_{A}, $\omega_{B\mathrm{i}}$, B^2, and $\tilde{B}^2$ are functions of x. Note that there is no contribution to the value of T from the source term, since T only determines the shape of the high energy tail of the distribution.

Equation (6) makes it possible to compare the observed T_{obs} values with calculated ones:

$$T_{\mathrm{c}}=\frac{1}{u(x)}\int dx\,\frac{1}{3}m_{\mathrm{i}}v_{\mathrm{A}}^2\omega_{B\mathrm{i}}\frac{\tilde{B}^2}{B^2} \qquad (8)$$

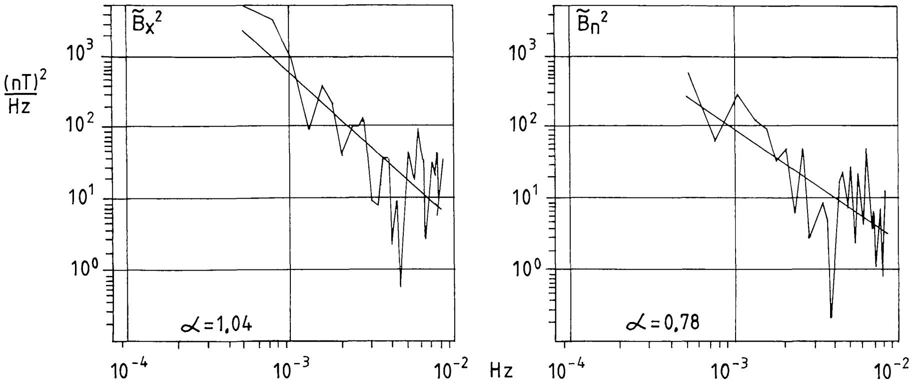

Fig. 1. Power spectrum density $[(nT)^2/\mathrm{Hz}]$ of magnetic fluctuations between 10^{-4} and 10^{-2} Hz. Values of α are spectral indices of power function fits. Left panel refers to B_x, the sun-spacecraft component of B; right panel: same for B_n (normal component)

3. Comparison of observed and calculated ion temperatures

To calculate T_c on the basis of Eq. (8) the functions $u(x)$, $B(x)$, $\rho(x)$, and $\tilde{B}^2(x)$ must be known. Values of $B(x)$ and $\tilde{B}^2(x)$ were taken from magnetic field measurements (Riedler et al., 1986), those of $u(x)$ and $\rho(x)$ from plasma measurements (Gringauz et al., 1986) made onboard VEGA-1 in the PBSh region between $r = 2.5\,10^6$ and 10^6 km. The calculated values of T_c are shown in the lower part of Fig. 2 as a function of time and the cometary distance.

To determine the values of T_{obs} on the basis of the intensity profiles of cometary ions by the instrument TUNDE-M onboard VEGA-1 (simultaneously with values of u, B, ρ, $\tilde{B}^2$), the procedure described in Sect. 4 of Kecskeméty et al. (1986) was used. This is an iterative process to transform the time profiles $I(E, t)$ observed in the spacecraft frame of reference in a fixed direction, into a velocity distribution in the SWRF which is assumed to be isotropic. Due account is taken of the geometric sensitivity of the measuring device which, because of the specific conditions mentioned, is energy dependent. Up to now, the process has only been used to calculate six T_{obs} values spread over the entire range of the trajectory part selected. The resulting T_{obs} values are shown in the upper panel of Fig. 2 as a function of time and distance r from the nucleus. For the sake of comparison, the observed $I(E, t)$ time profiles are shown for the four operational energy channels together with the measured $\tilde{B}^2(t)$ values in Fig 3.

4. Discussion

First of all, it should be noted that the pick-up mechanism alone cannot produce the ions observed because the viewing direction of the telescope (Somogyi et al., 1986 and Kecskeméty et al., 1986). The mere presence of ions observed proves the operation of an additional acceleration mechanism capable of producing abundant fluxes of ions: several thousands ions per (cm$^2 \cdot$ sr $\cdot$ s) of energies 78–88 keV and several tens of ions per (cm$^2 \cdot$ sr $\cdot$ s) of energies 119–132 keV (assuming O$^+$ ions, Fig. 3). The geometry factor of the telescope for isotropic distributions is 0.25 cm^2 sr.

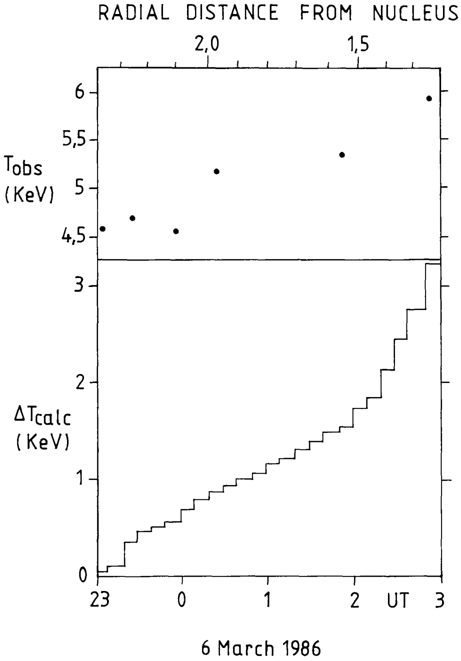

Fig. 2. Upper panel: observed ion temperatures from TUNDE-M using magnetic field (MISCHA) and solar wind (PLASMAG-1) data; lower panel: calculated ion temperatures based on stochastic Fermi acceleration

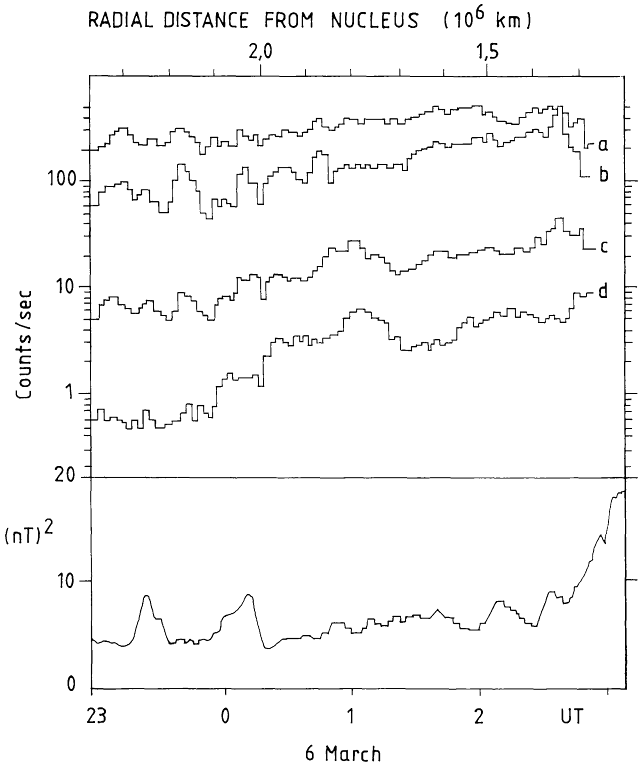

Fig. 3. Main input values used to calculate T_{obs} and T_c. Upper panel: counting rates of ions in the 4 operational channels (a: 78–88, b: 88–107, c: 107–119, d: 119–132 keV); lower panel: variation of $\tilde{B}^2$ as calculated from MISCHA measurements

The change of ionic temperatures predicted on the basis of the theory of the second order Fermi mechanism is shown in the lower panel of Fig. 2, the actually measured temperatures are shown in the upper panel. The theoretical values are averages of subsequent 10 minute intervals, the experimental values are also based on 10 min flux averages spaced at about 40 min distances from each other.

The experimental curve exhibits a rather uniform increase of about 1.4 keV during the period studied (from 2300 UT on March 5 to 0300 UT on March 6). The decrease of the solar wind speed was about 6% during this period (from 500 km s^{-1} to 470 km s^{-1}) resulting in a compression factor of $F \simeq 1.06$. Adiabatic compression with this factor gives rise to a temperature rise of $F^{2/3} \simeq 1.04$ which is negligible. The adiabatic compression is thus not efficient enough to produce the temperature increase observed. The second order Fermi mechanism would produce a temperature increase of about 3 keV, i.e. larger than the observed one.

The difference may, however, be explained by the approximations applied both in the theoretical part, both in the data reduction. In the theoretical part, the magnetic power spectrum was assumed to be proportional to k^{-1}. The main sources of error in the observed T_{obs} values come from the uncertainties of the background flux in the lowest energy channel and the deviations from exponential variation in the velocity distributions observed. At the present stage, no better quantitative agreement could have been expected.

In conclusion: The increase of ionic temperature between distances of 2.5 million and 1 million km from the comet nucleus is established with certainty and its most probable source is the second order Fermi mechanism.

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