Pickup Ions in the Unshocked Solar Wind at Comet Halley


The Tände-M experiment on board the VEGA 1 spacecraft detected energetic cometary ions as far as 10 million kilometers from comet Halley. The measured ion fluxes increased with decreasing radial distance from the nucleus, in agreement with theoretical expectations. Sharp enhancements spaced at approximately 4-hour intervals were superimposed on the general increase of the ion fluxes on the inbound leg of VEGA 1. Periodic neutral structures originating from gas production by active areas on the nucleus are suggested to explain the recurrent intensity peaks. These neutral density enhancements would then produce the ion density enhancements seen by Tände-M as the spacecraft traversed the structures. This explanation requires a considerably larger neutral expansion velocity (>6 km/s) than was actually measured near the nucleus in order to allow the rotation period of the nucleus to generate the observed period of the enhancements. No obvious correlations of the ion fluxes with the limiting energy for pickup were found. However, at a distance of about 10^7 km from the comet, a weak anticorrelation was found between the ion flux and the angle between the interplanetary magnetic field and solar wind direction. Cometary ion distribution functions in the solar wind reference frame are derived from measured counting rates. These distributions are approximately Maxwellian for energies between about 100 keV and 150 keV. The derived temperatures are between about 5 and 8 keV for most cometocentric distances, although in a region between 10 and 8 million km from the nucleus the ion spectra were harder, with temperatures ranging from 10 to 20 keV.

1. INTRODUCTION

Cometary ions, such as O⁺, OH⁺, and H₂O⁺, are created from cometary neutrals by photoionization, by charge exchange with solar wind particles, and by electron impact ionization [cf. Mendis et al., 1985; Cravens et al., 1987]. The freshly ionized particles, which are created almost at rest in the cometary frame of reference, are initially accelerated by the motional electric field of the solar wind and are partially "picked up" by the solar wind. The ions initially follow cycloidal trajectories in the E x B direction [cf. Ip and Axford, 1982; Galeev et al., 1985; Cravens, 1986]. The cometary ion distribution function is therefore initially a ring distribution in velocity space with a drift velocity parallel to the magnetic field with respect to the solar wind. This ring/beam distribution is highly unstable and generates Alfvén waves via an ion cyclotron instability. These waves can pitch angle scatter the ions, and thereby make the distribution nearly isotropic in the solar wind reference frame on a time scale of the order of several gyroperiods [cf. Sagdeev et al., 1986a; Gary et al., 1986]. This isotropization of the ion distribution completes the pickup process in that the ions are now drifting with the solar wind. Magnetic fluctuations can also result in stochastic acceleration of the ions via the second-order Fermi process [Ip and Axford, 1986; Gribkov et al., 1986; Gombosi, 1988].

The traversal of the cometary 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 [cf. Axford, 1981]. Further, acceleration of cometary ions up to several hundreds of keV should also be expected downstream of the bow shock, 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 bow shock, second-order Fermi acceleration is probably the most important process among the various mechanisms listed above [Ip and Axford, 1986].

Energetic particle measurements at comet Halley have been made by instruments on board the VEGA 1 spacecraft [Somogyi et al., 1986a; Keckeméty et al., 1986] as well as on the Giotto probe [McKenna-Lawlor et al., 1986a; Daly et al., 1986]. Cometary pickup ions were observed as far as 10 million km from comet Halley, in the energy range of about 96 to 153 keV (in the spacecraft frame of reference of VEGA 1) and 78 to 270 keV (Giotto, [McKenna-Lawlor et al., 1986b]), extending well above the energies expected on the basis of the original pickup mechanism. The maximum energy of a pickup ion in the cometary frame of reference, and before pitch angle scattering takes place due to magnetic fluctuations, is given by E_{max} = 2/3 an^2 sin^2 \Theta_{VB}, where n is the ion mass, v is the solar wind speed, and \Theta_{VB} is the angle between the interplanetary magnetic field and the solar wind. E_{max} is about 80 keV for u = 500 km/s, \Theta_{VB} = 90°, and for O⁺ ions. This energy is roughly the minimum energy at which heavy ions can be detected by the various energetic ion instruments. The initial pickup energy in the solar wind reference frame is just 1/2 an^2, which is typically about 20
keV for O\textsuperscript{+} ions. Energetic ion observations were made earlier at comet Giacobini-Zinner (G-Z) by instruments on the ICE spacecraft [Hyndes et al., 1986; Sanderson et al., 1986a; Ipavich et al., 1986]. The cometary ion distributions measured outside the comet G-Z bow shock by ICE 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; Sanderson et al., 1986a; Richardson et al., 1986, 1987]. The distributions measured in the vicinity of the shock by ICE appear to be almost completely isotropized.

In this paper we examine energetic cometary ion fluxes measured by the Ttinde-M experiment during the preencounter time period when VEGA 1 was still outside the bow shock of comet Halley. A later paper will investigate data from the region inside the shock. We will show here that, in order for ions to be observed by the Ttinde-M instrument, they must have both pitch angle scattered and accelerated. Possible acceleration processes are discussed in the light of these observations.

The instrument geometry and response of the Ttinde-M instrument are described in section 2. Section 3 gives the ion flux profiles measured by Ttinde-M and presents a correlation study of these fluxes with the magnetic field data measured by the magnetometer on board VEGA 1 [Riedler et al., 1986]. Section 4 presents the cometary ion distribution functions derived from Ttinde-M data for the frame of reference moving with the solar wind.

2. INSTRUMENTAL AND OBSERVING GEOMETRY

The VEGA mission and the trajectories of the space probes were discussed by Sagdeev et al. [1986b]. In the vicinity of the comet, the VEGA 1 trajectory formed an angle of approximately 111° with the Sun-comet axis, and the inclination angle (formed with the plane of ecliptic) was 4.6°. The Ttinde-M instrument consisted of a semiconductor telescope (for detailed information, see Somogyi et al. [1986b]), which pointed normal to the Sun-comet axis in the ecliptic plane and detected particles arriving from a direction approximately opposite to the spacecraft motion. The geometric acceptance was within a cone of about 25° half angle (see Figure 1). The geometric factor is 0.25 cm\textsuperscript{2}sr. The most likely candidates for heavy pickup ions far from the nucleus (r>10\textsuperscript{5} km) are O\textsuperscript{+} and OH\textsuperscript{+}, whereas H\textsubscript{2}O\textsuperscript{+} becomes dominant closer to the nucleus. Smaller abundances of other ion species such as CO\textsubscript{2}\textsuperscript{+}, CO\textsuperscript{+}, S\textsuperscript{+}, etc., can also be expected [Gringauz et al., 1986; Balsiger et al., 1986].

Energetic ions which are incident on the detector must first go through an aluminum window and lose some fraction of their energy in traversing this "dead layer." Once an ion enters the silicon semiconductor layer of the detector, it can deposit its energy both in ionizing and nonionizing collisions; only the ionizing collisions contribute to the signal from the detector (i.e., to the "measured" ion energy), and the resulting "defect" in the amplitude of the signal is usually called the "pulse-height defect" (or PHD [see Keppler, 1978]). The nonionizing energy loss, and thus the PHD, depend on both the mass and incident energy of the incident ions. For protons, the PHD is only important for incident energies less than about 10 keV, but for heavier ions (e.g., O\textsuperscript{+}) it is important even for energies as high as 100 keV [Ipavich et al., 1978].

![Figure 1. Diagram of velocity space in the ecliptic plane and of the Ttinde-M observing geometry. An approximate instrumental observing cone and energy channels are indicated for the Ttinde-M instrument. Possible locations in velocity space of solar wind protons and cometary pickup ions are shown.](image)

**TABLE 1. Ttinde-M Energy Channels**

<table>
<thead>
<tr>
<th>Channel No.</th>
<th>Channel Limits, keV</th>
<th>Estimated Actual Energies, keV, for O\textsuperscript{+} ions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43-50</td>
<td>96-106</td>
</tr>
<tr>
<td>2</td>
<td>50-64</td>
<td>106-126</td>
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<tr>
<td>3</td>
<td>64-74</td>
<td>126-138</td>
</tr>
<tr>
<td>4</td>
<td>74-85</td>
<td>138-153</td>
</tr>
</tbody>
</table>
Fig. 2. Tünde-M counting rate (counts per second) versus time (UT) for the inbound pre-bow shock phase of the VEGA 1 encounter with comet Halley. Counting rates \( C_i \) are shown for the lowest four effective energy channels: \( j = 1-4 \). The four channels were labeled as follows: \( a \ (j = 1), b \ (j = 2), c \ (j = 3), \) and \( d \ (j = 4) \), and the counting rates were multiplied by factors of \( 10^{0.5-1} \). The background counting rate in channel 1 is about \( 1.8 \times 10^2 \) counts/s. The smooth solid line shows the relative variation of the total cometary ion mass flux (i.e., the total cometary ion number density) along the VEGA 1 trajectory, calculated using a decay scale length of \( 2 \times 10^6 \) km.

Figure 1 is a diagram of velocity space in the comet reference frame which illustrates the Tünde-M observing geometry for VEGA 1. Positive \( V_x \) (x velocity) is oriented toward 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 preencounter time period. The apex of the Tünde-M observing cone is located at the spacecraft velocity vector (in the comet frame). Several of the lowest Tünde-M energy channels are indicated, as is the velocity vector of the solar wind (protons). Tünde-M pointed in the positive \( y \) direction.

Cometary pickup ions (of any species) will initially form ringbeam 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) on a spherical shell centered at the solar wind velocity and with a 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 Figure 1 for a solar wind speed of \( u = 480 \) km/s. It should be emphasized that Tünde-M is not able to differentiate whether or not these initially picked-up ions are isotropized, although since the ring will almost never intersect the observing cone, at least partial isotropization is a reasonable assumption. The cometary ions must also be accelerated in order to be observed by Tünde-M. A spherical shell of radius \( v = 1070 \) km/s (in the solar wind reference frame — SWRF) is also shown in Figure 1. This shell has an energy of \( 1/2 \, m v^2 = 101 \) keV in the SWRF for \( O^+ \) ions. The ion mass is designated \( m \) and 101 keV is roughly the lowest energy of \( O^+ \) ions which can be measured in the lowest (effective) energy channel of Tünde-M. Actually, Tünde-M had two-lower energy channels, but they exhibited very high noise levels at all times, and therefore they were not analyzed. One can conclude from the preceding discussion that some acceleration mechanism(s) is required to energize the ions from the initial pickup energy of about 20 keV to the observed energies of 90–100 keV and above (in the SWRF).

3. Observations

Time History of the Tünde-M Counting Rates

Time histories of the Tünde-M counting rates in the four 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 were detected as far as \( \approx 10^7 \) km from the nucleus. The ion fluxes (i.e., counting rates) tended to increase with decreasing distance from the shock as discussed by Somogyi et al. [1986a]. This increase is especially steep near a radial distance of \( r = 3 \times 10^6 \) km. The fluxes were especially large near the shock. Large flux
enancements were superimposed on a background that exhibits a slow increase with decreasing $r$ 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 a solar wind streamline upstream of the point where the measurement was made. The mass flux $\rho_u$ is then

$$\rho_u = \rho_u \omega_u + \int \left[ m n(t) \right] ds$$

where $u$ is the solar wind speed, $\rho$ the mass density, $m$ the mass of a picked-up ion, and $\omega$ the neutral density as a function of radial distance $r$ from the nucleus; $\rho_u$ and $\omega_u$ are, respectively, the density and velocity of the unperturbed solar wind; $\tau$ is the lifetime of a neutral against photoionization plus charge exchange with solar wind protons (e.g., $\tau \approx 2 \times 10^6 s$ for $O^+$); $s$ is the path length, and the integral over $s$ goes from $-\infty$ (toward the Sun) to $s = 0$, which corresponds to the location of the instrument. Wallis and Ong [1975] showed that, for a simple $1/r^2$ variation of the neutral number density, the relative mass flux (which is proportional to the number density of cometary ions) increases as $1/r$ along the Sun-comet axis. Galeev et al. [1985] calculated the variation of the relative mass flux along the Sun-comet axis taking into account the attenuation of cometary neutrals by photoionization (or any time-independent loss process). That is, for a neutral density $n = (Q/(4\pi v_s^2))\exp(-(r/\lambda))$ where $Q$ denotes the gas production rate and $v_s$ the neutral gas flow velocity, the relative mass flux varies as

$$\beta u - 1 = C \left( (\lambda u) e^{-\beta} - E_1 (r/\lambda) \right)$$

where $(\beta u - 1)$ is the relative mass flux ($\beta = u/\omega_u$), $C$ is a constant, $E_1$ is the exponential integral function, and $\lambda = v_s \tau$ is the neutral attenuation scale length which is equal to $2 \times 10^6$ km for comet Halley at the time of the VEGA encounters [Gringauz et al., 1986]; $v_s$ is about 1 km/s for water group molecules [Krakowsky et al., 1986]. The total cometary ion density is proportional to the relative mass flux. A more accurate cometary ion density can be calculated directly by numerically evaluating the integral over $s$ in equation (1) using the appropriate neutral density given above and for a path parallel to the Sun-comet axis but ending at the location of the spacecraft. The relative variation of the calculated total cometary ion density as a function of the radial distance of the VEGA 1 spacecraft is shown in Figure 2.

Overall, the ion flux at higher energies does not necessarily vary in the same manner as the total ion density. The overall trend of the ion flux for the second channel (50–64 keV "deposited" energy or 106–126 keV actual energy according to Table 1) appears to decrease approximately as the total cometary ion density, although the $r$ variation of the higher-energy channels appears to be more gradual. The overall trend of the ion fluxes measured near comet G-Z by the EPAS instrument on ICE varied with $r$ in a manner qualitatively similar to that shown by the Tünede-M fluxes although $\lambda \approx 1 \times 10^6$ km was used in that study and $1 \approx 2 \times 10^6$ km was used here [Sanderson et al., 1986a].

**Correlations with Magnetic Field Direction**

The overall $r$ dependence of the ion fluxes can be partially explained by the $r$ dependence of the total pickup ion density integrated along an upstream solar wind streamline (which in turn is closely related to the $r$ dependence of the neutral density), but this does not explain the large variability of the fluxes. For example, there are obvious spikes, or enhancements, between 2 and 10 million km radial distances. The energetic ion fluxes measured by the EPAS instrument near comet G-Z also exhibited large fluctuations [Hynds et al., 1986; Sanderson et al., 1986a], which were shown to be positively correlated with the maximum energy for $E \times B$ drifting pickup ions:

$$E_{max} = 2m u^2 \sin^2 \Theta_{VB}$$

where $m$ is the heavy ion mass, $u$ is the solar wind speed, and $\Theta_{VB}$ is the angle of the interplanetary magnetic field (IMF) with respect to the solar wind velocity vector. This correlation implies that a significant fraction of the detected ions were freshly picked up by the solar wind.

One expects a different pattern of correlation for the Tünede-M measurements because the EPAS experiment on ICE was able to observe ions moving in a generally antisolar direction (the direction in which the bulk of the pickup ions move), whereas the Tünede-M instrument only detected ions at right angles to the Sun-comet axis (Figure 1). One can see that in order for cometary ions to be detected by Tünede-M, they must have been both pitch angle scattered and accelerated. Moreover, if one wishes to explain the large ion velocities via $E \times B$ cycloidal motion, either an improbably high solar wind velocity (>1000 km/s) or a very large ion mass (in excess of 60 amu) would have to be assumed. Furthermore, even with these unlikely conditions, only an extremely narrow band of $\Theta_{VB}$ angles would produce ion "ring" distributions which would have access to the Tünede-M instrument. Practically then, in order for $O^+$, $OH^+$, and $H_2O^+$ pickup ions to be detected, they must be both pitch angle scattered (isotropized in the extreme case) and accelerated. Consequently, the nature of the correlations with IMF parameters should be different from those correlations characterizing the ICE energetic particle data.

Figure 3 shows $\sin^2 \Theta_{VB}$ and the Tünede-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 only a gradual decrease during the VEGA 1 preshock period (from about 550 to 420 km/s (K.I. Gringauz, private communication, 1986); so that $\sin^2 \Theta_{VB}$ closely corresponds to $E_{max}$.

The outer two energetic ion flux enhancements were located between cometocentric distances $8 \times 10^9$ and $10^7$ km and appear to anticorrelate with $\sin^2 \Theta_{VB}$; that is, relatively more ions were detected when the solar wind flow was almost parallel to the field direction. There is also a tendency for the ion fluxes at later times (smaller $r$) to anticorrelate with $\sin^2 \Theta_{VB}$, but these anticorrelations are weak. A possible explanation for these anticorrelations with $\sin^2 \Theta_{VB}$ is that the low-frequency electromagnetic waves, which can pitch angle scatter the ions, are more likely to grow for smaller values of $\Theta_{VB}$ [Sagdeev et al., 1986a; Winske et al., 1985]. In this case, one also expects a positive correlation with the
amplitude of the magnetic field fluctuations, but this seems to have been the case only for the 1200 UT March 5 peak, and for the region after 2300 UT and up to the shock [Gribov et al., 1986].

Large-Scale Magnetic Field Structure
Another possible explanation for the observed flux enhancements is that the energetic ions originate near the cometary bow shock or are ions which were reflected from the shock. In such a case, a first-order Fermi acceleration mechanism is operating [Axford, 1981]. In order for the Tünde-M instrument to observe ions accelerated in this manner, field geometries are required such that the observation point is connected to the shock along a magnetic field line. A variation on this theme is that the magnetosheath region is very turbulent and second-order Fermi acceleration can efficiently energize ions. These ions then leak through the shock and stream along field lines to the VEGA 1 spacecraft. Figure 4 shows magnetic field vectors (projected onto the ecliptic plane) which were calculated from VEGA 1 magnetometer measurements along the spacecraft trajectory. An approximate parabolic fit to the shock position is also shown. The field structure at a selected point along the spacecraft trajectory near 1600 UT, March 5 ($r = 4 \times 10^6$ km), has been estimated using the following procedure.

First, we assumed that a magnetic field vector does not change with time in the SWRF. This is equivalent to assuming that the field is frozen into the solar wind plasma moving with a constant flow speed. A second assumption is that the field in the SWRF is uniform in the direction perpendicular to the solar wind direction. The SWRF field vectors were obtained from the field vectors measured by the magnetometer along the VEGA 1 trajectory by using the first assumption, and the estimated field line shown in the figure was found from the SWRF vectors by using the second assumption. A solar wind speed of 450 km/s was employed. The component of the magnetic field perpendicular to the ecliptic was relatively small during the two days before the VEGA 1 encounter; therefore including this component would not change the picture appreciably. Hence, a plausible two-dimensional magnetic field line has been constructed in the vicinity of a selected observation point, as indicated in the figure. This field line does indeed connect the observation point to the bow shock. The figure suggests that when VEGA 1 was at a radial distance $\approx 4$ million km from the
nucleus (March 5, 1600 UT), the shock was quasi-parallel. This does not contradict the fact that VEGA 1 observed a quasi-perpendicular shock at a radial distance from the comet of approximately 1 million km (12 hours later than 1600 UT, March 5).

Can ions streaming from the shock explain the large flux enhancements seen by Tünde-M at 1200 UT, March 5? This is possible but unlikely for several reasons.

1. Enhanced fluxes should have existed (if the energetic ions originate at the bow shock) throughout all of the 1200 to 2400 UT, March 5, time period (with r ranging from 2 to 6x10^6 km) because it is probable that all of this region was connected to the bow shock. However, enhanced fluxes were present only during part of this time interval.

2. The bow shock must have certainly been extremely weak so far downstream from the nose [Wallis and Dryer, 1986] and incapable of producing such high ion energies via shock-drift acceleration plus reflection. In any case, the shock for this time period (not the same time that VEGA 1 encountered the shock) appears to have been quasi-parallel and hence turbulent.

3. Magnetic field fluctuations are large even far upstream of the shock [Kiedler et al., 1986]; hence, the second-order Fermi acceleration mechanism should be more important than the first order Fermi mechanism several million kilometers outside the shock.

It seems even less likely that the ion flux enhancements near 10^7 km were associated with the bow shock. These enhancements were instead probably associated with local magnetic fluctuations in the general vicinity of the spacecraft.

4. COMETARY ION DISTRIBUTION FUNCTIONS
IN THE SOLAR WIND FRAME

Particle detectors like Tünde-M measure the flux of particles in various channels defined by certain energy limits. However, knowledge of the particle distribution function $f(x,v,t)$ is needed in order to allow comparisons to theoretical predictions. The particle counting rate in channel $j$ (designated $C_j$) could be easily calculated with theoretical predictions. The particle counting rate $C_j$ can be found from the distribution function $f(E')$ using

$$C_j = \int f'(v') S_j(v') dv'$$

where $S_j(v')$ is the transformation function for channel $j$. The derived distribution will be relevant, in the strictest sense, only to this angular sector. However, if the distributions happened to be completely isotropic (and this cannot be determined from the Tünde-M data), then the derived distribution functions would obviously be more general.

The following assumptions are made in performing the transformation:

1. The ion distribution function in the SWRF, $f(E')$, is assumed to be uniform in the vicinity of the instrument acceptance angle. The derived distribution will be relevant, in the strictest sense, only to this angular sector. However, if the distributions happened to be completely isotropic (and this cannot be determined from the Tünde-M data), then the derived distribution functions would obviously be more general.

2. Magnetic field fluctuations are large even far upstream of the shock [Kiedler et al., 1986]; hence, the second-order Fermi acceleration mechanism should be more important than the first order Fermi mechanism several million kilometers outside the shock.

It seems even less likely that the ion flux enhancements near 10^7 km were associated with the bow shock. These enhancements were instead probably associated with local magnetic fluctuations in the general vicinity of the spacecraft.
Fig. 5a. Transformation function $S_j(E')$ versus energy in the solar wind reference frame ($E'$) for channels $j = 1-4$ and for a solar wind speed $u = 100$ km/s. O$^+$ ions are assumed.

The trial counting rates in channel $j$, $C_{ij}$, produced by such a distribution with $f_o = 1$ are given in Table 2 for several values of the temperature $T$, and for $u = 480$ km/s. Our use of a Maxwellian does not imply that the distribution function must be Maxwellian at all energies. All that is required is that $f$ falls off rapidly in the vicinity of a particular channel. The average energy of the ions detected in channel $j$ for a given $T$ is

$$\bar{E}_j = \frac{\int E f(E') S_j(E') dE'}{\int f(E') S_j(E') dE'}$$  \hspace{1cm} (7)

$\bar{E}_j$ is the energy at which a Maxwellian would make a maximum contribution to $C_{ij}$. Table 3 lists values of $\bar{E}_j$ for several values of $T$ and for $u = 480$ km/s.

The values of the distribution function in the SWRF at $\bar{E}_j$ are denoted $f_j$ and are found from the measured values of $C_j$ using the following procedure:

1. Estimate a reasonable temperature $T$ for energies near $\bar{E}_j$. For this paper, which concerns the region upstream of the bow shock, a single temperature was assumed for all $j$.  
2. Given this $T$, determine a value of $f_o$ from $C_j$ for each $j$ by using equations (5) through (6), with the appropriate value of $u$ and $T$. This parameter is called $f_{oj}$. Table 2 provides the necessary information in the form of $C_j$ for selected values of $T$ and for a particular value of $u$. One can write $f_{oj}$ as

$$f_{oj} = \frac{C_j}{C_{ij}}$$  \hspace{1cm} (8)

3. Given $T$, one can determine $\bar{E}_j$ from equation (7).

Table 3 provides values for selected values of $T$ and $u$.  
4. Now the distribution function can be found for each $j$:

$$f_j = f_{oj} \exp\left(-\frac{E}{T}\right)$$  \hspace{1cm} (9)

5. A least squares fit of the "measured" points ($f_j$ versus $\bar{E}_j$) is used to obtain a new value of $T$. Note that either 3 or 4 points are used to determine $T$, which is in turn used in the procedure to find $f_j$ for each of the channels.

The whole procedure is repeated until the process converges, that is, until the derived parameters vary by less than a part in $10^4$ from iteration to iteration. Note that this procedure could be generalized for other assumed functional forms of the distribution function, although only Maxwellians were used for the results shown in this paper. Tests made with a power law distribution are described later.

Distribution functions in the SWRF calculated using the above procedure are shown in Figure 6 for several points in the preshock period for VEGA 1. Temperatures found from the least squares fitting procedure are also indicated.

Consider now the major (known) sources of error in the above determination of the distribution function:

1. All channels were corrected for background. The background signal results in considerable uncertainty in $C_j$ for channel 1. For the other channels, the relative background is quite small at the ion flux enhancements. However, the background is especially a problem at large radial distances for those time periods between enhancements.

2. The channel limits (i.e., the energy discrimination levels set by the electronics of the instrument) were originally determined via a preflight calibration, and these were listed in Table 1 for the four lowest (effective) channels. Unfortunately, the electronic parameters are subject to possible long-term variations, and no in-flight calibration was performed. There are indications in the data shown here (Figure 6) and in data for the region downstream of the bow shock (not shown here) that the energy limit between channels 2 and 3 should be lower. In particular, the counting rate for channel 3 seems to be systematically too high relative to the adjacent channels. For a fairly steep distribution function and for solar wind speeds near 500 km/s, only the lower part of a channel makes a significant contribution to $C_j$. Table 3 lists values of $\bar{E}_j$ for several values of $T$ and for $u = 480$ km/s.
TABLE 2. Trial Counting Rates $C_{ij}$ for $f_0 = 1$ [s$^{-3}$ cm$^{-6}$]

<table>
<thead>
<tr>
<th>Channel No.</th>
<th>Temperature, keV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 10 15 20 25 30</td>
</tr>
<tr>
<td>1</td>
<td>3.82(21)* 3.85(25) 1.07(27) 6.24(27) 1.87(28) 3.98(28)</td>
</tr>
<tr>
<td>2</td>
<td>9.33(20) 2.51(25) 1.00(27) 7.04(27) 2.38(28) 5.48(28)</td>
</tr>
<tr>
<td>3</td>
<td>3.97(19) 4.51(24) 2.89(26) 2.57(27) 1.00(28) 2.54(28)</td>
</tr>
<tr>
<td>4</td>
<td>4.87(18) 1.66(24) 1.55(26) 1.67(27) 7.30(27) 2.01(28)</td>
</tr>
</tbody>
</table>

Solar wind speed is 480 km/s.

*The numbers in parentheses should be read as 1.00(20) = 1.00 x 10$^{20}$ s$^{-1}$.

contribution to the counting rate. In this case, lowering the existing energy limit between channels 2 and 3 will not seriously affect the derived $f_j$, but will lower the derived value of $E_j$ for $j = 3$ (but not for $j = 2$). In Figure 6 this would correspond to sliding the points for the third channel down to lower energies, but preserving the same values of the ordinate. The placement and slope (i.e., temperature) of the solid lines (the Maxwellian fits to all channels) in Figure 6 would not be significantly affected by this procedure.

3. The largest source of error is certainly the pulse height defect determination; that is, there is considerable uncertainty in assigning an actual energy (for a heavy ion) to the corresponding ionizing energy deposited in the silicon detector. As described in section 2, we used the results of Ipavich et al. [1978] who claim an error of 3%. Due to the difference between our detectors and Ipavich's we estimate that the error is more like 5% (and probably less than 10%). This corresponds to a 5-keV error in determining the energy of a 100-keV O$^+$ ion, and this uncertainty results in a factor of 2 or so uncertainty in the derived distribution function for steep energy spectra.

4. There is certainly some error in the transformation procedure itself; in particular, there is uncertainty in the choice of the functional form of the distribution function and uncertainty in the parameters used. A Maxwellian form was used for convenience only, and it seems to fit the data reasonably well. However, other functional forms, which exhibit similarly rapid falloffs at energies near 100 keV, could have been used. For instance, power law fits were also tried, and they also gave acceptable fits. But then, the average energy $E_j$ and the magnitude of the derived distribution function were somewhat different. The power law fit gave somewhat larger slopes than Maxwellsians would at lower energies and somewhat smaller slopes at higher energies. By fitting a straight line (for a logarithmic-linear scale) to the distribution function points calculated using the power law, one finds an "average temperature" for those points. The "temperatures" (i.e., just the slopes of the curves) from the power law fits are only slightly larger than

### TABLE 3. Average Energy in Solar Wind Reference Frame $E_j$, keV

<table>
<thead>
<tr>
<th>Channel No.</th>
<th>Temperature, keV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 10 15 20 25 30</td>
</tr>
<tr>
<td>1</td>
<td>88.8 97.0 103.3 108.0 111.5 114.2</td>
</tr>
<tr>
<td>2</td>
<td>98.1 107.5 114.5 119.7 123.7 126.7</td>
</tr>
<tr>
<td>3</td>
<td>112.8 121.6 128.6 134.0 138.1 141.3</td>
</tr>
<tr>
<td>4</td>
<td>123.6 132.8 139.9 145.6 150.0 153.5</td>
</tr>
</tbody>
</table>

Solar wind speed is 480 km/s.
Fig. 6. Cometary ion distribution function (in solar wind reference frame) versus energy (in solar wind reference frame) for several observation times associated with ion flux enhancements. A spectrum right at the location of the flux spike associated with the inbound bow shock crossing is also shown. O⁺ ions are assumed. A Maxwellian fit is shown for each spectrum, as well as the resulting temperature. Each spectrum is based on 10 min worth of data. The statistical error associated with the counting rate is only 15% at the very worst and usually is much less than 15%. However, there are other more serious sources of error, as discussed in the text.

6. The shape of the sensitivity function $S_j$ significantly affects the transformation and is not known very accurately, since no preflight calibration was performed. This probably results in an uncertainty of a factor of 2 or so in the distribution function, but only a small uncertainty in the derived temperature. Other, smaller errors can be introduced by uncertainties in the solar wind velocity used in the transformation and in the pointing direction of the instrument relative to the solar wind direction.

In summary, the largest error is probably caused by the determination of the pulse height defect. All these uncertainties probably yield an error of less than 1 keV in the derived temperatures $T$ for temperatures less than 10 keV. The errors in the derived distribution function are certainly less than a factor of 10, and probably more like a factor of 2 to 3.

Several features are apparent in the distribution functions shown in Figure 6. Overall, $f$ tends to increase with decreasing radial distance $r$, as discussed in section 3 for the counting rates. Temperatures were derived for a large range of $r$ and are shown in Figure 7. The temperatures (i.e., the slopes of the distribution functions) in Figure 7 exhibit little variation with cometocentric distance and vary between 5 and 8 keV, apart from a region about 10 and 8 million km from the comet, where the temperatures seem to be significantly higher ($T$ is between 10 and 20 keV).

Temperatures derived for this 10 – 8 million km region using the "standard" 10-min integration time fluctuated rapidly from point to point. The temperatures displayed in Figure 7 for this region were found using a larger integration time in order to smooth out these fluctuations. The temperatures derived in the 10 – 8 million km region are larger and also have a larger error associated with them than those derived outside this region. For $r$ less than ~2.4
million km the ion fluxes increase rapidly with decreasing \( r \), but the temperature increases only slightly. Some possible interpretations of these spectra will be given in the next section.

5. SUMMARY AND DISCUSSION

The Tündé-M experiment has shown that the energetic ion flux starts to increase (Figure 2) at a distance of \( 10^7 \) km outside of Halley's bow shock, with a number of large flux enhancements superimposed on the general flux level. The overall shape of the spatial distribution of the flux agrees roughly with what would be expected from the total density of pickup ions, as a function of distance from the comet.

A study of possible correlations between the ion flux and \( \cos \Theta \) did not provide any evidence for the dependence of the flux on the maximum pickup energy, unlike the energetic ions measured by EPAS on ICE [Sanderson et al., 1986a]. The flux enhancements within 2 million km of the bow shock upstream are not correlated with \( \cos \Theta \), while the outermost two peaks even anticorrelate with it. A possible explanation of the anticorrelation is that during times when \( \Theta \) is small (i.e., when the magnetic field is quasi-parallel to the solar wind flow direction), the growth rate of magnetic field fluctuations is larger [Sagdeer et al., 1986a].

The observation that the maximum pickup energy does not control the flux level is reasonable, since the initial ion pickup process by itself is not sufficient to produce ions which are detectable by Tündé-M. Ion acceleration might also be associated with the cometary bow shock. This possibility is supported by the observation [Somogyi et al., 1986a,b] that the flux of energetic ions reaches a maximum in the close vicinity of the bow shock, whereas at comet G-Z the ion intensity did not peak at the inbound wave although it did so outbound [Hynds et al., 1986]. However, the cometary bow shock is very weak, and therefore the first-order Fermi process and the gradient drift acceleration process are probably insufficient to produce the measured energies. Second-order Fermi acceleration in the enhanced magnetic field turbulence associated with the shock is probably a more effective mechanism [Gribov et al., 1986]. But shock acceleration mechanism of any type is not a likely explanation for energetic ions detected more than a couple million kilometers from the shock, as discussed in section 3.

Energy spectra of ions were determined in the solar wind reference frame by fitting Maxwellian distributions to the ion fluxes in the relevant energy range (between about 90 and 150 keV). The derived distribution functions indicate that the temperatures of the Maxwellian at cometary distances of \( 1-2 \times 10^6 \) km are similar to the temperatures measured just outside the bow shock of comet G-Z near a cometary distance of \( 2 \times 20^3 \) km [Gloeckler et al., 1986]. We are not suggesting that the distributions are complete Maxwellians, only that they fall off rapidly with energy for energies near 100 keV. Since we have four spectral points in a relatively narrow energy band, we cannot extrapolate much below our lowest-energy channel. Therefore, all functions which have similar rapid falloffs near 100 keV are also possible. Other functional forms of \( f \) (e.g., \( f = f_0 \exp (-\nu/\nu_0) \) and power law) have been used by Richardson et al. [1986, 1987]. However, higher energy resolution Tündé-M data available downstream of the bow shock indicate that the Maxwellian form is plausible. The most important role of the assumed functional form is in the determination of the average energy corresponding to each energy channel, and this does not depend strongly on the actual functional form chosen.

The magnitudes of the distribution functions found in this paper can be compared to those found by Gloeckler et al. [1986] if one slightly extrapolates the Gloeckler et al. functions up to energies of 90–100 keV. The comet Halley distribution functions are about a factor of 10 greater than the G-Z distribution functions for the regions just outside the respective bow shocks. The total number density of pickup ions for the two comets should be very similar just outside the shock, regardless of the relative gas production rates, because the shock is located where the total pickup ion number density (i.e., mass addition to the flow) attains a critical value [Galeev et al., 1985]. The fact that \( f(E) \) at \( E' \) = 100 keV is larger for comet Halley than for comet G-Z, in spite of similar total cometary ion densities, indicates that the ions at comet Halley have undergone more acceleration than the G-Z ions. Perhaps this is just due to the larger length scale of the Halley pickup process.

Now we will discuss the detection of ions at distances of several million kilometers from the nucleus. Accepting the proposition that second-order Fermi acceleration is likely to energize particles, there is still the question of how cometary neutrals (which eventually get ionized) could travel such a great distance (\( 10^7 \) km) from the nucleus. Typically, such neutrals have lifetimes against ionization of \( 1-2 \times 10^6 \) s, which gives an attenuation scale length of \( \lambda = v_\lambda \times \sigma \), where \( v_\lambda = 1 \) km/s. The travel time from the nucleus to such distances is more than 100 days for this flow velocity. The neutral density is severely attenuated by ionization for these long times (i.e., large distances).

Furthermore, the spatial distribution of neutrals might be seriously modified by the time variation of the gas production of comet Halley. If \( \lambda = 2 \times 10^6 \) km, as assumed in the calculations of the total ion density shown for Figure 2, then only 1% of the neutrals survive out to a cometary distance of \( 10^7 \) km. Figure 2 indicates this might be sufficient to account for the detected flux levels. But if \( \lambda \) were only \( 10^6 \) km, then only \( \approx 0.01\% \) of neutrals traveling at 1 km/s would survive out to \( 10^7 \) km, in which case another source of neutrals is needed.

A surprising feature of the ion fluxes detected by Tündé-M (see Figure 2) is that the peaks appear to vary quasi-periodically in time with a period of four hours. There are additional narrow peaks at 0700 UT on March 5 in the \( f = 3 \) and 4 channels which also exhibit this periodicity but which were not included in Figure 2 because of the large background level associated with a different operational mode of the instrument. A similar periodicity (7 hours) was seen in the flux of picked-up cometary protons measured by the ion mass spectrometer (IMS) on Giotto several million kilometers from comet Halley [Neugebauer et al., 1986].

The observation of quasi-periodicity in the ion flux enhancements observed between 3 and 10 million km from the nucleus suggests an explanation based on the spatial distribution of the neutrals. The television observations made by VEGA and Giotto around their closest approach to the nucleus [Sagdeev et al., 1986c; Keller et al., 1986]
Millis and Schleicher [1986]). A 53-hour period requires a nucleus. This is a very high velocity for O molecules and is be observed.

The above model of periodic neutral structures places severe restrictions on the velocity distribution of the neutrals. First, the average velocity should strictly correspond to the spatial periodicity. Second, the thickness of the spatial density shells should be small enough such that the shells would not be unduly smeared out as they propagate outward. The observation of peaks separated by about 4 hours along the path of VEGA 1 corresponds to spatial intervals of about $10^6$ km (here we did not take into account the bending of the neutral trajectories in the cometary frame which affects the spatial structures of neutrals at large distances from the nucleus as pointed out by Erdős and Kecsákméthy [1987] and Daly [1987]). The rotation period of the nucleus of comet Halley has been so far most reliably established by spacecraft optical measurements [Sagdeev et al., 1986] which gave \( \approx 53 \) hours (however, a longer, 7.7-day period is favored by some other experiments Millis and Schleicher [1986]). A 53-hour period requires a neutral velocity of \( \approx 6 \) km/s in order to permit the neutrals to travel a sufficient distance during one rotation of the nucleus.

This is a very high velocity for O molecules and is much larger than the neutral velocities measured by Giotto (0.9 km/s Krankowsky et al. [1986]) in the inner coma. In addition, a rather low dispersion in the velocity distribution is needed so that the shells do not become thicker than was observed. The observed thickness is roughly \( \Delta r = 0.3 \times 10^6 \) km at a cometaryentric distance \( r = 10^7 \) km, and the required velocity dispersion is \( \Delta V/V = \Delta r/r = 0.03 \).

One possible source of such high-velocity O atoms is the dissociative recombination of CO\(^+\) ions in the inner coma of comet Halley (\( r < 5 \times 10^6 \) km):

\[
\text{CO}^+ + e \rightarrow C + O
\]

Reaction (10) will produce O and C atoms with velocities of several kilometers per second and very small velocity dispersion. Dissociative recombination proceeds rapidly only for cold electrons, and thus these fast atoms can be produced only within the inner coma where the electron temperature is low [cf. Mendis et al., 1985]. These fast atoms will move out isotropically from the inner coma and produce shells even if the parent CO\(^+\) ions are distributed highly asymmetrically (e.g., jets). The fast atoms appear to be produced isotropically due to the small size of the inner coma compared with scale lengths of millions of kilometers.

The assumption of a large neutral expansion speed could also explain one more observation: the appearance of ions at the ICE spacecraft at large distances (\( \approx 3 \times 10^7 \) km) from Halley's comet [Wenzel et al., 1986; Sanderson et al., 1986b; Daly, 1987]. It is also in agreement, on one hand, with theoretical expectations based on the travel time needed for neutrals to reach the distances required by the VEGA 1 and ICE observations, and on the other hand, with the minimum velocities calculated by Erdős and Kecsákméthy [1987] based on particle trajectories.

Another possibility is that the ions seen by Tunde-M were protons. The initial pickup energy for protons is very low compared to that for heavier species; thus, the required acceleration would have to be quite significant. The protons need to be accelerated above the pickup energy by a factor of \( \approx 100 \) in order to be detected by Tunde-M. This might be possible if one considers that stochastic Fermi acceleration is \( \approx 15 \) times more effective for protons than for O\(^+\) ions [Ip and Axford, 1986] at the strong turbulence limit. Still, heavy ions seem preferable.

Acknowledgments. The authors thank the referees for suggestions which significantly improved this paper. The part of the work carried out at The University of Michigan was supported by NASA grants NGR 13-005-015 and NAGW-15, and NSF grants ATM 84-17804 and INT 8319732.

The Editor thanks S. M. P. McKenna-Lawlor and I. G. Richardson for their assistance in evaluating this paper.

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(Received December 30, 1986; revised June 28, 1988; accepted June 29, 1988.)