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AUTHOR(S): B. Wilken, K. Jockers, A. Johnstone, A. Coates, J. Heath, V. Formisano, E. Amata, J.D. Winningham, M. Thomsen, D.A. Bryant and H. Borg

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COMET TAIL FORMATION - GIOTTO OBSERVATIONS

B.Wilken[1], K.Jockers[1], A.Johnstone[2], A.Coates[2],
J.Heath[2], V.Formisano[3], E.Amata[3],
J.D.Winningham[4], M.Thomsen[5], D.A.Bryant[6],
H.Borg[7].

Katlenburg-Lindau
[1]Max-Planck Institut fur Aeronomie, D-3411 FRG; [2]Mullard Space Science Laboratory, Holmbury St.Mary, Surrey, RH5 6NT, UK; [3]Istituto di Fisica dello Spazio Interplanetario 00044, Frascati, Italy; [4]Southwest Research Institute, San Antonio, Texas 78284, USA; [5]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA; [6]Rutherford Appleton Laboratory, Didcot, OX11 0QX, UK; [7]Kiruna Geophysical Institute, 90187 Umea, Sweden.

ABSTRACT

The process of mass loading of the solar wind by cometary ions, which forms comet tails, has been observed throughout the coma of comet Halley. Three distinct regimes were found where the nature of the energy and momentum coupling between solar wind and cometary ions is different. Outside the bow shock, where there is little angular scattering of the freshly ionised particles, the coupling is described by the simple pickup trajectory and the energy is controlled by the angle between the flow and the magnetic field. Just inside the bow shock, there is considerable scattering accompanied by another acceleration process which raises some particle energies well above the straightforward pickup value. Finally, closer to the nucleus, the amount of scattering decreases and the coupling is once more controlled by the magnetic field direction.

INTRODUCTION

In 1957 Alfvén /1/ described how a comet tail could be formed by partially-ionised cometary gas loading the solar wind flowing past the comet. The fundamental process in the formation of the tail is the transfer of energy and momentum from the solar wind to freshly-ionised cometary particle. The plasma analysers on Giotto were able to observe this process in detail as the spacecraft crossed the coma of Halley's comet at 73° to the comet-sun line, passing 600km sunward of the nucleus, even though they did not observe the structure of the magnetic tail itself.

OBSERVATIONS

The entire process is illustrated in figure 1 which shows data from the Implanted Ion Sensor (IIS) of the JPA instrument /2/. Each panel contains data from one of five sensors set at five different angles with respect to the spacecraft spin axis. The sensor divides the data into 5 broad mass groups on-board. The group shown here is the water-ion group from 12-22amu. The panels also show solar wind ions because their flux is so high that it causes a pile-up of pulses in the time-of-flight system which allows some protons to masquerade as heavier ions. We take advantage of this effect here in order to show solar wind and cometary ions in the same panel. Since the two populations are completely separated in the energy spectrum, there is no ambiguity in the interpretation.

The solar wind is seen predominantly in the central panel at energies between 200eV and 1keV. The plot begins at 13:16GRT (Ground Received Time) on March 13th when the spacecraft was 2.7×10^6 km from the nucleus. The solar wind speed at this time, obtained from the Fast Ion Sensor /2/, was 340±5km/s. As the spacecraft neared its closest approach to the comet at 00:11GRT, the speed of the solar wind decreased as expected due to mass loading by heavy cometary ions. The cometary ions are seen in the upper part of each panel. At the beginning of this period their mean energy is approximately 32keV. As the comet is approached, the fluxes increase, the average energy decreases and the width of the band in energy increases.

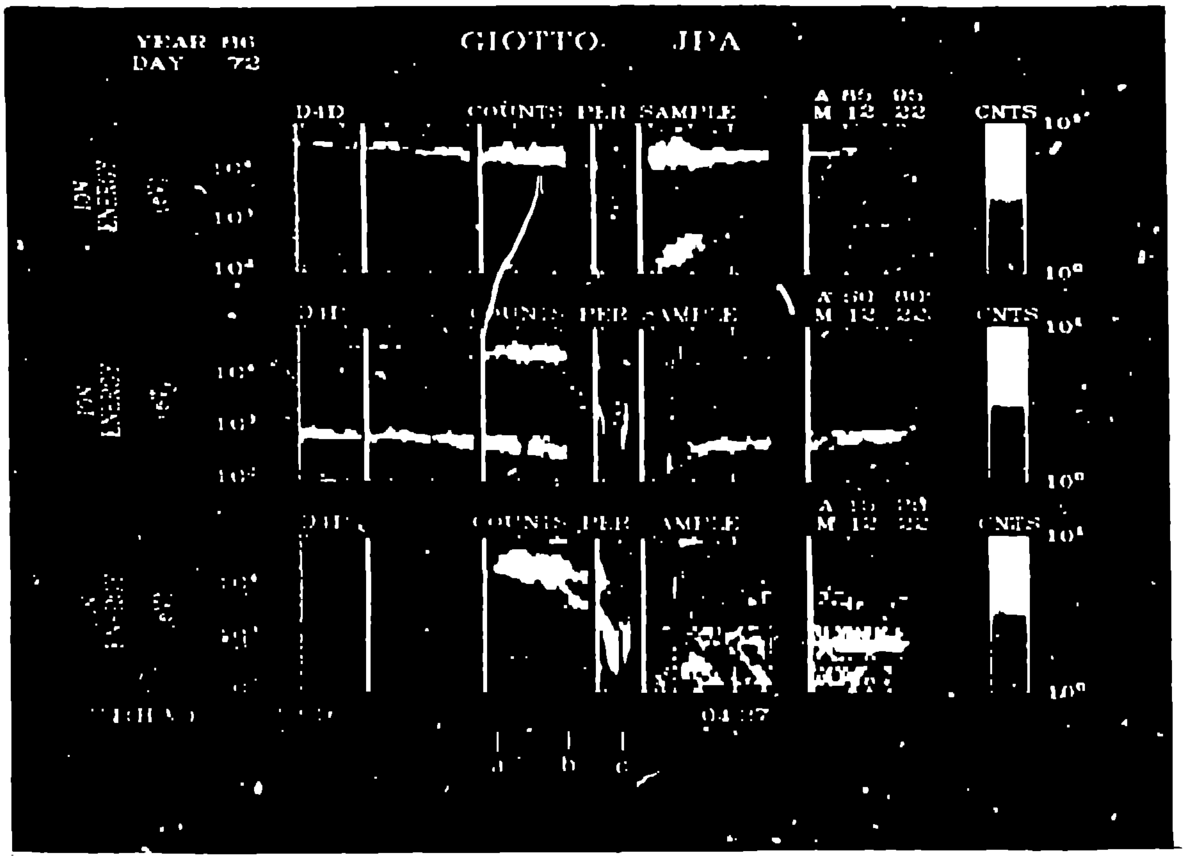

Fig.1. An overview of the cometary ions (upper line or lines in each panel) and solar wind during Giotto's encounter with Comet Halley for three directions of motion relative to the spin axis. The three points marked in the diagram correspond to the times discussed in the text; a - 19:30 GMT, b - 22:00 GMT; and c - the position of the closest approach. At closest approach the sensor became switched into a non-operating state and could not be restored for 30 mins. At closest approach the sensor whose data are shown in the bottom panel became noisy.

Within this overall pattern there are a number of structural features. We call attention here to two of them. The first is the event at 19:30 GMT where there is an increase in the flux of cometary ions and a change in the angular distribution of both solar wind and cometary ions. This has been identified as the bow shock of the comet /3/. The second is at 22:00GMT where the spectrum of the cometary ions splits into a double-peaked structure with another change in the angular distributions.

While this plot illustrates in a general way the phenomenon of mass-loading and hence the formation of a cometary tail, there is more detailed information on the process in the data.

The ion pickup process is illustrated in figure 2. The velocity coordinate system is chosen so that the solar wind velocity $\underline{V}_{sw}$ is parallel to the x-axis, while the xy plane also contains the magnetic field direction $\underline{B}$, drawn through the solar wind velocity. A spherical shell, of radius V_{sw} is drawn about $\underline{V}_{sw}$. Ion pickup injects the new ion into a narrow circular band on this shell, perpendicular to the magnetic axis, and passing through the origin. After injection it is expected that pitch angle scattering diffuses the ring over the spherical shell /4/. These processes have several observable consequences. The ion pickup ring has a maximum energy E_r

$$E_r = 4ME_p \sin^2\theta_{VB}$$

where E_p is the solar wind proton energy, M the mass of the cometary ion in atomic mass units and θ_{VB} the angle between $\underline{V}_{sw}$ and $\underline{B}$. The direction of the velocity of the ions with this maximum energy is perpendicular to the magnetic field.

If the distribution has diffused over the shell the maximum energy is E_s

$$E_s = 4ME_p$$

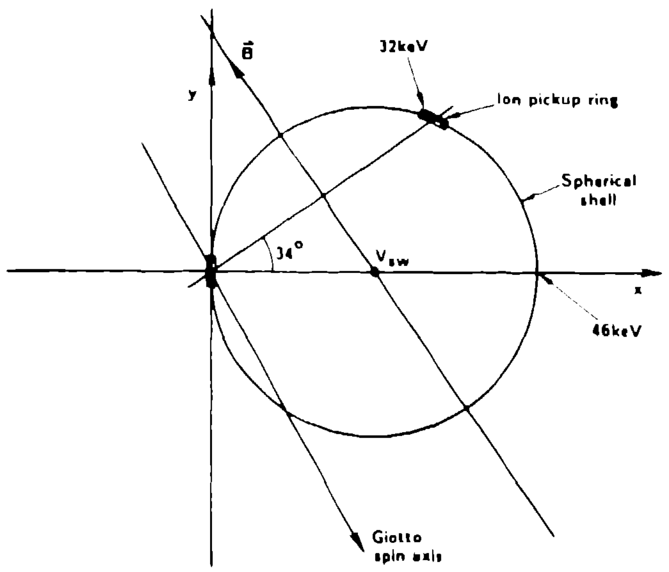

Fig.2. A diagram in velocity space illustrating the ion pick-up process. The coordinate system is chosen so that x is parallel to the solar wind velocity V_{sw} and the xy plane contains the magnetic field direction B. During the encounter the Giotto spin axis also lay nearly in this plane. Ions are picked up initially in the ring perpendicular to the magnetic field (a narrow circular band on the spherical shell) and are then expected to diffuse in pitch angle around the spherical shell.

in a direction parallel to the solar wind flow. Taking M = 18, the peak in the mass spectrum as shown by detailed time-of-flight spectra from the Implanted Ion Sensor, and E_p = 639 eV (350 km/s) from Fast Ion Sensor data gives

E_s = 46 keV

At the beginning of figure 1 the energy is only 32 keV, so taking this to be the value of E_r, we can obtain θ_{VB}, the magnetic field direction.

$$\theta_{VB} = \sin^{-1} (E_r / E_s)^{0.5} = 56^{\circ}$$

This has not yet been confirmed by observations by the magnetometer on Giotto.

As shown in figure 2 the ions with energy E_r should be observed at an angle 34° to the solar wind flow. Data from the Fast Ion Sensor shows that the solar wind flow is observed at an angle of 65° to the spacecraft velocity vector, and spin axis. Data from the closest sensor of the IIS, covering the angular range 50° - 60°, shown in the middle panel of figure 1, confirms that intensities in this region are relatively high. The cometary ions should then be detected at an angle of 65 + 34 = 99° to the spin axis. They are found to be most intense in the 85° -90° sector at the beginning of the pass, in agreement with this interpretation.

After crossing the bow shock at 19:30 GRT /3/, the situation changes. Cometary ions are observed at energies up to 55keV, even though the solar wind speed has dropped to 200km/s (E_p = 205eV and at this point E_r = 14.7 keV. The distribution is much broader in angle, covering all the sectors in figure 1 and peaking in the angular range 15° -25°. The solar wind direction has been deflected towards this sector but still peaks in the 50° -60° range. Thus in this region the cometary ions are being accelerated above straightforward pickup energies by another mechanism, possibly Fermi acceleration /3/.

The situation changes again at 2200GRT, when the energy distribution develops two branches in energy. The upper branch continues at the same energy but decreases in intensity. The lower branch decreases rapidly in energy, increases in intensity and is deflected even more strongly into the angular sector closest to the spacecraft velocity vector. We interpret this second line as ions created locally, perhaps by charge-exchange with the more energetic ions, at an energy appropriate to ion pickup, without pitch angle scattering. The steadily decreasing ratio $E_p(WG^+)/E_p(H^+)$ (with energies obtained from the count rate spectrum) has been plotted in figure 3 in the upper panel (WG = Watergroup), and interpreted in the lower

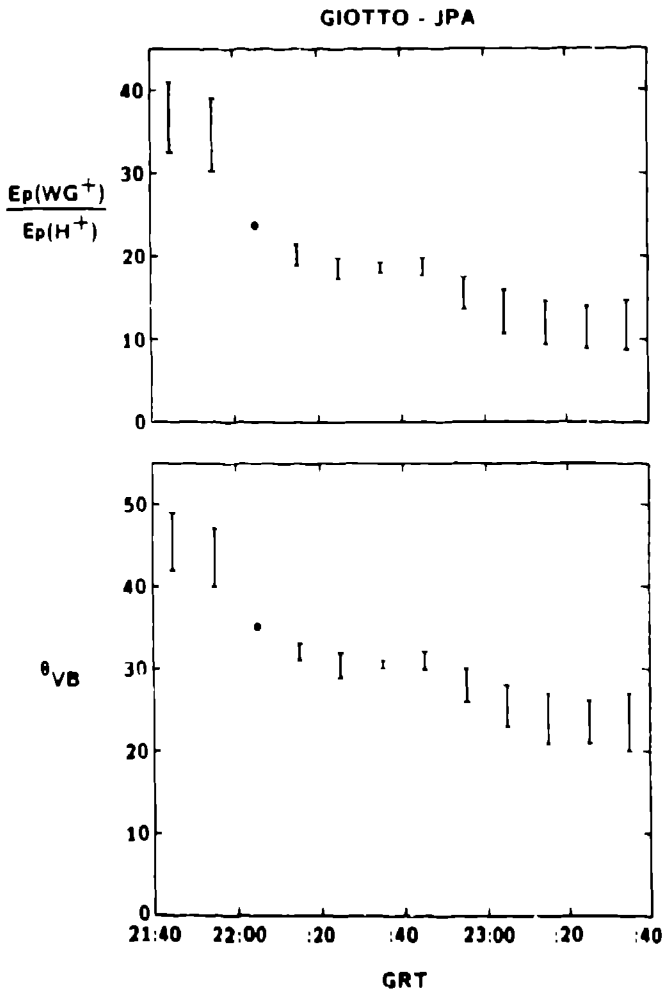

Fig. 3. The ratio between the energies of water group ions ($E_p(WG)^+$)) and solar wind ions $E_p(H^+)$ as the comet is approached interpreted as a change in the angle between magnetic field and flow direction θ_{VB}.

panel as the change in magnetic field direction caused by draping near the comet. The angle between field and flow decreases from ~46° at 2140GRT to 23° at 2330GRT. Recall that the angle was 56° at the beginning of the encounter. However this calculation has not taken account of the spacecraft orbital velocity, 30km/s, which is becoming significant at this stage since at 2330 GRT the speed of the water ions in the spacecraft frame is less than 100km/s. This factor will also contribute to changing the direction of the observed flow away from the perpendicular to the magnetic field. Confirmation of this requires a more detailed analysis.

SUMMARY

Three different ion pickup regimes have been found in the coma of Halley. Outside the bow shock ions are injected into ring distributions with little pitch angle scattering. From the bow shock at 1.13×10^6 km, in to a distance of 0.54×10^6 km there is considerable pitch angle scattering and secondary acceleration to energies well above the maximum energy attainable through straightforward pickup. Inside 0.54×10 km the pitch angle scattering ceases and the energy of the pickup ions is once again controlled by the magnetic field direction, which is by then showing the effects of draping around the comet.

Recently Wu et al /4/ have published the results of numerical simulations, based on the magnetic turbulence observed at Comet Giacobini Zinner by the ICE spacecraft which indicates that there should be little pitch angle scattering outside the shock, as we find, and an isotropic pitch angle distribution inside. Their simulations do not show the acceleration which we observe.

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