ENERGETIC PICK-UP IONS OUTSIDE THE COMET HALLEY BOW SHOCK

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ABSTRACT

The TUNDE-M experiment on board the VEGA-1 spacecraft has detected energetic cometary ions as far as 10 million km from comet Halley. The measured ion fluxes increase as the radial distance to the nucleus decreases. Sharp enhancements spaced at four hour intervals are superimposed on the general increase of the ion fluxes on the inbound leg of VEGA-1. No obvious correlations between the ion fluxes and the interplanetary field direction were found. Distribution functions in the solar wind reference frame were derived from measured counting rates. The distributions are approximately Maxwellian for energies about 100 keV and the derived temperatures vary from about 20 keV for large radial distances ($r \approx 10^7$ km) to about 4 keV at about 1.5×10^6 km before the bow shock ($r \approx 2.5 \times 10^6$ km).

Keywords: VEGA, cometary ions, energy spectra, magnetic field correlations

1. INTRODUCTION

Cometary ions such as O^+, OH^+ and H_2O^+ are created from cometary neutrals by photoionization, by charge exchange with solar wind particles, or by electron impact ionization (cf. Mendis et al., 1985; Cravens, 1986). The freshly ionized particles, which are created almost at rest in the comet frame of reference are initially accelerated by the motional electric field of the solar wind. The ions follow cycloidal trajectories in the ExB direction due to the electric field (E) and the interplanetary magnetic field (B) (cf. Ip and Axford, 1982; Galeev et al., 1985; Cravens, 1986). The cometary ion distribution function therefore forms a ring distribution in velocity space drifting parallel to the magnetic field. This type of distribution is highly unstable and generates Alfven waves via ion-cyclotron instability which pitch-angle scatter the ions and thereby make the distribution nearly isotropic on a time-scale of several gyroperiod (cf. Sagdeev et al., 1986; Gary et al., 1986). The traversal of the bow shock by ions created upstream is expected to lead to further acceleration and energization of these ions by some combination of gradient B drift, Fermi acceleration, and adiabatic compression (Axford, 1981). Further acceleration of cometary ions downstream of the bow shock should also be expected due to second order Fermi processes, compression, and perhaps magnetic reconnection of field lines close to the nucleus. Due to the enhanced magnetic field turbulence observed upstream and downstream of the comet, second order Fermi acceleration is probably the most important process among the various mechanisms listed above (Ip and Axford, 1986).

Energetic particle measurements have been made by instruments onboard the VEGA - 1 spacecraft (Somogyi et al., 1986) as well as on the GIOTTO probe (McKenna - Lawlor et al., 1986). Cometary pick-up ions were observed as far as 10 million km from comet Halley. Similar observations were made earlier at comet Giacobini - Zinner by instruments on the ICE spacecraft (Hynds et al., 1986; Ipavich et al., 1986). The cometary ion distributions measured by ICE even outside the shock appear to be at least partially isotropized in the solar wind frame, and furthermore indicate that significant particle acceleration has taken place (Gloeckler et al., 1986).

In this paper we examine energetic cometary ion fluxes measured by the TUNDE-M experiment during the pre-encounter time period when VEGA - 1 was still outside the bow shock. Another paper (Gribov et al., 1986) deals with the ion fluxes observed along the last 1.5 million km outside of the bow shock. The bow shock structure and the regions inside the shock will be investigated in papers to be published later on.

The instrument geometry and response of the TUNDE-M telescope are described in section 2. Section 3 gives the ion flux profiles measured by TUNDE-M, and presents a correlation study of these fluxes with the mag-

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Proc. 20th ESLAB Symposium on the Exploration of Halley's Comet, Heidelberg, 27–31 October 1986, ESA SP-250 (December 1986)

netic field data measured by the magnetometer onboard the same spacecraft (Riedler et al., 1986). Section 4 deals with the energy distribution function in a frame of reference moving with the solar wind as derived from TUNDE-M observations.

2. INSTRUMENTAL INCLUDING OBSERVING GEOMETRY

The VEGA mission as a whole and the trajectories of the space probes are discussed by Sagdeev et al. (1986). In the vicinity of the comet, the VEGA-1 trajectory formed an angle of approximately 110 deg with the sun-comet axis. The telescope of TUNDE-M pointed normal to this axis in the ecliptic plane and detected particles arriving from a direction approximately opposite to the spacecraft motion. The TUNDE-M instrument is capable of measuring fluxes of ions in 10 keV intervals in the energy range of 40 to 490 keV and in 20 keV intervals from 490 to 630 keV (the energy values mentioned refer to protons). Observations are made within a cone of 25 degrees half-angle, while the geometry factor is 0.25 cm^2 ster. Electrons, protons, and higher energy ions are also registered but not discussed here.

The most likely candidates for heavy pick-up ions far from the nucleus ($r > 10^5$ km) are O^+ and OH^+, whereas H_2O^+ becomes dominant closer to the nucleus. Smaller abundances of the ion species as CO^+, CO_2^+, S^+ etc., can also be expected (Gringauz et al., 1986; Balsiger et al., 1986). The deposited (i.e. measured) energies are calculated on the basis of pre-flight calibrations. Due to the pulse-height defect in silicon detectors, the deposited energies are less than the actual (primary) energies of particles stopped in the detector, Ipavich et al. (1978) used laboratory experiments to quantify this effect for several heavy ion species. We used their measured relationship between actual energy and deposited energy for O^+ to construct Table 1. This table lists the boundary energies for the 4 lowest TUNDE-M channels which have been operating (in the pre-shock region). The speed of an O^+ ion (in the spacecraft reference frame) varies from 955 km/s for channel 1 up to 1195 km/s for channel 4. The estimated error in the pulse height defect determination is probably not more than 5 % (Ipavich et al., 1978). A similar procedure was used to estimated the actual energies for comet Giacobini-Zinner energetic ion data from the EPAS instrument on ICE (Hynds et al., 1986).

Figure 1 is a diagram of velocity space in the comet reference frame and the TUNDE-M observing geometry for VEGA-1. Positive V_x (x-velocity) is oriented towards the sun. The plane of the figure lies in the VEGA-1 orbital plane with positive V_y pointing generally away from the comet in the pre-encounter time period. The apex of the TUNDE-M observing cone is located at the spacecraft velocity vector (in comet frame). Several of the lowest TUNDE-M energy channels are indicated as is the location of the solar wind (protons). TUNDE-M detects particles travelling in the negative V_y direction and around (within 25°).

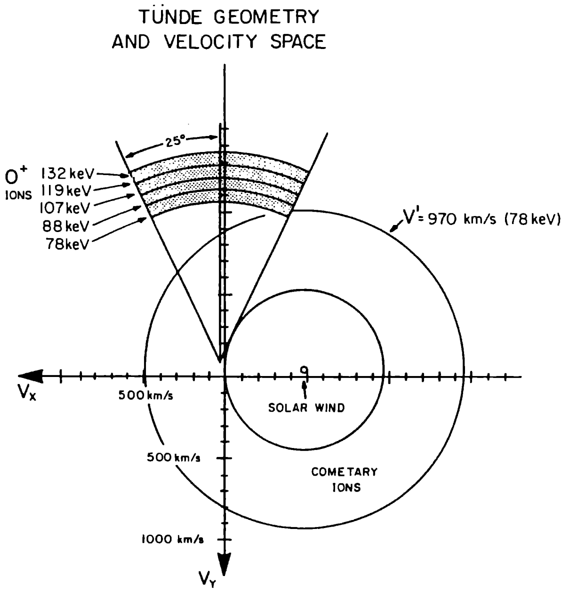

Figure 1. Diagram of velocity space and TUNDE-M geometry.

Cometary pick-up ions (of any species) will initially form ring distributions, as discussed earlier. However, in the presence of significant levels of magnetic fluctuations, the cometary ion distribution will rapidly isotropize due to pitch-angle scattering of the ions off the ring and onto a spherical shell centered at the solar wind velocity and with radius equal to the solar wind speed u. The intersection of such a spherical shell with the V_x-V_y plane is indicated in Fig. 1 for $u = 480$ km/s. Notice that TUNDE-M is not able to differentiate whether or not these pick-up ions are isotropized.

The cometary ions must be accelerated in order to be observed by TUNDE-M. A spherical shell of radius $v = 970$ km/s (in the solar wind rest frame - SWRF) is also shown in Fig. 1. This is the velocity of O^+ ions having an energy of 78 keV in the SWRF, which roughly corresponds to the smallest energy of O^+ ions which can be detected in the lowest effective TUNDE-M channel. Additional acceleration is required to energize the ions from 20 KeV to 80 KeV or beyond (in the SWRF).

3. OBSERVATIONS

3.1 Time history of the TUNDE-M counting rate

The time histories of the VEGA-1 TUNDE-M counting rate in the 4 lowest effective channels are shown in Figure 2 for the time period preceding the VEGA-1 inbound crossing of the bow shock of comet Halley. Energetic ions are detected as far as 10^7 km from the nucleus. The ion fluxes (i.e., counting

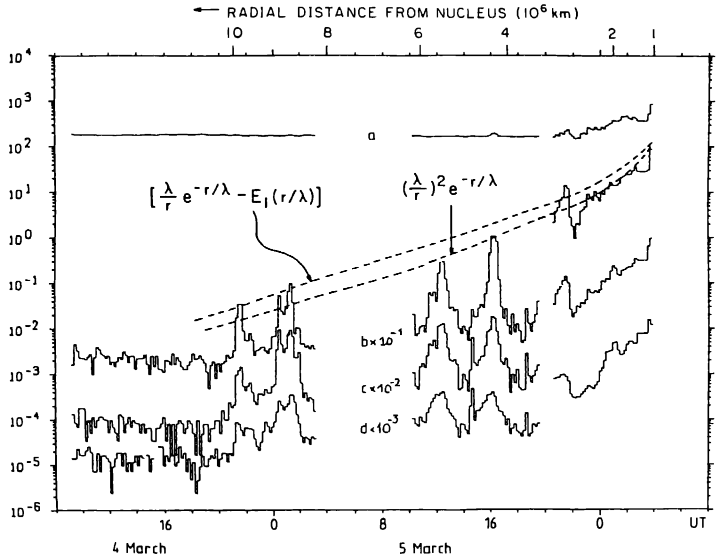

Figure 2. TUNDE-M counting rate vs. time for the VEGA-1 encounter in the lowest 4 energy channels. The dashed lines indicate two types of functions of radial distance from the nucleus.

rates) tend to increase with decreasing distance from the shock as discussed by Somogyi et al. (1986). This increase is especially steep beginning with a radial distance of $r \approx 3 \times 10^6$ km and the fluxes near the shock are large. Large flux enhancements are superimposed on this general trend as will be discussed later. First, the overall trend and its possible explanation will be discussed.

The total density of heavy cometary ions contaminating the solar wind is expected to be proportional to the ionization rate times the column density of heavy neutral molecules (i.e. H_2O, OH, O, CO, etc.) along the solar wind streamline upstream of the point where the measurement is being made. The mass flux, u, is then:

$$\rho u = \rho_\infty u_\infty + \int (m_i n/\tau)\, ds \qquad (3.1)$$

where u is the solar wind speed, ρ is the mass density, m_i the mass of the picked-up ion, n the neutral density as a function of r radial distance from the nucleus (ρ_∞ and u_∞ are the density and velocity in the unperturbed solar wind). τ is the lifetime of a neutral against ionization or charge exchange with solar wind protons ($\approx 10^6$ s) and s is the pathlength. The integral over s goes from $-\infty$ to the point in question.

For a simple 1/r variation of the neutral number density, Wallis and Ong (1975) showed that the relative mass flux (which is proportional to the number density of cometary ions) increases as 1/r along the sun-comet axis. Galeev at al. (1985) calculated the variation of the relative mass flux along the sun-comet axis including the attenuation of cometary neutrals by photoionization (or any constant loss process). That is, for $n = (Q/4\pi V_g r^2)\exp(-r/\lambda)$ the relative mass flux varies as:

$$\hat\rho\,\hat u - 1 =$$

$$= C[\lambda/r \exp(-r/\lambda) - E_1(r/\lambda)] \qquad (3.2)$$

where $(\hat\rho\hat u - 1)$ is the relative mass flux, $\hat\rho = \rho_\infty/\rho$, $\hat u = u_\infty/u$, C is a constant, E_1 is the exponential function and $\lambda = V_g\tau$ is the neutral attenuation scale-length which is equal to 2×10^6 km for comet Halley at the time of the VEGA encounters (Gringauz et al., 1986). V_g is the neutral gas outflow speed which is about 1 km/s for water group molecules (Krankowsky et al.,1986). The total cometary ion density is proportional to the relative mass flux.

The relative variations with radial distance of both the neutral density and the relative flux (eq. 3.2) are both shown in Figure 2. Because the actual paths of integration to the observing points on the VEGA - 1 trajectory are not along the sun-comet axis, the actual r-dependence of the cometary ion density lies somewhere between these two curves. The overall trend of the ion flux for second channel (50-64 keV deposited energy or 88-107 keV actual energy according to Table 1) appears to decrease approximately as the relative mass flux, although the r - variation of the higher energy channels appears to be more gradual. Certainly, if the character of the ion energy spectrum changes with r as it appears to be doing, the ion flux at a given energy does not in general vary with r in the same manner as the total cometary ion density. Similar radial variation was seen at comet Giacobini-Zinner by ICE (Sanderson et al., 1986).

3.2 Correlations with magnetic field direction

The overall r-dependence of the ion fluxes can be partially explained by the r-dependence of the neutral density and additional acceleration, but this does not explain the large variability of the fluxes. For example, there are obvious spikes near 22 UT March 4 and near 12 UT on March 5. The energetic ion fluxes measured by the EPAS instrument near comet G-Z also exhibited large fluctuations (Hynds et al., 1986). These fluctuations seen by ICE were shown to be positively correlated with the maximum energy for the ExB drifting pick-up ions:

$$E_{max} = 2 m_i u^2 \sin\theta_{vB}$$

where m_i is the heavy ion mass, u is the solar wind speed, and θ_{vB} is the angle of the IMF with respect to the solar wind velocity vector. Larger fluxes were measured when E_{max} exceeded the 65 keV (O^+ ions) energy threshold of the EPAS instrument. Hence, if θ_{vB} was too small, much lower fluxes were observed (Sanderson et al., 1986).

One expects a different pattern of correlation for the TUNDE-M measurements because the EPAS experiment on ICE was able to observe ions moving in a generally anti-solar direction (the general direction in which the bulk of the pick-up ions move) whereas the TUNDE-M instrument only detects ions at right angles to the sun-comet axis (Fig. 1). One can see that in order for the cometary pick-up ions to be seen by TUNDE-M they must be both pitch-angle scattered and accelerated. Moreover, ions that are just ExB drifting with cycloidal motion can not reach TUNDE-M unless the solar wind speed is improbably large or for ion species with masses in excess of 60 amu. Furthermore, even with these unlikely conditions only an extremely narrow band of θ_{vB} will produce ion "ring" distributions that will permit access into the TUNDE-M instrument. Practically, then for O^+, OH^+, H_2O^+ pick-up ions to be detected they must be both pitch-angle scattered (isotropized in the ideal case) and accelerated. Consequently, the types of correlations with IMF parameters should be different than the correlation in evidence for the ICE energetic particle data.

Figure 3 shows $\sin^2\theta_{vB}$ and the TUNDE - M counting rate for channel 2. The IMF direction was derived from magnetic field vectors measured by the magnetometer experiment on VEGA-1 (Riedler et al., 1986). The solar wind speed exhibited slow decrease during the VEGA-1 pre-shock period (Gringauz et al., 1986); hence $\sin^2\theta_{vB}$ closely corresponds to E_{max}.

The outer two energetic ion flux enhancements between 8×10^6 and 10^7 km from the nucleus appear to anti-correlate with $\sin^2\theta_{vB}$; that is, relatively more ions were detected when the solar wind flow was roughly parallel to the field direction. There is a tendency for the ion fluxes at later times to also anti-correlate with $\sin^2\theta_{vB}$, but certainly these anti-correlations are weak. The question is then, why should the ion fluxes anti-correlate with $\sin^2\theta_{vB}$? One explanation is that low frequency electromagnetic waves which can pitch-angle scatter the ions are more likely to grow for smaller values of θ_{vB} (Sagdeev et al., 1986; Winske et al., 1985). Furthermore, one expects a positive correlation with the power of the magnetic field fluctuations, which seems to be the case only for the 12 UT March 5 peak and for the region close to the shock (Gribov et al., 1986).

3.3 Large scale magnetic field structure

Another possibility to explain the peaks is that the observed energetic ions originate near the cometary bow shock or are ions reflected off the shock. Then, probably a first-order Fermi acceleration mechanism is operating (Axford, 1982). In this case, one requires field geometries such that the observation is connected to the shock. The post-shock region can also be a significant source of high energy ions, for the level of magnetic fluctuations is rather large (Riedler et al., 1986), which indicates that second order Fermi acceleration may energize the ions effectively. Then, since the shock is practically transparent, the ions can penetrate easily.

Can ions streaming from the shock explain the large flux enhancements seen by TUNDE-M near 12 UT, March 5 ? This is possible but unlikely for several reasons:

(1) Enhanced fluxes should exist (if the energetic ions originate at the bow shock) throughout all of the 12 to 24 UT, March 5 time period (with r ranging from 6 to 2×10^6 km) because it is probable that all this region is connected to the bow shock.

(2) The bow shock must certainly be extremely weak this far downstream from the nose (Wallis & Dryer, 1986) and incapable of reflecting such energetic ions. Furthermore, the shock for 12 UT is quasi-parallel and hence turbulent.

(3) It is even less likely that the ion flux enhancements near 10^7 km can be associated with the bow shock. These enhancements seem to be associated with magnetic fluctuations in the general vicinity of the observations, and hence quite far from the bow shock.

Magnetic field fluctuations are large in several regions upstream of the shock (Riedler et al., 1986); hence, second order Fermi acceleration may be more important than first order Fermi mechanism.

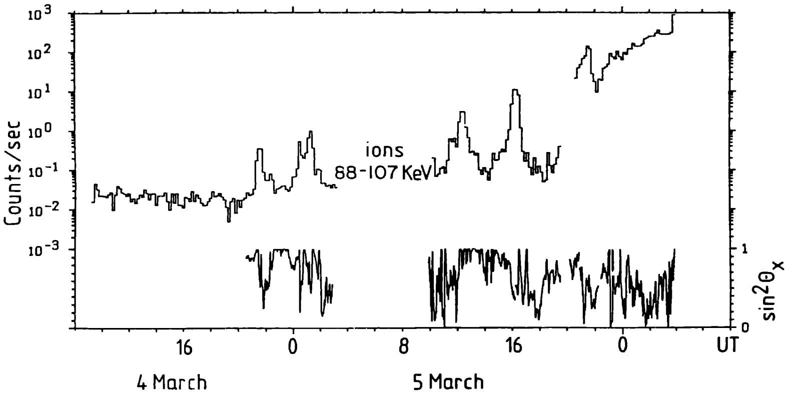

Figure 3. TUNDE-M counting rate vs. time for the 88-107 keV channel together with $\sin^2\theta_{vB}$, where θ_{vB} is the angle of the IMF with the sun-comet axis.

Quantitative evaluation of the effect of the second order Fermi acceleration in the region of $10^6 < r < 3 \times 10^6$ km is given in the paper of Gribov et al., 1986 (this issue).

4. COMETARY ION DISTRIBUTION FUNCTIONS IN THE SOLAR WIND FRAME

The counting rates in the various channels, C_i, were used to find distribution functions for energetic ions in the pre-encounter time period. C_i was converted to a distribution function, f_i at an appropriate energy E_i, using a transformation which will be shortly described in this section (the detailed description will appear in an extended version of this paper). This general type of transformation was used by Erdős (1981) for low energy interplanetary particles and by Gloeckler et al. (1986) and Ipavich et al. (1986) to find cometary ion distribution functions in the vicinity of comet P/G-Z from the EPAS data.

The TUNDE-M observing geometry was described in Section 2 and Figure 1. We assume that the ion distribution is completely isotropic in the solar wind reference frame. We use solar wind (proton) velocities measured by the PLASMAG instrument on VEGA - 1. The solar wind speeds as measured in the pre-shock region, vary between 550 and 420 km/s approximately. To perform the transformation, the measured solar wind velocities were used.

We assume that the distribution function of ions is a Maxwellian (at least in the narrow energy band in which ions were detected):

$$f(E,r) = f_o(r)\exp(-E/T) \qquad (4.1)$$

where r is the radial distance from the comet. First, a reasonable temperature T is estimated to calculate the contribution to the counting rate of each channel from the distribution function. Then, the measured counting rates of the channels serve as a basis for a least-squares fit from which a new value of T can be obtained. The procedure is repeated until it converges.

Distribution functions in the SWRF which were calculated using the above procedure are shown in Figures 4 and 5 for several times in the pre-shock period of VEGA - 1. Figure 4 shows the calculated ion spectra at the peaks of flux enhancements. Temperatures found from the final least-squares fit at each time are indicated in the figure.

Several features are apparent in the calculated distribution functions. First, the overall trend of f is to increase with decreasing r radial distance, second, the slopes of the distribution function in Figure 4 tend to increase with decreasing r; that is, the temperature T is larger farther from the nucleus between 3 and 10 million km radial distance. The spectra at the first flux enhancement regions are quite flat with temperatures ranging from 16 to 21 keV, whereas for radial distances less than 5 million km the spectra are much steeper ($T \approx 5$ to 7 keV). Some possible interpretations of these spectra will be discussed in the next section.

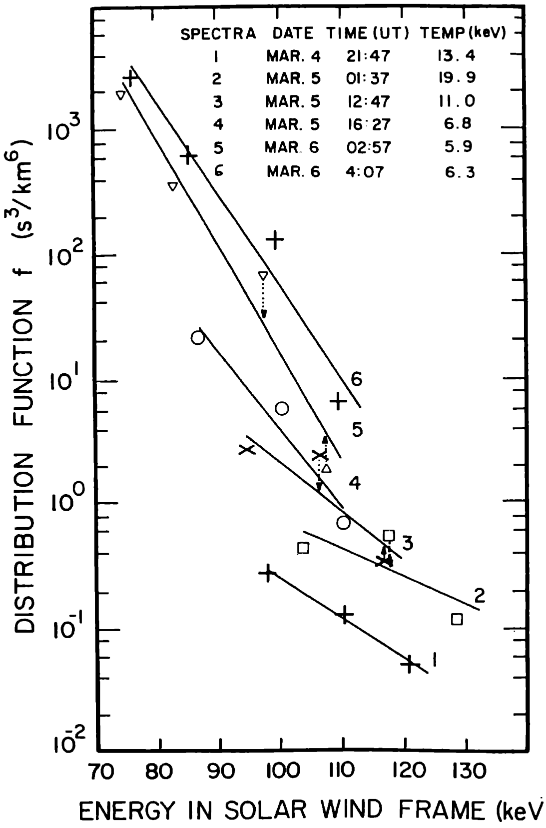

Figure 4. Cometary ion distribution function vs. energy in solar wind reference frame for several times associated with ion flux enhancement.

5. DISCUSSION

The TUNDE-M experiment shows that the energetic ion flux starts to increase (Figure 2) far outside of Halley's bow shock, with a number of large flux enhancements superimposed on the general background flux level. The overall shape of the spatial distribution of the flux agrees roughly with what would be expected from the total density of pick-up ions as a function of the distance from the comet.

A study of possible correlations between the flux and $\sin^2\theta_{vB}$ does not provide any evidence for the dependence of the flux on the maximum pick-up energy unlike the energetic ions measured by ICE (Hynds et al., 1986). The flux enhancements at a few million km from the nucleus are not correlated with $\sin^2\theta_{vB}$, while the outermost two peaks ($r \approx 9$ and 10 million km, respectively) even anticorrelate with it. A possible explanation of the anticorrelation is that at times when θ_{vB} is small (i.e., when the magnetic field is quasi-parallel to the solar wind flow direction), the growth rate of magnetic fluctuations is larger and these fluctuations accelerate particles via second order Fermi mechanism. Another possibility is that the angular distribution may be highly anisotropic (isotropization is probably slower at these distances) and during the enhancements the instrument looks toward preferred directions.

The observation that the maximum pick-up energy does not control the flux level is reasonable, since the solar wind pick up acceleration alone is not sufficient to provide ion energies which are detectable by TUNDE-M. An additional acceleration mechanism could be associated with the cometary bow shock. This possibility is supported by the observation (Somogyi et al., 1986) that the flux of energetic ions peaks at the close vicinity (closer than 10^5 km) of the bow shock. However, the cometary bow shock is very weak, and therefore the first order Fermi process and the gradient drift acceleration process are probably insufficient in out case. A second order Fermi acceleration by the enhanced magnetic field turbulence associated with the shock is more likely to operate (Gribov et al., 1986).

Energy spectra of ions were determined in the solar wind reference frame by fitting Maxwellian distributions to the ion fluxes near relevant energies. Both the temperature of the Maxwellian and the magnitude of the distribution function at radial distances of 1-2 million km from the nucleus agree with energetic ion distribution functions measured at P/G-Z (Gloeckler et al., 1986). We are not suggesting that the distributions are Maxwellian; only that they fall off rapidly with energy for energies near 100 keV. The temperature is generally larger at larger distances from the comet. Figure 4 suggests that at the enhancements, the total cometary ion density is larger but there is less particle scattering, however, no clear relation is found between ion flux and the level of magnetic fluctuations in the regions envisaged in this paper ($2.5 \times 10^6 < r < 10^7$ km). Whatever the mechanism of the additional acceleration should be, there is still the question how either cometary neutrals or ions could travel so far (10^7 km) from the nucleus. The possibility of ions being created close to the comet and travelling this distance is improbable, since if the particles were created close to the comet, the solar wind would convect them in a tailward direction. Even if this convection is overcompensated by an additional acceleration, it is very unlikely that charged particles could propagate as far as 10^7 km in a direction which is nearly perpendicular to the direction of the solar wind flow. Also, the peaks in the counting rates do not show any correlation with time intervals when the magnetic field lines can have good connections to the bow shock. Assuming that the particles observed by TUNDE-M were ionized (and then further accelerated) in the vicinity or upstream of the location of the spacecraft, we meet the difficulty that the travel time of the neutrals from the nucleus to such distances is more than 100 days for a flow velocity of 1 km/s. At this distance the neutral density is severely attenuated by ionization. Furthermore, the spatial distribution of neutrals might be seriously modified by the time variation of the gas production of comet Halley.

A surprising feature of the ion flux detected by TUNDE-M (see Figure 2) is that the peaks appear quasi - periodically in time with a period of roughly four hours. No really satisfactory explanation of this feature has been found yet. However, if one assumes (in accordance with Wenzel et al., 1986 for ICE observations of Halley) that neutrals might have larger velocities, then the attenuation is much weaker. This tends us to speculate that neutrals could exhibit quasi-periodic density fluctuations. These fluctuations have, however, probably much smaller amplitudes than the ions do, thus some additional process must still be operational in producing the large quasi-periodic enhancements of the ion fluxes.

Table 1.

j(channel No)	channel limits (keV)	estimated actual energies for O^+ (keV)
1	43 - 50	78 - 88
2	50 - 64	88 - 107
3	64 - 74	107 - 119
4	74 - 85	119 - 132

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