GEOPHYSICAL RESEARCH LETTERS, VOL. 13, NO. 7, PAGES 613-616, JULY 1986

DETECTION OF A NEW "CHEMICAL" BOUNDARY AT COMET HALLEY

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Abstract. Plasma observations near comet Halley indicate that around 1.6x10^{5}km from the nucleus a newly discovered sharp boundary (cometopause) separates the solar wind controlled external and the heavy cometary ion dominated internal regions. Such a discontinuity was previously not predicted by theoretical models. Inside the cometopause (in the cometary plasma region) the protons and heavy ions move with different speeds: the heavy ion velocity is less than a few km/s throughout this region, while the protons decelerate from several tens of km/s (observed near the cometopause) to a few km/s (near 1.5x10^{4}km).

Introduction

The first in situ plasma observations near comet Halley by instruments carried onboard the VEGA spacecraft (Gringauz et al., 1986) resulted in the detection of a rather broad cometary bow shock at about 1.1x10^{6}km from the nucleus (along the trajectory of the spacecraft) surrounding an extended region of increasingly mass loaded shocked plasma flow, called cometosheath. Approximately ten times closer to the nucleus the spacecraft practically ceased detecting the solar wind controlled cometosheath plasma flowing around the cometary obstacle and a region dominated by a very slowly moving magnetized cometary plasma was observed. These two regions were separated by a rather sharp boundary, the cometopause. This unexpected "chemical" boundary is different from the theoretically predicted ionopause, which separates the magnetized plasma from the unmagnetized cometary ionosphere (cf. Mendis et al., 1985). This general picture is consistent with the first results of other VEGA and Giotto experiments (see the May 15, 1986 special issue of Nature).

The overall plasma behavior at comets is now reasonably well understood in terms of mass loading effects (cf. the reviews of Galeev and Lipatov, 1984, and Mendis et al., 1985). Far upstream from the comet, the implanted ions increase the solar wind mass density and thermal energy while reducing the flow velocity. The flow is further decelerated by a relatively weak, structured bow shock. Downstream of the shock additional mass loading slows the flow down even more. Hot cometary ions implanted in the unshocked solar wind are gradually replaced by colder ones, probably due to charge exchange, thus cooling the cometosheath flow (Galeev et al, 1985). Both multidimensional MHD calculations (Schmidt and Wegman, 1982, Fedder et al., 1986) and approximate analytical solutions (Galeev et al., 1985) predicted a plasma stagnation region at a few tens of thousands of kms from the nucleus. These theoretical models assumed a single flow velocity for the multi-species stagnating plasma and did not consider the possibility of a "chemical" boundary.

In this paper we present observational evidence concerning the region of plasma stagnation at Halley's comet. It will be shown that in the cometary plasma region the ion component of the plasma is composed of two partially decoupled populations; the decelerating proton flow and an increasingly dominant almost stagnating heavy ion component. At about 1.6x10^{5}km from the nucleus a sharp boundary (cometopause) separates the solar wind controlled region from the cometary plasma region dominated by stagnating heavy ions. Significant heating of the proton population is observed at the cometopause. These observations are indications of a more complex behavior of the plasma than theoretically predicted.

Instrumentation

Each VEGA spacecraft carried a plasma instrument package (PLASMAG-1) comprised of six different sensors (Gringauz et al., 1983, Gringauz et al., 1985). Here we very briefly describe those detectors which were used in the present analysis.

Two hemispherical electrostatic analyzers observed the energy spectra of ions arriving from (1) the spacecraft-comet relative velocity direction and (2) from the direction of the sun. These sensors will be referred to as the cometary ram analyser (CRA) and solar direction analyser (SDA), respectively. Because of the three axis stabilization of the spacecraft, electrostatic lenses were installed at the entrance slits of both ion analysers in order to widen the acceptance angle without decreasing the energy resolution.

The CRA had a rectangular angular acceptance area. It detected particles from a 14° wide angle in the ecliptic plane and from a 32° angle in the perpendicular direction. Ions were registered in the energy/charge range 15-3500 eV/q (where q is the charge state) in 120 logarithmically spaced intervals which provided a complete coverage of this range without any gaps. The energy resolution was $\Delta E/E=0.055$. It should be noted that all acceptance angle and energy resolution values presented refer to the 10% level.

The SDA sensor had an 30° acceptance angle in the ecliptic plane and 38° in the perpendicular direction. It measured ions in the range 50-25,000 eV/q in 60 logarithmically spaced energy intervals with an energy resolution $\Delta E/E=0.055$. It should be noted that there is an approximately 45° gap in the sun-comet-spacecraft plane between the detection areas of the SDA and CRA. This gap may cause spurious effects when the flow is slow and relatively cold, so one has to be careful when interpreting stagnation region data.

A cylindrical electrostatic electron analyser with an acceptance angle of 7°x7° was oriented perpendicular to the ecliptic plane. It had 90 logarithmally spaced intervals with $\Delta E/E=0.075$ in the energy range 3-10,000 eV. The effective detecting area was 3.6x10^{-3}cm^2.

For the time period we study in this paper, the ion and electron energy spectra were measured at a rate 1 spectrum per second (each sensor measured a full spectrum every second). It should be noted that the present analysis is based on channeltron count rates, which reach the level of ~8x10^5 counts/s near closest approach. At such rates the channeltrons which were used operate in a nonlinear regime; significant flux increases result in only small changes in count rate making accurate estimates of the plasma parameters difficult. This effect will be taken into account in later publications.

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Paper number 6L6207.
0094-8276/86/6L-6207$03.00

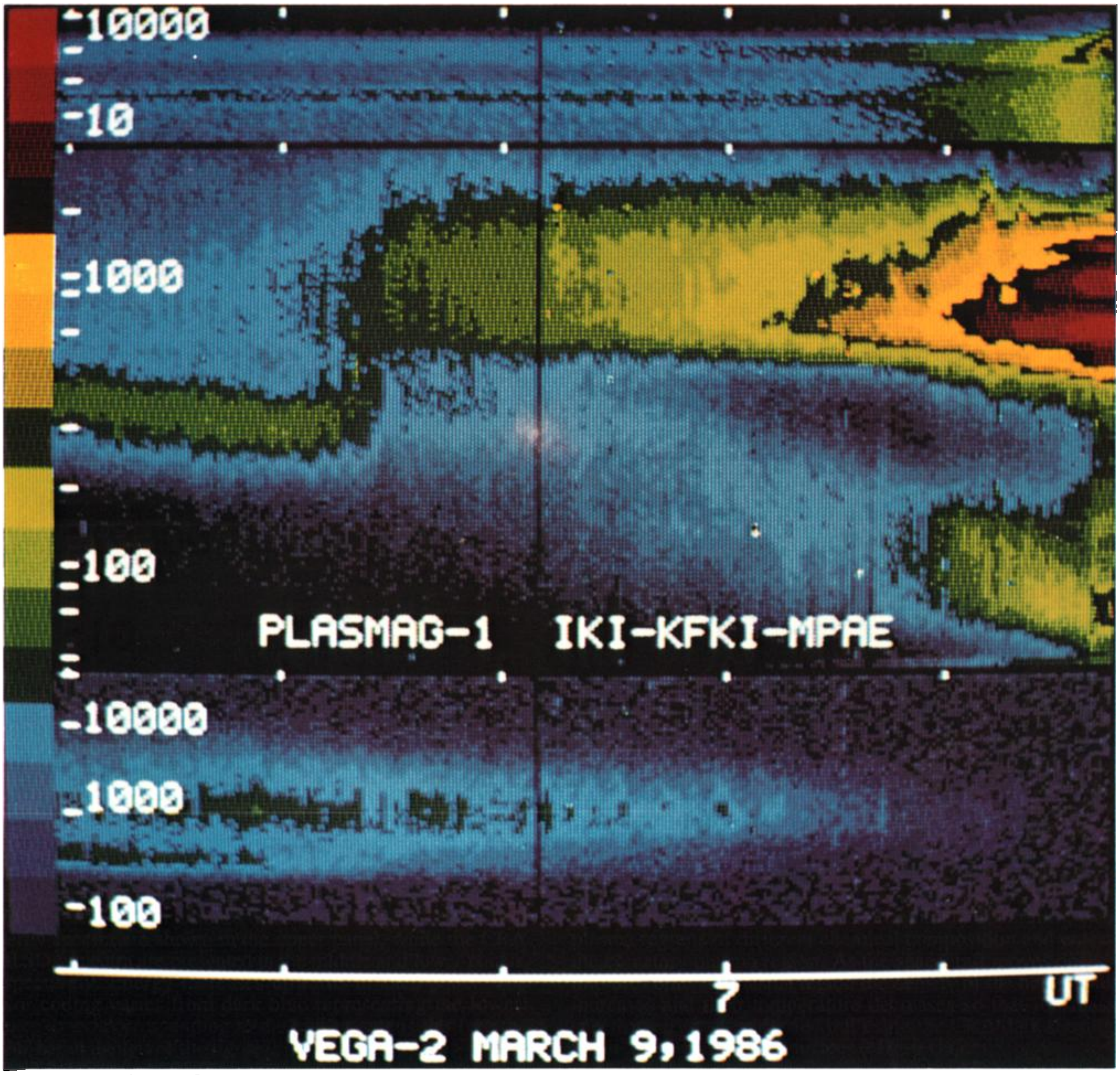

Fig. 1. Color coded summary representation of the VEGA-2 plasma measurements between 2.3×10^5km and 1.4×10^4km. Time runs from left to right (there are ten minutes tickmarks in the Figure). Electron energy spectra are shown in the upper panel, while CRA and SDA spectra are presented in the middle and lower panels, respectively. Energy increases upwards in each panel. The color coding varies from dark blue representing the lowest fluxes to red corresponding to the highest intensities (see the color bar at the left of the figure).

Observations

Figure 1 is a color coded summary representation of the VEGA-2 plasma measurements between 2.3×10^5km (0630 UT on March 9, 1986) and 1.4×10^4km (0717:29 UT) where the PLASMAG-1 instrument became temporarily disabled (the SDA analyser resumed measurements about 27 minutes later). Time (and consequently cometocentric distance) runs from left to right (there are ten minutes tickmarks in Figure 1). Electron energy spectra are shown in the upper panel, while the CRA and SDA spectra are presented in the middle and lower panels, respectively. Energy increases upwards in each panel. The color coding varies from dark blue representing the lowest fluxes to red corresponding to the highest intensities (see the color bar at the left of the figure).

At 2.3×10^5km (0630 UT) from the nucleus the heavily mass loaded solar wind population is decelerated to a velocity of about 230km/s and has a temperature of about 5×10^5K. The proton flow further decelerates to 190km/s as the spacecraft approaches the cometopause. Upstream from this boundary the deviation angle (angle between the antisolar and the plasma flow directions) determined from proton fluxes simultaneously detected by the CRA and SDA is 10° - 15°. Between 0643 and 0645 UT (1.7-1.6×10^5km) VEGA-2 intersects a sharp ($\sim 10^4$km wide) boundary separating two plasma regions of different chemical composition and enters the cometary plasma region. As the spacecraft moves deeper into the cometary plasma region the density of the heavy ions increases and their temperature decreases so that ion mass spectrometry can be carried out using the CRA data starting about 5×10^4km from the nucleus (~0710 UT).

As one can see from the lower panel, the SDA sensor does

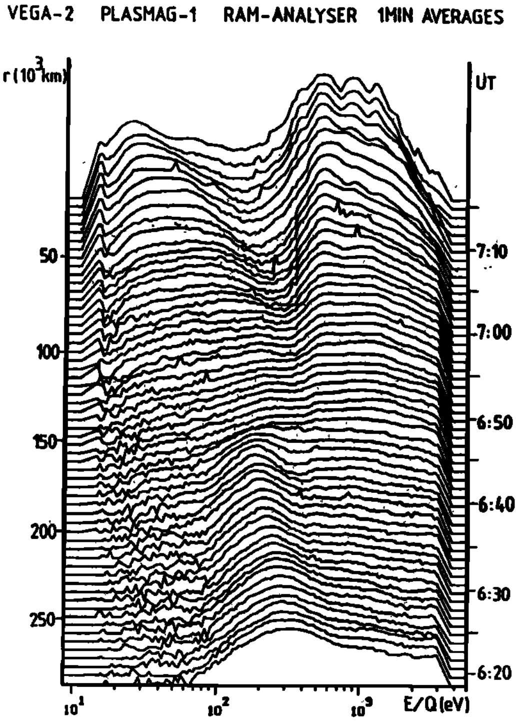

Fig. 2. One minute averages of the ram ion analyser spectra in the near cometary region.

not detect protons inside the cometopause and the proton fluxes observed by the CRA inside the cometary plasma region are significantly depleted inside the cometopause until about $5x10^4$ km (0710 UT). Heavy ions are detected by the SDA until about $5x10^4$km when they disappear from the solar direction (the peak of these particles can be seen at about 1000eV).

It should be noted that the electron spectra (upper panel) exhibit a dramatic change deep in the cometary plasma region: inside $5x10^4$km the overall electron flux exceeds the cometosheath level by at least an order of magnitude and significant fluxes of energetic electrons (E_e>1000eV) are simultaneously observed.

Another representation of the CRA data in the above discussed plasma region is presented in Figure 2 which shows 1 minute averaged spectra measured between $2.8x10^5$km and $1.4x10^4$km from the nucleus (between 0620 and 0717 UT). It can be clearly seen that between $2.8x10^5$km and $1.6x10^5$km the shocked and hot proton population gradually slows down and the detected distribution narrows considerably. At the cometopause the proton fluxes decrease significantly and become comparable to the more energetic heavy ion fluxes, so the two plasma populations become almost indistinguishable. Simultaneously the proton distribution broadens indicating some kind of heating around this boundary.

The cometary plasma region between the cometopause and the closest approach is characterized by increasing fluxes of heavy cometary ions in the energy range of 300 - 3000 eV and a proton population which is continuously cooled and decelerated. Five second averages of CRA spectra measured deep inside the cometary plasma region (between $6x10^4$km and $1.4x10^4$km from the nucleus) are shown in Figure 3. It can be seen that this region is dominated by cometary ions which have several orders of magnitude higher fluxes than the protons. Inspection of Figure 3 also reveals that the location of the heavy ion distribution does not change in this region, i.e. the cometary ions almost stagnate (their velocity in the cometary frame is not more than a few km/s). There are two heavy ion "hot spots" around $4x10^4$ and $3x10^4$km, respectively, which probably are caused by local plasma effects. It can be seen that the cometary ions cool considerably as one approaches the comet: the fine structure of the distribution (corresponding to different cometary ions) becomes more and more prominent.

The proton population (<100eV) exhibits a significant change between $6x10^4$ and $1.5x10^4$km: it slows down considerably and simultaneously becomes much colder. In this process an increasing fraction of the H^+ population enters into the velocity space region monitored by CRA, consequently it is fairly complicated to determine the proton density variation.

There is an increasing flux observed in the first few energy intervals of the CRA spectra (15-20eV) as the spacecraft approaches the comet. This is probably due to the detection of the increasing plasma cloud surrounding the spacecraft and caused by impacting small dust grains and neutral particles.

In order to investigate the deceleration and cooling of the proton population we estimated the proton temperatures and flow velocities for the CRA spectra shown in Figure 3. The results which are plotted in Figure 4 indicate that the proton temperature decreases from about 10^5K at $6x10^4$km to ~4000K at $1.5x10^4$km. It should be noted that at the beginning of this interval the proton distribution is highly non-Maxwellian, therefore the above mentioned temperature values have to be taken with great caution. The e-folding spatial scale length of the temperature variation is about $1.5x10^4$km. It is interesting to note that there are local proton temperature increases around $4x10^4$ and $3x10^4$km corresponding to the heavy ion "hot spots" seen in Figure 4. The estimated proton flow velocity decreases in the cometary frame from 10 - 20 km/s around $6x10^4$km to 1-2km/s at about $1.5x10^4$km.

Discussion

There is an increasing number of model calculations describing the solar wind interaction with comets in terms of mass-loading effects (for a recent review see Mendis et al., 1985 and references therein). Magnetohydrodynamic numerical calculations (e.g. Schmidt and Wegmann, 1982, and Fedder et al., 1986) as well as semikinetic analytical approximations (Wallis and Ong, 1975, Galeev et al., 1985,

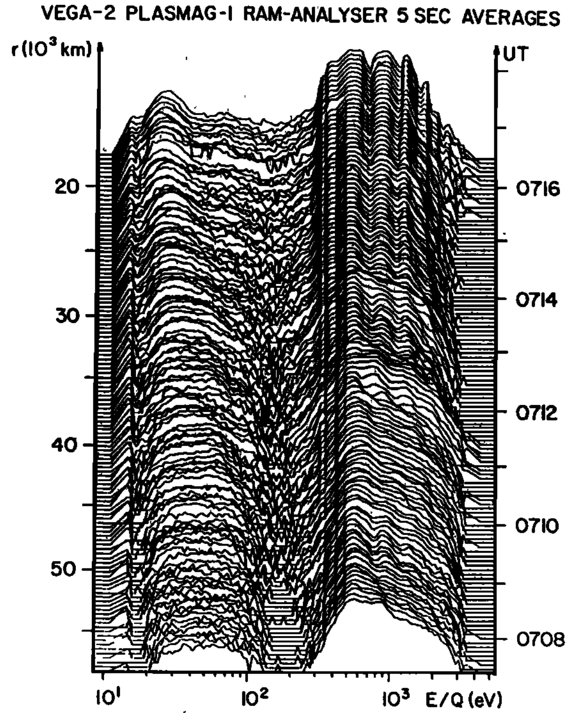

Fig. 3. Five second averages of the ram ion analyser spectra inside the cometary plasma region.

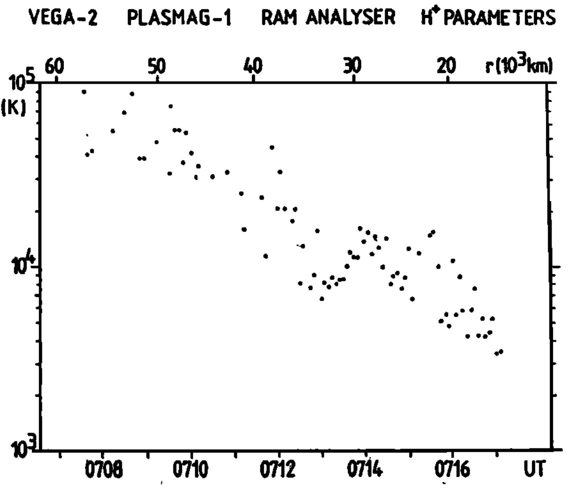

Fig. 4. Estimated proton temperatures inside the cometary plasma region.

Galeev and Lipatov, 1984) predicted a gradually decelerating mass loaded plasma flow which comes to stagnation at a subsolar cometocentric distance of about

$$R_L = \frac{Q_n\ M_i}{12\,\pi\,\lambda\ n_\infty u_\infty}$$

where Q_n is the cometary production rate, M_i is the average mass number of cometary ions, λ is the ionization scale length, n_∞ and u_∞ are the number density and velocity of the undisturbed solar wind, respectively. Using $Q_n \approx 1.3x10^{30}s^{-1}$, $\lambda \approx 2x10^6$km, $u_\infty \approx 620$km/s, $n_\infty \approx 11cm^{-3}$ (Gringauz et al., 1986) and $M_i \approx 20$, one obtains $R_L \approx 5x10^4$km. This value for R_L is in a reasonable agreement with the observed distance of the cometopause at about $1.6x10^5$km if one takes into account that VEGA-2 intersected the stagnation region near the terminator.

Theoretical models predict that at a distance of $r \sim R_L$ the shocked flow velocity is approximately $0.1u_\infty$ and it keeps gradually decreasing as one approaches the ionopause located at about $5x10^3$km from the nucleus as observed by the magnetometer on Giotto spacecraft (Neubauer et al., 1986). There was no discontinuity predicted in the deceleration region between the bow shock and the ionopause.

The VEGA plasma observations indicate a general agreement with theoretical models at cometocentric distances larger than $1.7x10^5$km where a decelerating and charge exchange cooled solar wind population was observed as well as picked up cometary ions. At a distance of about $1.6x10^5$km, R_{cp}, from the nucleus VEGA-2 intersected the $\sim 10^4$km wide cometopause (Gringauz et al., 1986) and entered the cometary plasma region. This "chemical discontinuity" (separating two plasma regions of different chemical composition) was not foreseen by theoretical studies and thus represents an unexpected feature of the cometary plasma environment.

Proton heating was also observed at the cometopause resulting in a significant broadening of the proton spectra. In the cometary plasma region where heavy ion fluxes were much larger than the proton fluxes, a significant velocity difference exists between protons and the heavier ions. One possible explanation of this unexpected plasma behavior is that the two ion populations are partially de-coupled, so that there is no common flow velocity, but there might be a significant momentum transfer between them. At about 10^5km the proton flow is sufficiently decelerated and it again becomes clearly distinguishable from the heavy ion distribution.

The decoupling of the two plasma components in the presence of a strong magnetic field is only possible if the proton flow is more or less parallel to the magnetic field direction. This condition is probably fulfilled in that part of the cometary plasma region where our observations were carried out. Here the draped magnetic field direction is approaching the solar direction. The heavy cometary ions have only a very small bluk velocity and are continuously cooled, because the resonant charge exchange process with cometary neutrals in effect couples the heavy ions and neutrals together. On the other hand, due to relatively small neutral hydrogen population the proton-hydrogen resonant charge exchange is not so important, and protons are mainly cooled and decelerated by elastic collisions with heavy neutrals. This process has a relatively small cross section and therefore the protons are not coupled to the neutrals as much as the heavy ions, possibly explaining the velocity difference between the two plasma populations.

Acknowledgements. The authors are indebted to Dr. R.Z. Sagdeev for illuminating discussions. We also thank Drs. E.G. Eroshenko, N.G. Khavelson and Ms. K. Lorenz for their help in the data analysis. We are grateful to Dr. B.S. Novikov and the VEGA project team for their devoted support of the Plasmag-1 experiment.

References

Fedder, J.A., Lyon, J.G., and Giuliani, J.R., Numerical simulations of comets: predictions for comet Giacobini - Zinner, EOS, 67, 17, 1986.

Galeev, A.A., and Lipatov, A.S., Plasma processes in cometary atmospheres, Adv.Space Res., 4, 229,1984.

Galeev, A.A., Cravens, T.E., and Gombosi, T.I., Solar wind stagnation near comets, Astrophys. J., 289, 807, 1985.

Gringauz, K.I., et al., The VEGA probe instrument package for measuring charged particles with energies less than 25 keV, in Cometary Exploration (ed. T.I. Gombosi), p333, Central Res. Inst. Phys. Press, Budapest, 1983.

Gringauz, K.I., et al., The VEGA Plasmag-1 experiment: description and first results, in Field-, Particle-, and Wave- Experiments on Cometary Missions (eds. K. Schwingenschuh and W. Riedler), p157, Austrian Academy of Scieneces Publication, Graz, 1985.

Gringauz, K.I., et al., First *in situ* plasma and neutral gas measurements at comet Halley, Nature, 321, 282, 1986.

Ip, W.H., and Axford, W.I., Theories of physical processes in the cometary comae and ion tails, in Comets (ed L.L. Wilkening), p588, Univ. Arizona Press, Tucson, 1982.

Mendis, D.A., Houpis, H.L.F., and Marconi, M.L., The physics of comets, Fundamentals of Cosmic Physics, 10, 1, 1985.

Neubauer, F., et al., First results from the Giotto magnetometer experiment at comet Halley, Nature, 321, 352, 1986.

Schmidt, H.U., and Wegmann, R., Plasma flow and magnetic fields in comets, in Comets (ed. L.L. Wilkening), p538, Univ. Arizona Press, Tucson, 1982.

Wallis, M.K., and Ong, R.S.B., Strongly cooled ionizing plasma flows with application to Venus, Planet. Space Sci., 23, 713, 1975.

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(Received May 19, 1986;
Accepted May 22, 1986.)