COMPLETE POSITIVE ION, ELECTRON, AND RAM NEGATIVE ION MEASUREMENTS
NEAR COMET HALLEY (COPERNIC) PLASMA EXPERIMENT FOR THE EUROPEAN
GIOTTO MISSION

Contract NASW-3575

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I. Introduction

One of the most exciting space explorations of the 1980's was the close flyby of Halley's Comet by the Giotto spacecraft of the European Space Agency. This contract covered the participation in the activity of U.S. scientists as part of the team of investigators on the COPERNIC (COmplete Positive ions, Electrons and Ram Negative Ion measurements near Comet Halley) plasma experiment selected by ESA for flight on Giotto. Professor Henri Rème of CESR, Toulouse, France was the Principal Investigator for the overall experiment.

The experiment consisted of two detectors: the EESA (Electron Electrostatic Analyzer), which provided three-dimensional measurements of the distribution of electrons from 10 eV to 30 keV, and the PICCA (Positive Ion Cluster Composition Analyzer), which provided mass analysis of positively charged cold cometary ions from mass 10 to 210 amu (*Rème et al.*, 1986). In addition, a small 3° wide sector of the EESA looking in the ram direction was devoted to the detection of negatively charged cold cometary ions. Both detectors operated perfectly up to near closest approach (~600 km) to Halley, but impacts of dust particles and neutral gas on the spacecraft contaminated parts of the data during the last few minutes.

Although no flight hardware was fabricated in the U.S., The U.S. Co-I's made very significant contributions to the hardware design, GSE design and fabrication, and flight and data reduction software required for the experiment. In addition, they participated fully in the data reduction and analysis, and theoretical modeling and interpretation.

II. Hardware Fabrication Phase

The role of the U.S. Co-I's in the COPERNIC experiment was based on their unique capabilities in three major areas: 1) electrostatic analyzer design; 2) fast on-board processing techniques for plasma data; and 3) theoretical modeling and interpretation for comets. Drs. C. W. Carlson, R. P. Lin, and K. A. Anderson have more than fifteen years' experience in the design, development and flight of electrostatic analyzers on spacecraft and rockets. Dr. Carlson was the co-inventor of the novel analyzer concept used for the EESA.

The U.S. scientists were heavily involved in defining the scientific objectives and the instrument parameters, and in providing the conceptual design. Computer codes developed at UCB were used to make detailed trajectory calculations for analyzer designs. UCB provided the preliminary designs for both the EESA and PICCA, including detailed response calculations.

These plasma instruments, particularly the EESA, made measurements at a rate far too high to be completely telemetered back. This data transmission problem was especially acute for the

limited Halley comet flyby period since the plasma parameters changed very rapidly. At UCB we have developed hardware and software techniques for on-board data compression which derive significant physical parameters for the plasma. On Giotto we devised a method to compute on-board every half spin the electron pressure tensor in different energy ranges and diagonalize it to obtain the axis of symmetry (the magnetic field direction). This direction was used to organize the EESA electron data into pitch angle bins and thus substantially reduce the data rate needed to obtain high time resolution. Mr. D. Curtis developed the fast computational microprocessor system, and wrote the flight software to implement this compression scheme (see *Curtis et al.*, 1989).

Dr. Mendis at UCSD brought unique theoretical expertise on comets and cometary plasmas. He provided modeling and theoretical interpretation for the plasma-neutral cometary gas interaction and, in particular, for the processes of formation of ionized species in that environment.

III. Mission Operations and Data Reduction for the GSE

UCB provided all the software for the GSE, which was also used for mission operations, data capture and storage, and quick-look data reduction and analysis. This software, written for an IBM PC, provided for both extensive graphics and color displays. The data were stored on tape and then transferred to Bernoulli hard disks and then to WORM (write once, read many times) disks for analysis. The data reduction software was also PC-based and evolved from the GSE software. Computation of intensive tasks was handled through a network to a VAX750.

IV. Data Analysis

The data from this experiment cover a wide variety of scientific topics relevant to comets, their interaction with the solar wind, their composition, and their origin. Below we describe some of the data analysis conducted under this contract. The data analysis effort is continuing under a separate grant. Publications and talks resulting from the studies discussed here are listed in Appendix A.

A. The cometary plasma and solar wind/comet interaction

The interaction of the comet with the solar wind depends on the ionization of the heavy cometary neutrals (mostly H_2O and its dissociation products O, OH and H) which flow out from the nucleus. The "pick-up" of these newly produced heavy ions mass loads and slows the solar wind such that a shock may form. Depending on θ_B, the angle between the magnetic field and the solar wind flow velocity, the pick-up ions initially form a ring/beam distribution which is unstable to wave growth. The EESA instrument first detected waves at ~3 million km from the nucleus.

Large density fluctuations were observed at ~2.5 to ~2 million km distance. These may be due to the growth of the waves to a compressional form. These large fluctuations abruptly disappear at ~1.8×10^6 km, possibly due to a drop in θ_B from near 90° to $\lesssim$45°. Only small, $\Delta n/n \approx 10\%$ fluctuations were observed near the bow shock, which was crossed at 1.16×10^6 km.

Hot electrons are occasionally seen streaming away as the shock is approached. About 2.5×10^5 km in front of the shock an electron foreshock is observed, similar to that in front of the earth's bow shock (Figure 1). Bursts of energetic, keV electrons are detected just in front of the shock, again strikingly similar to the energetic electron spikes observed near the earth's bow shock. In the foreshock the solar wind speed is reduced (a similar reduction is seen in the earth's foreshock, where it results from the coupling of backstreaming ions to the solar wind); here it is unclear whether such backstreaming ions are present (*Fuselier et al.*, 1987).

Our analysis of the Comet Halley bow shock (*Coates et al*, 1987) shows that it consists of a relatively abrupt increase in density, followed by a decrease in solar wind density and velocity which occurs simultaneously with a spike in the pick-up ion density (Figure 2). The solar wind velocity, however, jumps back up and it is not until ~8 minutes (~3×10^4 km) later that it reaches and stays at its post-shock value. The shock structure appears similar to that seen in simulations of the mass loading process (*Omidi and Winske*, 1986). Throughout the shock transition the pick-up ions, which account for only ~0.5% of the total ion density, dominate the solar wind plasma thermal and magnetic energy density. In this respect this cometary shock may be similar to supernova shocks, where shock-accelerated cosmic rays, although very low in density, are expected to exert a significant dynamic pressure in the shock.

Inside the shock a complex and highly turbulent cometosheath region is encountered, with a number of apparent boundaries which may be either temporal or spatial in nature (see Figure 1). Electrons are observed to be accelerated to keV energies by processes which are not understood at present. A clear and abrupt transition is seen at ~5.5×10^5 km, after which the sheath plasma becomes stable and quiescent, and the plasma bulk velocity and electron temperature monotonically decrease. The density of hot, presumably cometary ions also abruptly increase at this transition.

At ~1.2×10^5 km cold cometary ions are observed, followed by an abrupt increase in the magnetic field strength. The EESA data show that inside this cometopause or collision-pause there is strong streaming of the plasma electrons along the magnetic field away from the subsolar point.

At a distance of ~4800 km the magnetic field is observed to decrease rapidly to zero (*Neubauer*, 1986) and the cometary plasma temperature also abruptly decreases to $\lesssim$300°K (*Schwenn et al.*, 1986). This transition has been identified as the ionopause. The region from the ionopause inward shows many peculiar phenomena (see section C) which are not understood at present, partly because there are intense fluxes of neutrals and dust hitting the spacecraft and perhaps
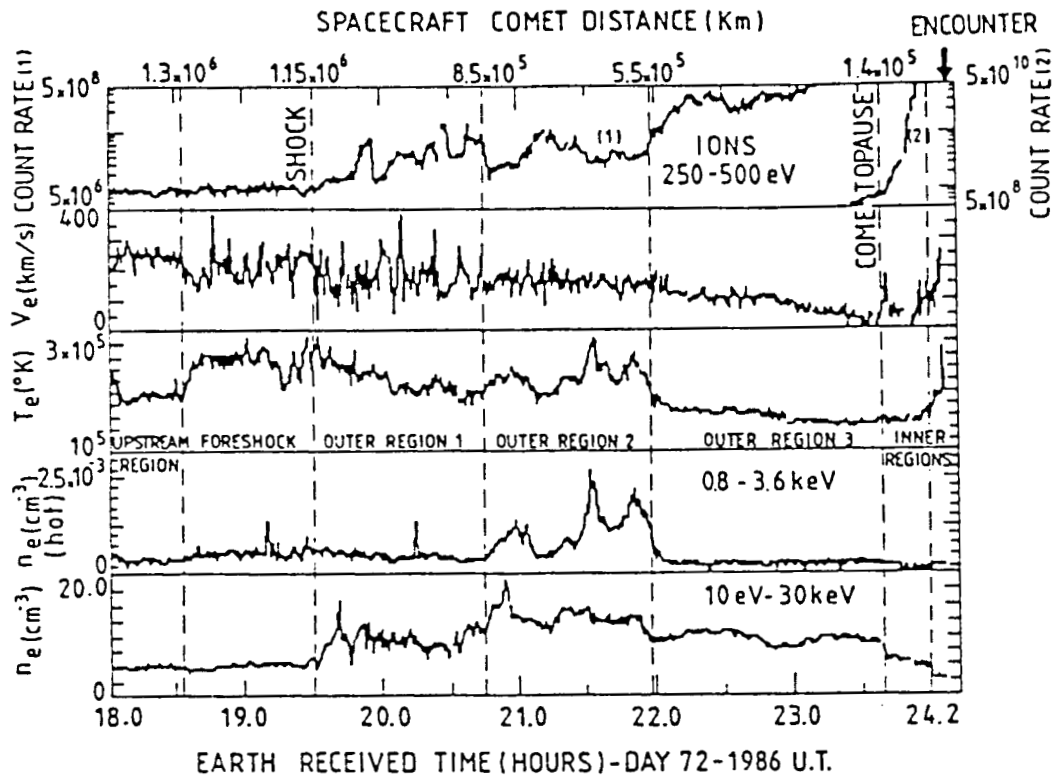
Figure 1. Plasma data during the last 6.2 hours before the Giotto encounter with Comet Halley. From bottom to top panels: n_e, the density of 10 eV–30 keV electrons; n_e (hot), the density of the 0.8–3.6 keV electrons; T_e, the electron temperature estimated from the slope of the energy spectra near 70 eV; V_e, the electron bulk velocity calculated from the electron distribution; and the count rate of RPA2-PICCA in the ram direction for 250–500 eV/q ions [note a change of scale from count rate (1) to count rate (2) at time ~23.5]. Times given are UT earth received times (~8 minutes later than spacecraft event times).
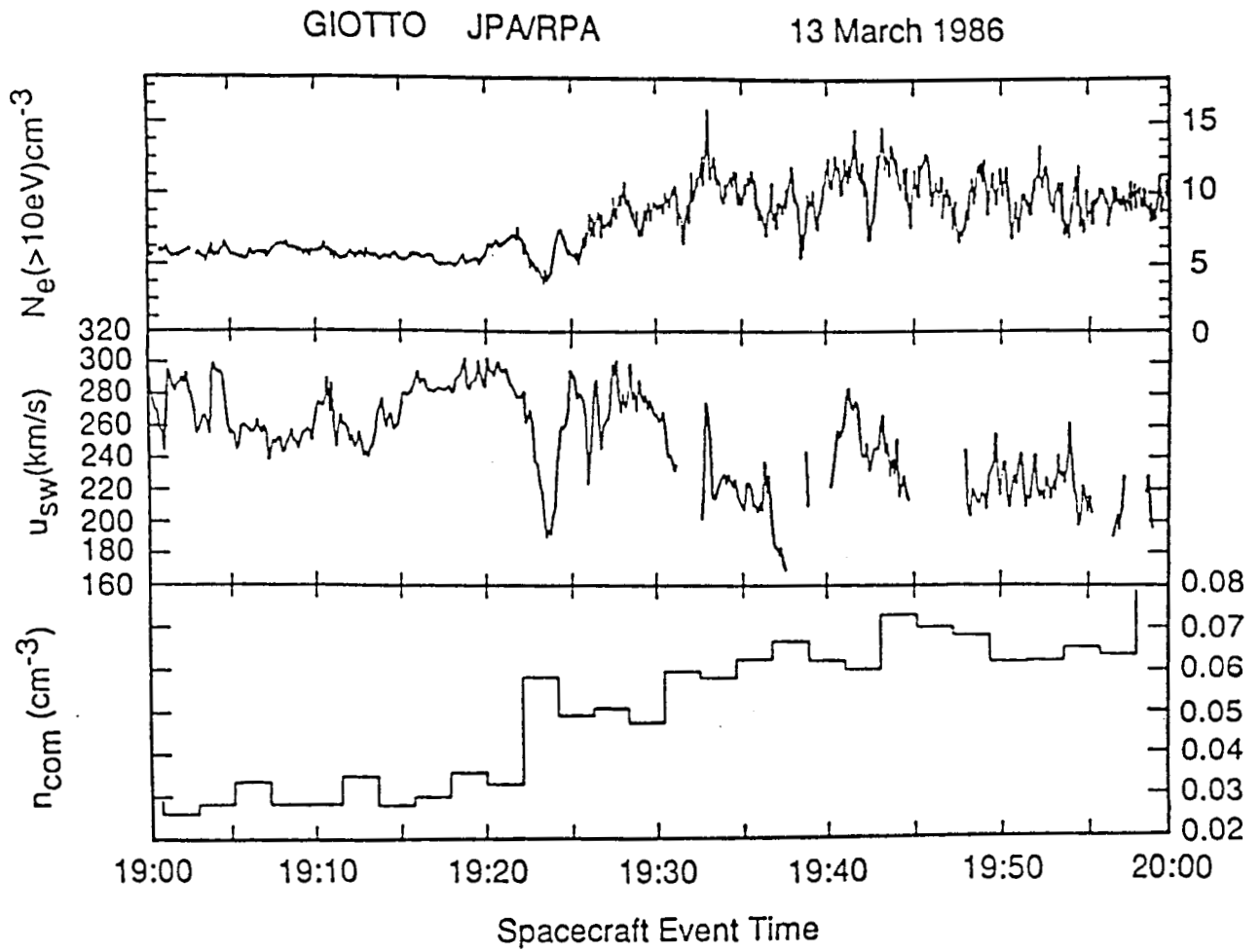
Figure 2. Electron density (top panel), solar wind proton speed (middle panel), and cometary water group ion density (bottom panel) for the hour on 13 March 1986 containing the Comet Halley bow shock crossing.

producing contamination.

The ICE encounter with Comet Giacobini-Zinner and the Vega and Giotto encounters with Comet Halley appear to be quite different (Figure 3). We believe that these differences must be due to a combination of different neutral gas production rates, solar wind velocities, θ_B, ionization rates, etc. We have yet to understand these differences in terms of the physical processes that are occurring. Particular questions of interest include:

1. Why is the level of density fluctuations in front of the Giacobini-Zinner bow wave so much larger than in front of Halley's bow shock? How is the level of fluctuations related to θ_B and cometary ion production rate?

2. What are the physical processes underlying the complex structure of the Halley bow shock?

3. What accelerates electrons to keV energies near the shock and in the turbulent cometosheath region?

4. What causes the sudden transition from turbulent to quiescent cometosheath?

5. What causes the electron streaming observed inward of the cometopause? Why is the cometopause such an abrupt boundary?

6. What processes are responsible for the unusual phenomena seen at the ionopause?

The EESA observations of the 3-D electron distributions provide a probe to help answer these questions. Since the effects on the electron distribution are sometimes subtle, we have begun detailed analysis of the behavior of the detector and the effects of spacecraft charging.

B. Heavy ions

The PICCA detector is the only instrument on the Giotto spacecraft capable of detecting and mass analyzing very heavy, positively charged ions. It has two mass ranges: m = 10–50 amu with Δm = 0.4 amu resolution, and m = 50–213 amu with $\Delta m \approx 1$ amu. In the mass range 10–30 amu, which includes the water group, the dynamic range of PICCA is increased with a second, much smaller channeltron detector for the anticipated intense fluxes of the water group.

PICCA is not a true mass spectrometer but rather a simple electrostatic system which provides discrimination in E/q (*Rème et al.*, 1986). If the ion temperature is low enough the ion energy, $E \approx \frac{1}{2}mv^2$, is dominated by the large relative velocity between the spacecraft and the comet, so if the ions are singly charged then E/q is proportional to mass. Thus the mass scale and the mass resolution depend on the ion flow velocity and temperature in the comet frame. In the past year we have analyzed the effects of these parameters on the water group of ions (masses 17, 18, 19). The flight spare PICCA unit has been carefully calibrated to obtain its detailed 2-D angular response for a range of incoming E/q.
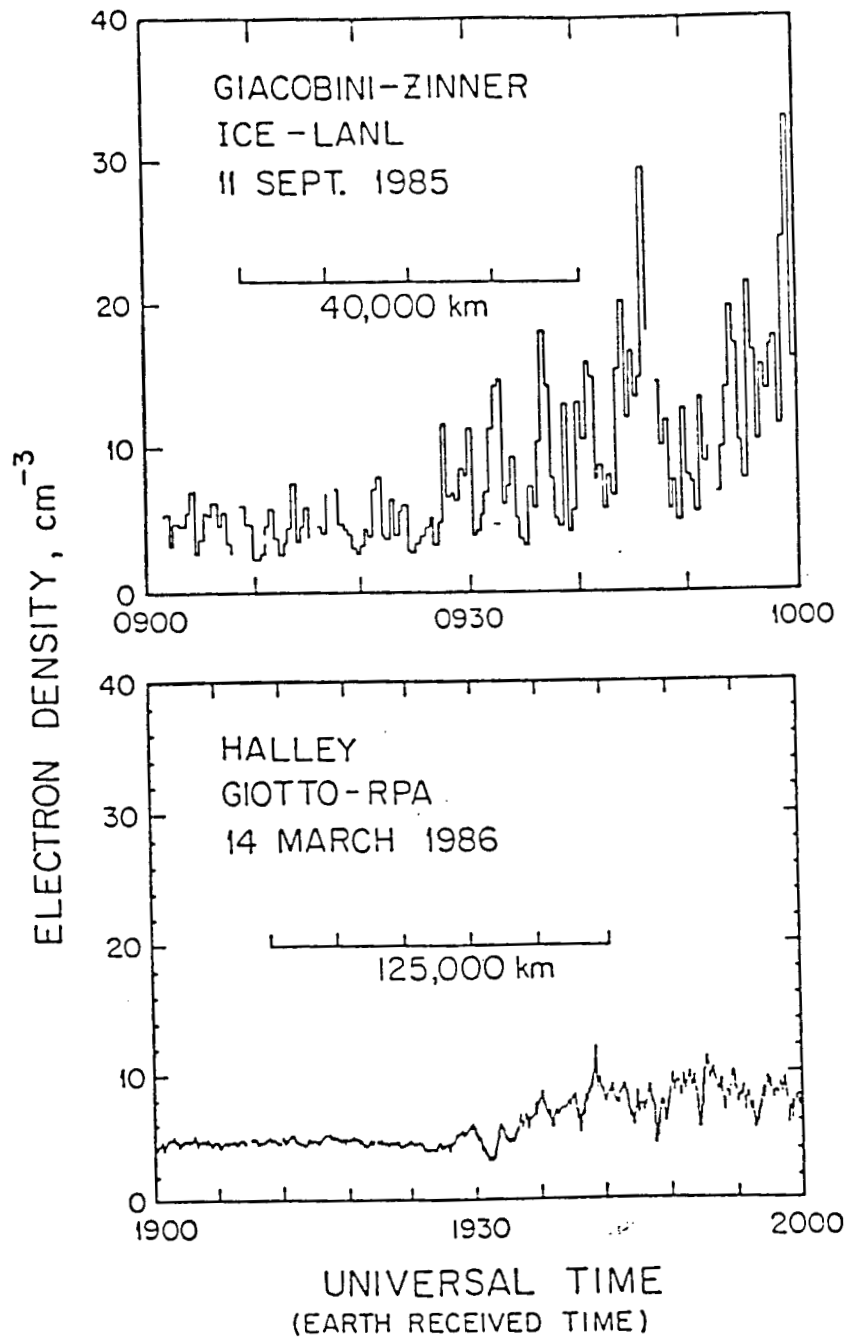
Figure 3. The scales have been chosen in order to directly compare the size of the fluctuations in electron density at comets Giacobini-Zinner and Halley. The intervals include crossing of the bow shock. The density fluctuations are very much larger at Giacobini-Zinner.

In our analysis we assume Maxwellian distributions with the same temperature, T, and flow velocity component along the ram direction, V_{fx}, for all mass species. Standard chi-square minimization techniques are used to give the best fit to T, V_{fx}, and ratios of the intensities for the water group. For a starting point, we use the $OH^+/H_2O^+/H_3O^+$ ratios published by *Balsiger et al.* (1986). The values of T and V_{fx} obtained from the PICCA data (*Mitchell et al.*, 1986) agree well with values obtained by other experiments. Because the response of the PICCA is not symmetric in angle we can also obtain some information on the direction of flow by analyzing the spin modulation (the full cycle time for PICCA is 3.2 s while the spin period is 4 s). A strong spin modulation is observed in the density of cold ions, since the flow is not right along the ram direction. These density oscillations are particularly useful for separating the heavy cold ions from a hot $(E/q \gtrsim 2.5$ keV) isotropic component whose flux increases rapidly in the inner coma as the comet nucleus is approached.

Using the parameters derived from the water group, we then fit the rest of the mass range to obtain composition as a function of mass (Figure 4). Some of the most exciting results pertain to the heavy masses, $\gtrsim 60$ amu. Several broad peaks are persistent and clearly visible in the data, centered at masses ~ 61, ~ 75, ~ 91, and ~ 105 amu (*Mitchell et al.*, 1987). Each of these peaks appears to be at least several amu wide, i.e., a single mass could not produce the peak profile, given the temperature inferred from the water group. The spacing between peaks is $\sim 14-16$ amu.

Figure 5 shows the radial density profiles of the mass groups indicated in Figure 4 from a distance of 45,000 km to nearly closest approach. The abundances of the 61–105 amu peaks decrease smoothly with increasing mass. The abundance of cold ions in the 117–130 amu range, estimated from the density oscillations, is about a factor of three smaller than that of the 105 amu peak. The total abundance of ions in the mass peaks 61–120 amu relative to water ions is 0.3%.

The systematic behavior of the spectrum suggests a long repeating chain molecule, rich in C, H, O and possibly N, and its breakup into shorter pieces. A 14 amu peak separation could be due to CH_2 or N, but probably CH_2 since carbon appears to be very abundant (Figure 5) and much more abundant than nitrogen (*Balsiger et al.*, 1986). Similarly, a 16 amu separation is probably due to oxygen. The width of each mass peak probably results from the dissociation or attachment of one or more H atoms to unsaturated bonds on the heavy molecules.

The mass peaks at 61, 75, 91 and 105 amu dominate all heavy mass spectra obtained by the PICCA instrument. We find no evidence for a significant abundance of iron (56 amu), as reported by *Gringauz et al.* (1986a). The dissociation products of polymerized formaldehyde (POM) coincide with the observed peak locations (*Huebner et al.*, 1987). Modeling of the progressive dissociation of the C-O bonds of a long chain of POM results in a smooth decrease in abundance with increasing mass. Hydrogen atoms can attach to the carbon or oxygen at the open ends of the chain, or be dissociated from the CH_2 within the chain to provide some peak width. The observed mass
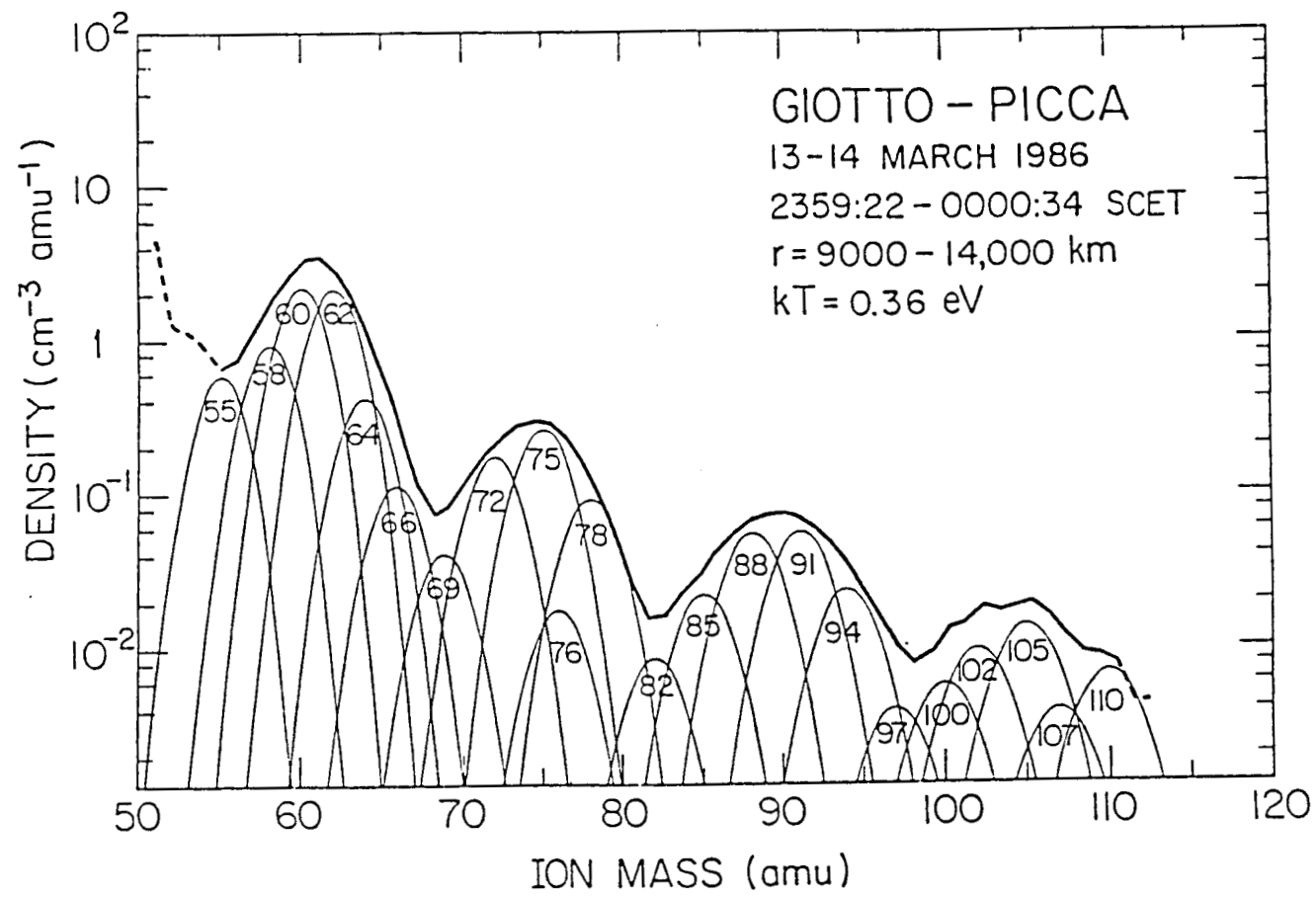
Figure 4. Mass spectrum of the cold thermal ions in the inner coma region. The thick line is data from which a hot component has been subtracted (see text). The thin lines are the Maxwell-Boltzmann distributions of many masses. The sum of these distributions is indistinguishable from the data between 55 and 98 amu and within a line thickness beyond 98 amu. A temperature of $kT = 0.36$ eV is determined from the water group ions and assumed to apply to all mass constituents.
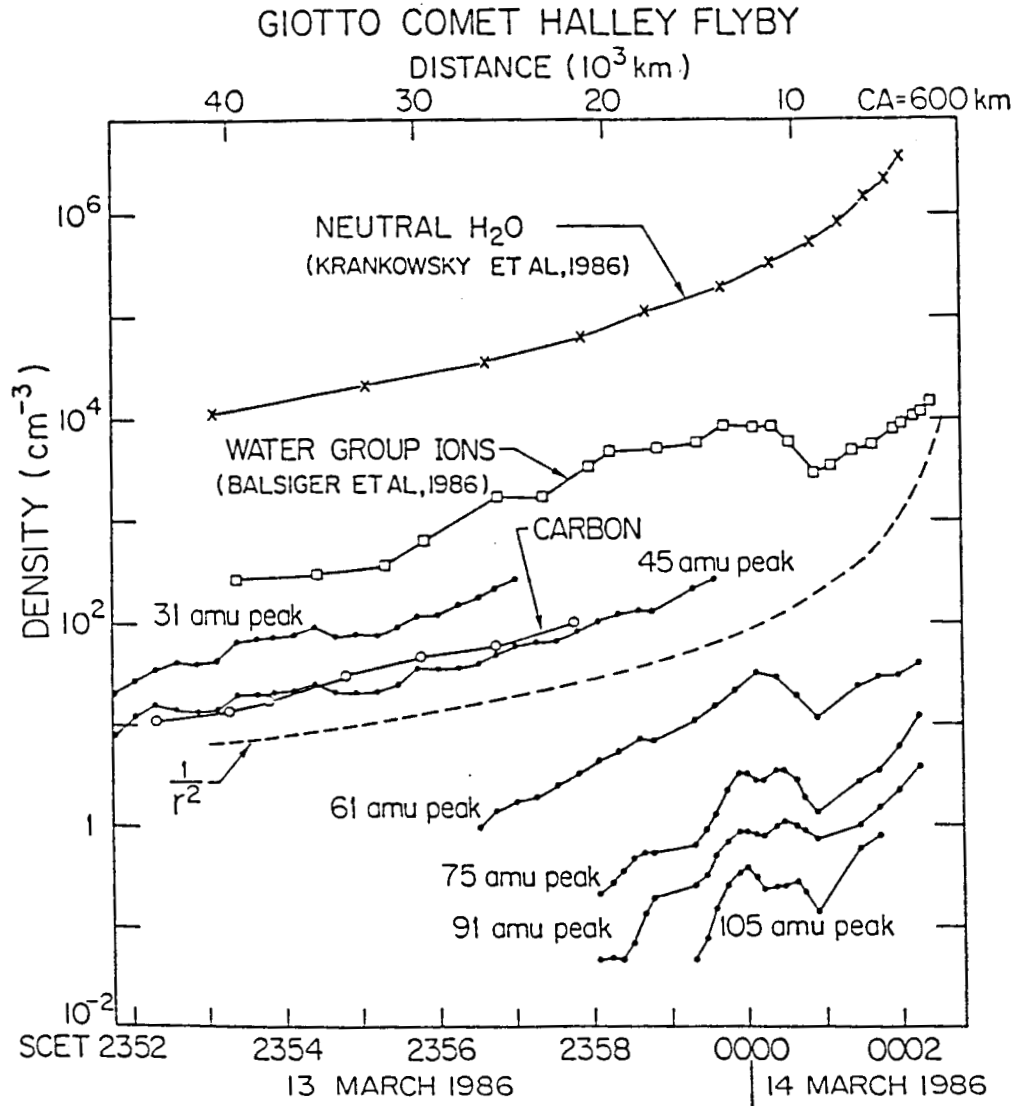
Figure 5. Radial density (cm^{-3}) profiles for the mass peaks shown in Figure 1 as well as mass peaks centered at 31 and 45 amu. The mass ranges summed for each peak are as follows: 31 amu peak = 24–39 amu; 45 amu peak = 39–55 amu; 61 amu peak = 55–69 amu; 75 amu peak = 69–83 amu; 91 amu peak = 83–98 amu; 105 amu peak = 98–114 amu. The C$^+$ profile is obtained from detailed fits to the 10–24 amu range. The profiles of neutral water and water group ions are shown for comparison.

spectrum (Figure 4), however, clearly shows the presence of ions in the 63–67 amu and 93–95 amu ranges that cannot be a product of the breakup of POM. Ions in these mass ranges cannot be readily explained by the attachment of unrelated molecules (such as CN) to the unsaturated bonds of POM; thus some other species must be present.

These data are particularly intriguing since they are suggestive in many ways of the large molecules found in the interstellar clouds which appear to be the birthplace of stars. Possibly these heavy ions may provide a link between comet and cloud material. The chemistry of heavy molecular ions appears to be particularly relevant.

Inside the contact surface where the ion temperature drop to $\lesssim 300°K$, the individual masses which comprise the broad mass peaks can then be resolved and identified by PICCA; however, the rapid increase in the hot ion component limits this analysis to the broad peaks at 45 and 61 amu.

C. Electron and ion measurements very close to the nucleus

Measurements in the last few minutes before closest approach are contaminated by intense neutral gas bombardment and frequent dust impacts with the spacecraft and the detectors. Thus the analysis of those data has progressed slowly, even though the data are clearly of great interest. Several features, whether due to real phenomena or contamination, are apparent in the data:

1. The EESA observed intense fluxes of low energy $\lesssim 100$ eV electrons coming symmetrically from about $\pm 100°$ to the ram direction. These are probably due to neutral gas ejecting electrons by collisions with the posts which supported our aperture and collimator plates.

2. The PICCA observed a broad, relatively smooth and intense ($\gtrsim 10^3$ counts/readout), relatively isotropic, hot ion component, particularly noticeable at $\gtrsim 100$ amu ($\gtrsim 2.5$ keV). The rapid increase in this component as Giotto approached the nucleus was entirely unexpected. After the ionopause contact surface was crossed, this hot component increased to completely dominate the mass peaks above 70 amu, and inside ~ 3500 km it dominates above ~ 50 amu. The origin of this hot component is unknown. Hot ions were also observed by other Giotto experiments (*Goldstein et al.*, 1986).

3. Negatively charged heavy ions are observed to increase rapidly as the ionopause is approached (see section D). The density of these ions is far too high to explain by normal processes of polar photodissociation and electron attachment.

4. Large fluxes of energetic (>20 keV) ions and electrons appear to be present in these inner regions (*Kirsch et al.*, 1986).

5. Inside the contact surface, the EESA detector showed the presence of solar wind-like fluxes of electrons in the energy range 10 eV–1 keV. Since the piled-up interplanetary magnetic field is excluded from the cavity, it would be surprising for solar wind electrons to have access to this region.

Clearly, detailed and careful analysis will be required to obtain the plasma conditions in this near-nucleus region.

D. Negative ions

A variety of processes involving interactions between neutrals, ions, photons, dust, micrometeoroids and the comet nucleus can produce negatively charged ions in the vicinity of comets. Theoretical estimates (*Wekhof*, 1979) indicate that the major sources of negative ions would be polar photodissociation of HCN ($HCN + h\nu \rightarrow H^+ + CN^-$) to form CN^-, and electron attachment to OH to form OH^-. The EESA detector was designed with a small 3° wide sector to detect negatively charged particles flowing in the ram direction. If cold negative ions were present they should appear in this sector with ~25 eV/amu due to the Giotto spacecraft velocity relative to Comet Halley. Electrons with comparable total energy could be distinguished from cold negative ions by comparison with the adjacent sectors of the EESA, since these should be free of cold negative ions.

In our preliminary analysis of the EESA data we have found the signature of cold negative ions near closest approach to the nucleus (Figure 6). Although the mass resolution is very poor due to the large $\Delta E/E$ of this analyzer, it does appear that the most prominent peaks are consistent with CN^- (26 amu) and OH^- (17 amu). In addition, however, a peak near 100 amu and a shoulder at ~30–50 amu, as well as other features, are present which are as yet unidentified. For heavy negative ions there is the possibility for formation of clusters $A^-(H_2O)_n$ (*Wekhof*, 1979).

The radial variation of the 15–19 amu and 25–32 amu channels is shown in Figure 7. The densities increase much more rapidly than $1/r^2$ as the nucleus is approached. The absolute densities reach 10^{-2}–10^{-1} cm^{-3}, compared to ~10^{-5}–10^{-4} cm^{-3} expected from polar photodissociation and electron attachment. Thus some other, at present unknown, process(es) must be responsible for these ions. We suspect that the formation of negative ions may be related to the other mysterious phenomena detected very close to the nucleus.

E. Electron ionization processes

We have made preliminary estimates of the rate of ionization from various processes such as photoionization by solar ultraviolet, electron impact, and charge exchange with solar wind ions (Figure 8). In the undisturbed solar wind, solar UV is the strongest source of ionization, but the combined effect of electron impact plus charge exchange is comparable at times near solar minimum (1986–87). Inside the bow shock, where the electron density and average energy increases, electron impact dominates, and ionization rates can be several times faster than from solar UV alone. Thus the pick-up process should proceed much faster inside the bow shock. We plan in the coming year to assess the effect of electron impact ionization on the comet interaction with the solar wind.
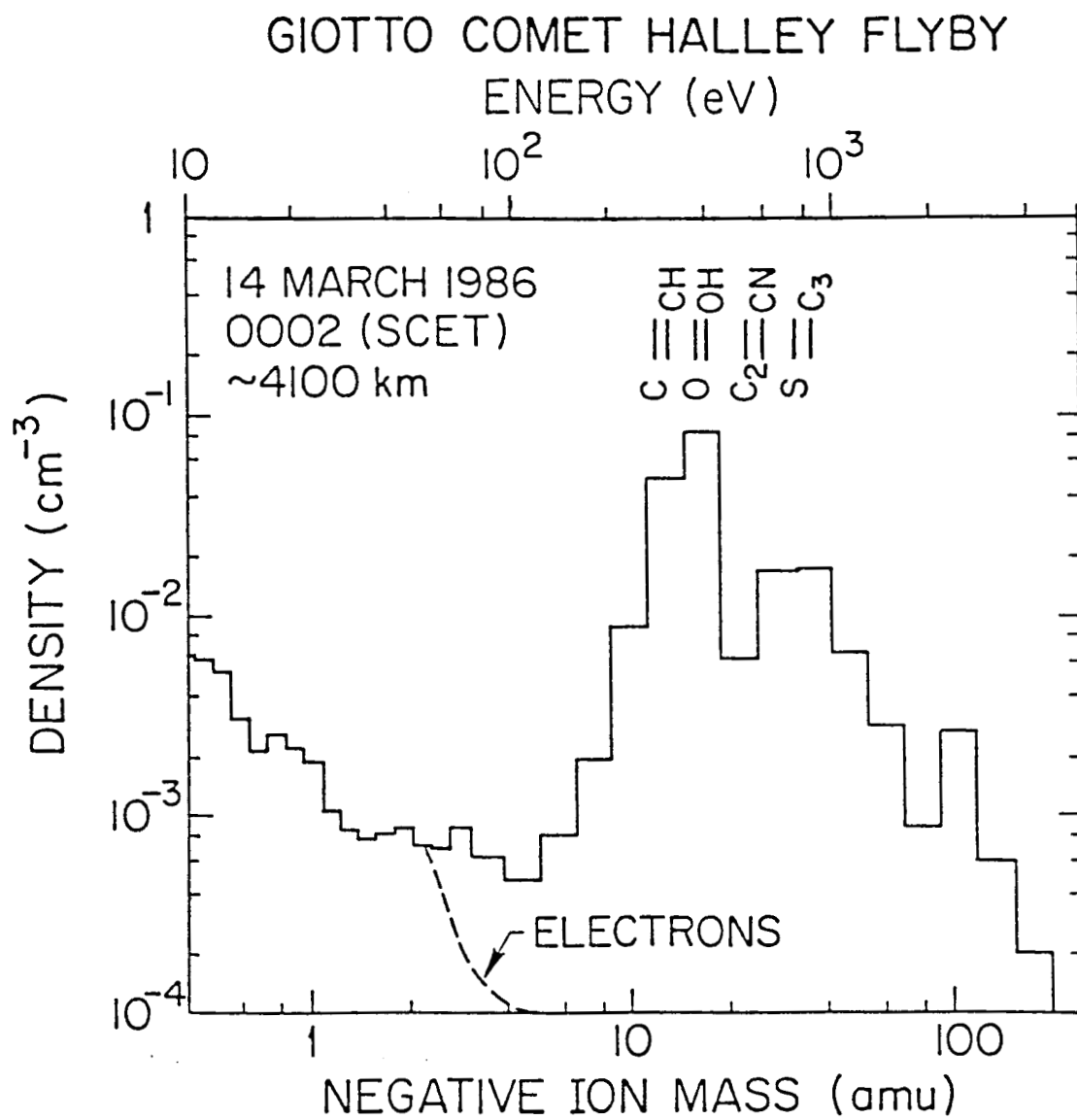
Figure 6. Mass spectrum of negatively charged ions obtained from the ram direction sector of the EESA detector. The dashed line indicates the electron spectrum observed in the adjacent sectors. Various negative ion species are indicated at the top.
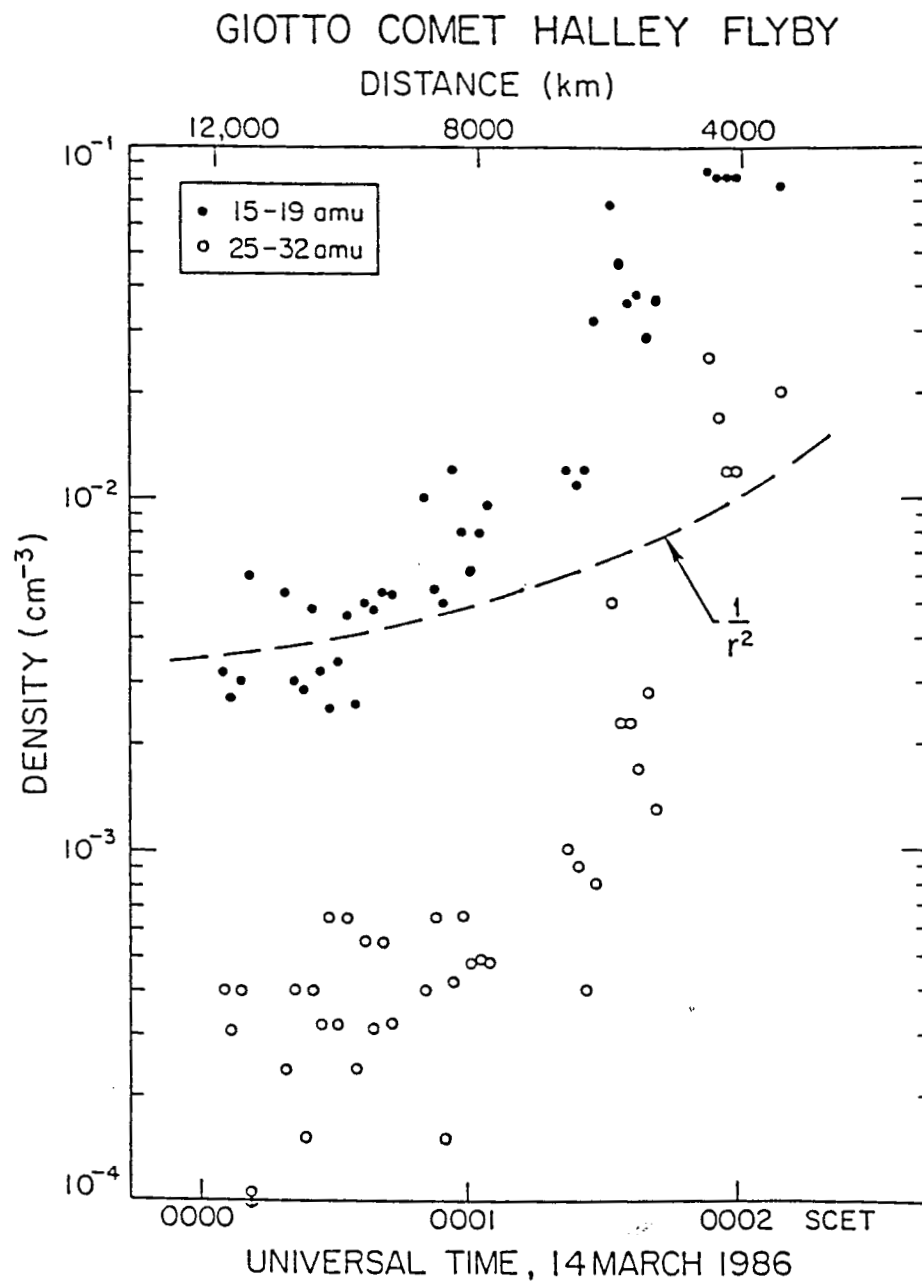
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Figure 7. The radial dependence of the 15–19 amu and 25–32 amu negative ion mass peaks. Note that both increase much more rapidly then $1/r^2$ as the nucleus is approached.
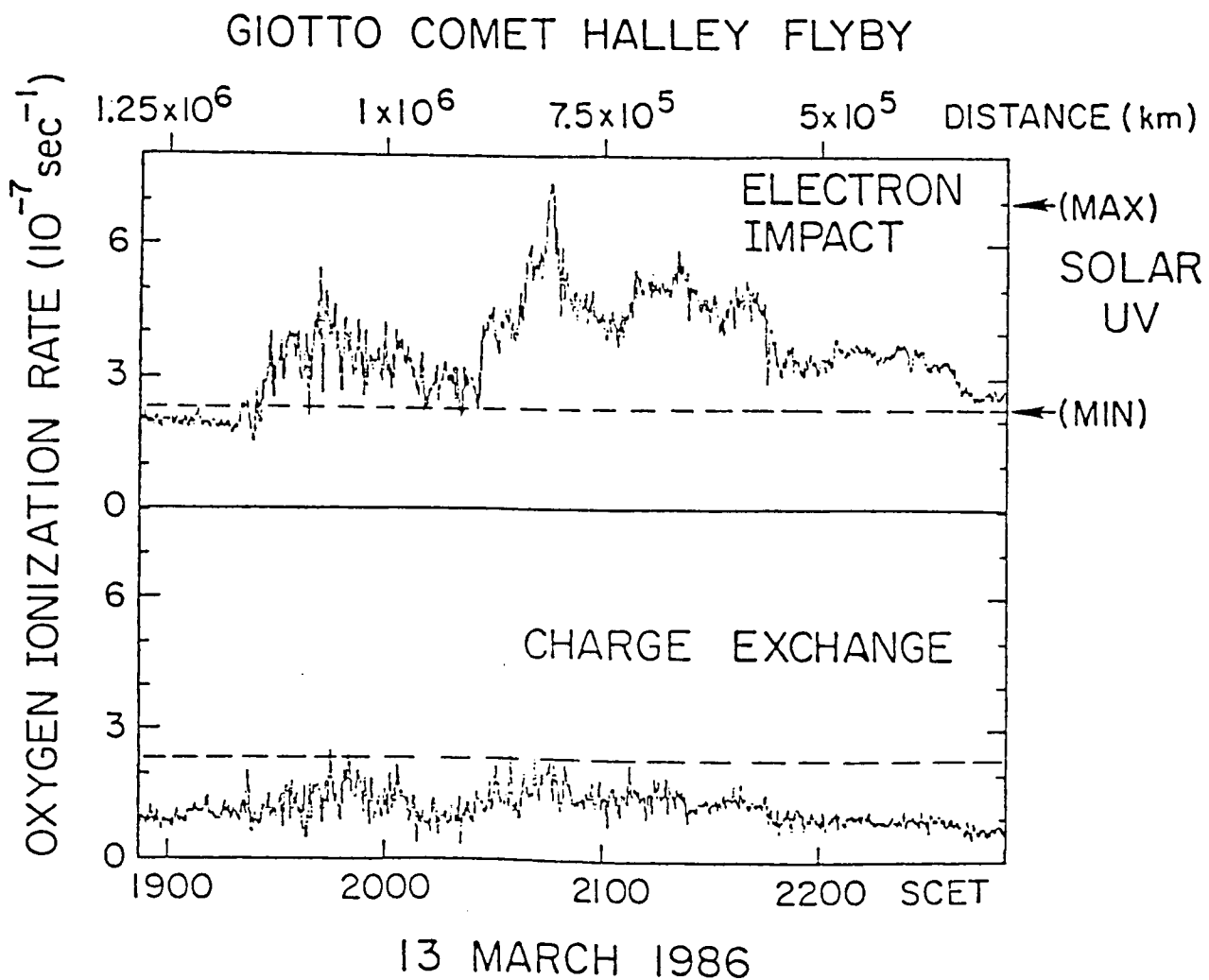
Figure 8. Ionization rates for oxygen from electron impact and charge exchange, compared to solar ultraviolet (right scale). The Giotto encounter occurred close to solar minimum.

Ionization of cometary neutrals by energetic keV electrons was suggested as a mechanism to account for the rapidly evolving narrow ion rays that are observed in comets (see *Ip and Axford*, 1982). Also, plasma measurements on Vega-1 appear to detect enhanced fluxes of keV electrons inside of ~50,000 km (*Gringauz et al.*, 1986b). These electrons have been attributed to the occurrence of critical velocity ionization (*Sagdeev et al.*, 1986; *Formisano et al.*, 1982). Furthermore, there is a clear pile-up in the ion density just outside 10^4 km from the nucleus (*Balsiger et al.*, 1986), which those authors and others suggest may be due to ionization by energetic electrons. Although the EESA is an extremely sensitive detector of electrons over the energy range up to 30 keV, we have not found any significant increase in energetic electrons at those distances.

F. Theoretical modeling

While the PICCA heavy ion analyzer has provided us with data about heavy ions at least up to 105 amu, these data are largely confined to regions outside the ionopause (at $r \approx 5 \times 10^3$ km). The detailed ionosphere models that have been developed by us as well as others (e.g., see *Mendis et al.*, 1985, for a detailed review), which assume spherical symmetry and absence of magnetic fields, are applicable only inside the ionopause. A self-consistent, multi-species, multi-fluid MHD model of the flow outside the ionopause is a formidable problem and will not be attempted by us. We have developed a simpler approach, wherein we adopt a 2-D axi-symmetric plasma flow profile outside the ionopause constructed from the in-situ observations. Inward integrations of the continuity and energy equations are performed for the various chemical ion species along the stream lines starting at the bow shock. Simultaneously, an outward integration is performed for the neutrals, in order to evaluate their radial profiles.

The PICCA data (*Mitchell et al.*, 1987) indicated well-defined peaks around 45, 61, 75, 91 and 105 amu (with perhaps one also barely discernable above the noise at ~120 amu). It has been suggested by *Huebner et al.* (1987) that these may be associated with the ions of various photodissociation fragments of $(H_2CO)_n$ (polyoxymethylene). While this identification is consistent with the main peaks, the peaks are too broad to be associated with a single species (*Mitchell et al.*, 1987). Consequently, we have used our model to check the possible role of the parent molecule CS_2 providing the ions CS_2^+, S_2^+, CS^+, S^+ and C^+. Our calculations are very preliminary, but they do indicate that in order to provide the observed radial profiles of the various groups, a distributed source, rather than a central source, is necessary. Furthermore, POM by itself cannot be responsible for all the ions at the various observed peaks. Consequently, a mixed-polymer for this species, as well as the H_2CO and HCN, may be indicated.

Two rather sharp transitions observed by the EESA and PICCA instruments (as well as other particle and field instruments) in the plasma flow between the bow shock and the ionopause are not well understood at present. The first, now called the "cometopause," we tentatively identify as the earlier predicted "collisionopause," where the ion-neutral drag between the outflowing

neutral H_2O and the inflowing solar wind (which is highly contaminated with H_2O^+) is expected to become large. While the observed transition takes place approximately at the distance where it is expected if we regard that the drag is due entirely to $H_2O - H_2O^+$ collisions, it is still not clear why the transition is so sharp. We believe that it may be due to the fact that this cross section increases with lower relative velocities and temperatures, thereby leading to a positive feedback effect.

The second of these transitions is the so-called "ion pile-up" region just ahead of the ionopause, where the ion density reaches a maximum around 12,000 km from the nucleus and drops sharply by about a factor of 3 by about 8,000 km from the nucleus before increasing again. The description of this feature as an "ion pile-up" region is a misnomer. It is really a region of ion depletion and appears to be largely due to the rapid decrease in the plasma temperature, which increases the loss rate of the ions by dissociative recombination. A similar effect, in the reverse, was observed in the numerical simulations of the cometary ionosphere (*Marconi and Mendis*, 1984). That plasma cooling may be the cause of the ion depletion has already been suggested by *Baumgärtel and Sauer* (1987) in a recent study. They, however, imposed the plasma cooling arbitrarily in an ad hoc manner.

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Appendix A

PAPERS AND TALKS RESULTING FROM RESEARCH SUPPORTED
BY NASA CONTRACT NASW-3575

A. PAPERS

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Anderson, K. A., Comparisons between comets Halley and Giacobini-Zinner, Bay Area Magnetospheric Physics Meeting, Palo Alto, CA, May 1986 (*invited*).

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Mazelle, C., H. Rème, J. Sauvaud, C. d'Uston, C. Carlson, K. Anderson, D. Curtis, R. Lin, A. Korth and D. Mendis, Analysis of plasma electron properties near the cometopause of comet P/Halley, European Geophysical Society Meeting, Bologna, Italy, March 1988.

Popular Talks

Anderson, K. A., Report on Halley's Comet, Unitarian-Universalists of UC Meeting, University of California, Berkeley, CA, April 1986 (*invited*).

Anderson, K. A., Comet Halley—new results, Students Promoting Aerospace Career Education, University of California, Berkeley, CA, April 1986 (*invited*).

Anderson, K. A., Comets, NASA and space politics, Chemistry Graduate Students Assn. Meeting, University of California, Berkeley, CA, May 1986 (*invited*).