

# Results of the space missions to comet Halley

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The typical features of comets in the solar system have been described to show that these are quite different from many planets. A brief development of understanding and explanation of comets from the 17th century to the recent-most mission is described and discussed here. The solar wind is shown to interact quite differently and give rise to interesting results in each case.

COMETS are quite different from other solar system bodies. They become active and catch our attention only for a short time during their orbits when they pass close to the Sun. Only a fraction of all comets plunge into the inner solar system from the Oort cloud where comets are stored at 10 to 100 thousand AU from the Sun on orbits taking  $10^6$  yr or longer to wander around the Sun. The number of comets in this cloud is estimated to be  $\approx 10^{12}$ . Perturbed by a passing star or a molecular cloud they may become lost to interstellar space rather than fall towards the Sun on a very elliptical orbit.

The sudden, unforeseen appearances of comets – sometimes becoming the brightest objects on the night sky (next to the moon) for a few weeks – have intrigued mankind. At the end of the 17th century it was Sir Edmund Halley who predicted the return of a bright comet with a period of 75 yr leading Newton's theory of gravity to a new triumph and showing at the same time that comets are members of the solar system. Halley's comet is in some sense unusual. It is the brightest, most active member of the family of short-period comets (with periods  $< 200$  yr). Therefore it was best suited for investigations of its activity and interaction with the solar wind by space probes although its orbit is retrograde. This accounts for a high relative velocity ( $\approx 70 \text{ km s}^{-1}$ ) between any space probe and the comet.

After support for a cometary mission failed in the United States the European Space Agency (ESA) continued and introduced its first interplanetary mission Giotto aiming to encounter comet Halley after perihelion in March 1986. Other space agencies followed. Intercosmos redirected two probes (Vega 1 and 2) from Venus and the Japanese sent their first two spacecraft (Suisei and Sagigake) in the vicinity of comet Halley. The US supported the endeavours by stimulating and coordinating a large ground-based observational programme (IHW).

## Solar wind comet interaction

The  $L_\alpha$  camera on board the Japanese Suisei spacecraft was the first to observe comet Halley and took images of the extended hydrogen coma of comet Halley. Fluctuations of the central intensity were interpreted as being invoked by the rotation of the nucleus with a period of 2.2 d<sup>1,2</sup> similar to a value derived by an analysis of the 1910 ground-based observations<sup>3</sup>. The minimum distance of this spacecraft to comet Halley was 150,000 km flying through the bow shock formed by the interaction of the cometary coma with the solar wind. The solar wind passed the comet with a speed of  $\sim 400 \text{ km s}^{-1}$ . Neutral cometary compounds (mostly atoms as final dissociation products) from the coma were ionized by charge exchange, in this way 'mass loading' the solar wind upstream since protons were substituted by heavy atoms such as C or O.

The solar wind was slowed down and transgressed to subsonic speed at the bow shock about  $10^6$  km upstream of the central coma. The diversion of the solar wind around the 'obstacle' coma was well demonstrated by the Japanese observations (Figure 1). The former cometary atoms were coupled to the solar wind with high energies ( $\sim 10^5$  eV). These pick-up ions made the solar wind flow turbulent and were observed at distances many gigameter away from the comet.<sup>4,5</sup>

On moving further towards the comet the solar wind speed decreased more and more reaching the stagnation point around  $10^5$  km. The decrease of flow speed of the solar wind ions and the pick-up ions was depicted in the

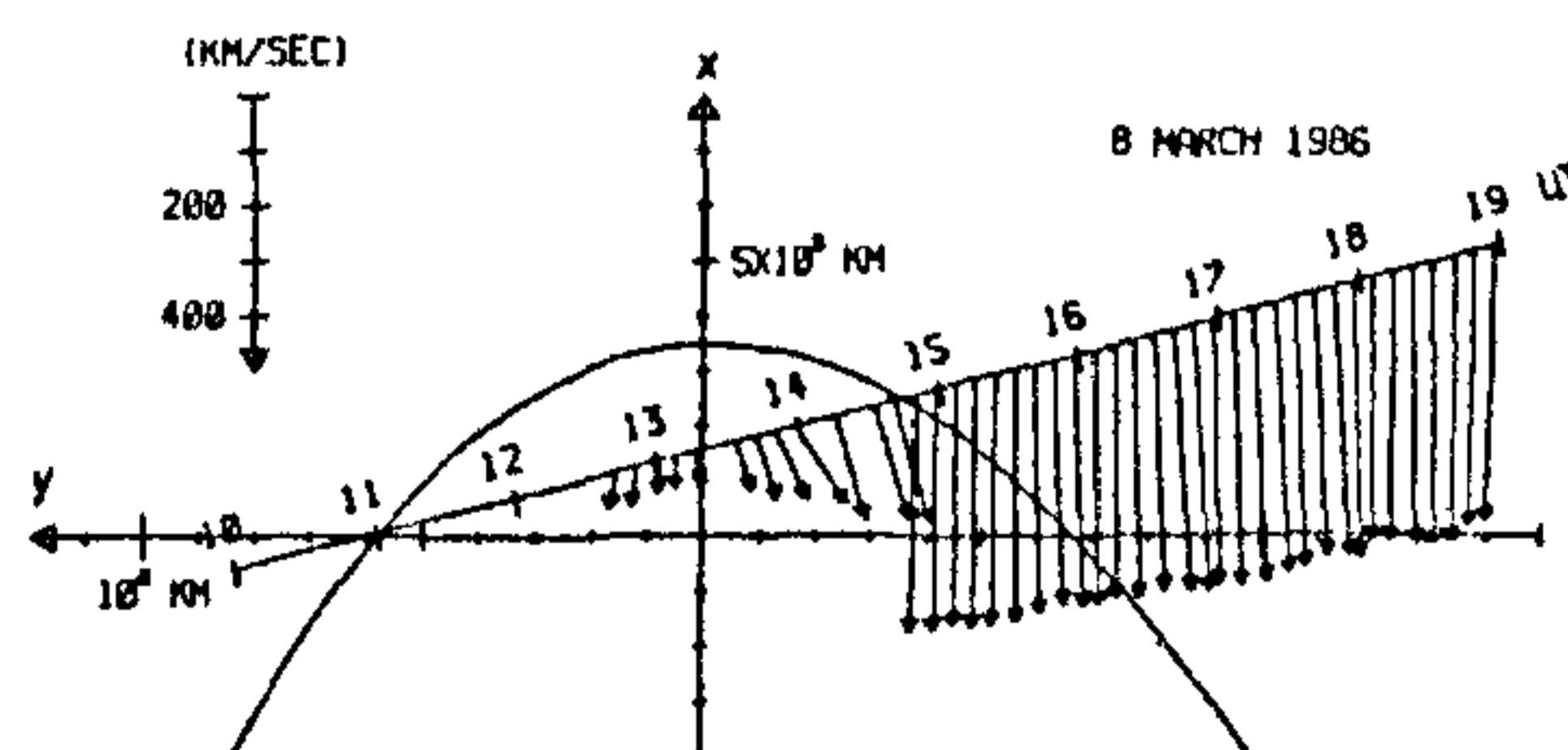


Figure 1. Solar wind flow vectors obtained during the encounter of the Japanese spacecraft Suisei with comet Halley on 6 March 1986. The flow vectors and angles are represented in the rest frame of the comet<sup>41</sup>.

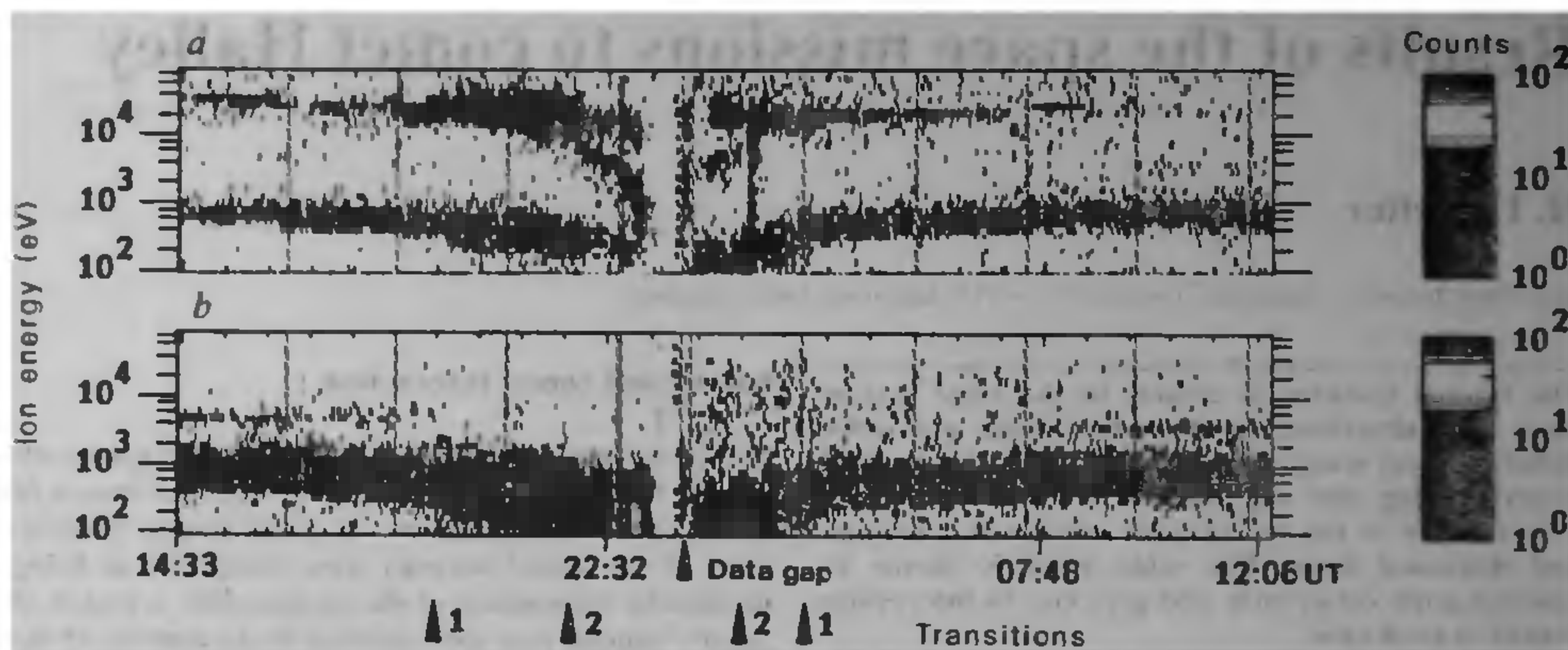


Figure 2. Data for two mass groups obtained by one IIS time-of-flight sensor<sup>2</sup>. The two mass groups are protons (mass 1 AMU) from solar wind (lower panel) and implanted cometary ions of mass 12–22 AMU (upper panel). Disregard the "ghost" of the proton signal.

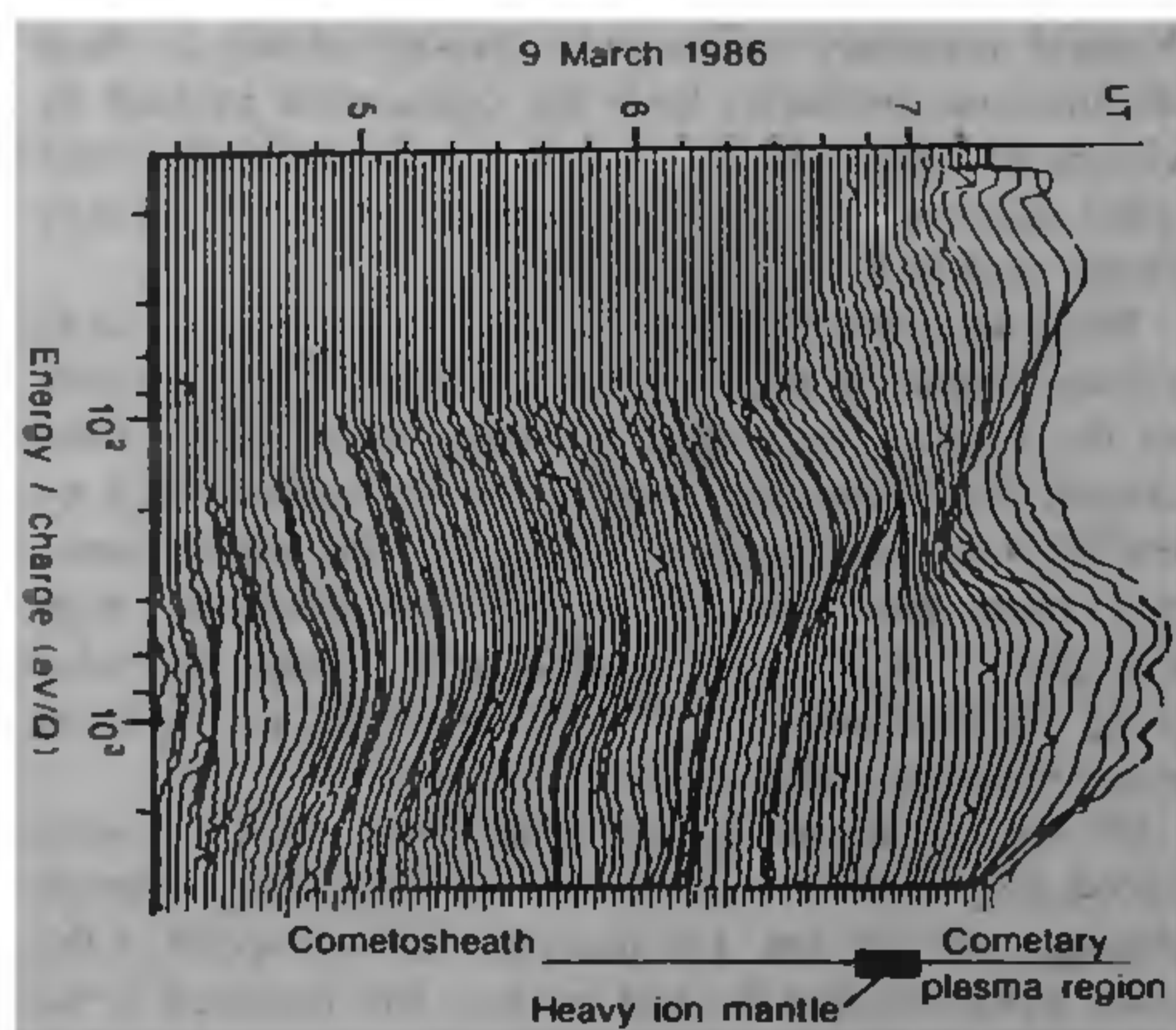


Figure 3. High-time-resolution ion energy spectra (2 min average) measured by the Vega 2 cometary ion analyser (CRA) during encounter on 9 March 1986 by Gringauz *et al.*<sup>4</sup>.

measurement by the IIS instrument on board Giotto (Figure 2). The two separate populations, solar wind ions and pick-up ions, converged. Once the ions were cold the mass resolution was sufficient to show the dominant peak of the water group ions inside the inner coma (Figure 3).

Even further in, the Giotto spacecraft detected a diamagnetic cavity when it crossed the contact surface (Figure 4) at a distance of 4500 km. The magnetic field dropped from the piled up value of  $\approx 80$  nT down to

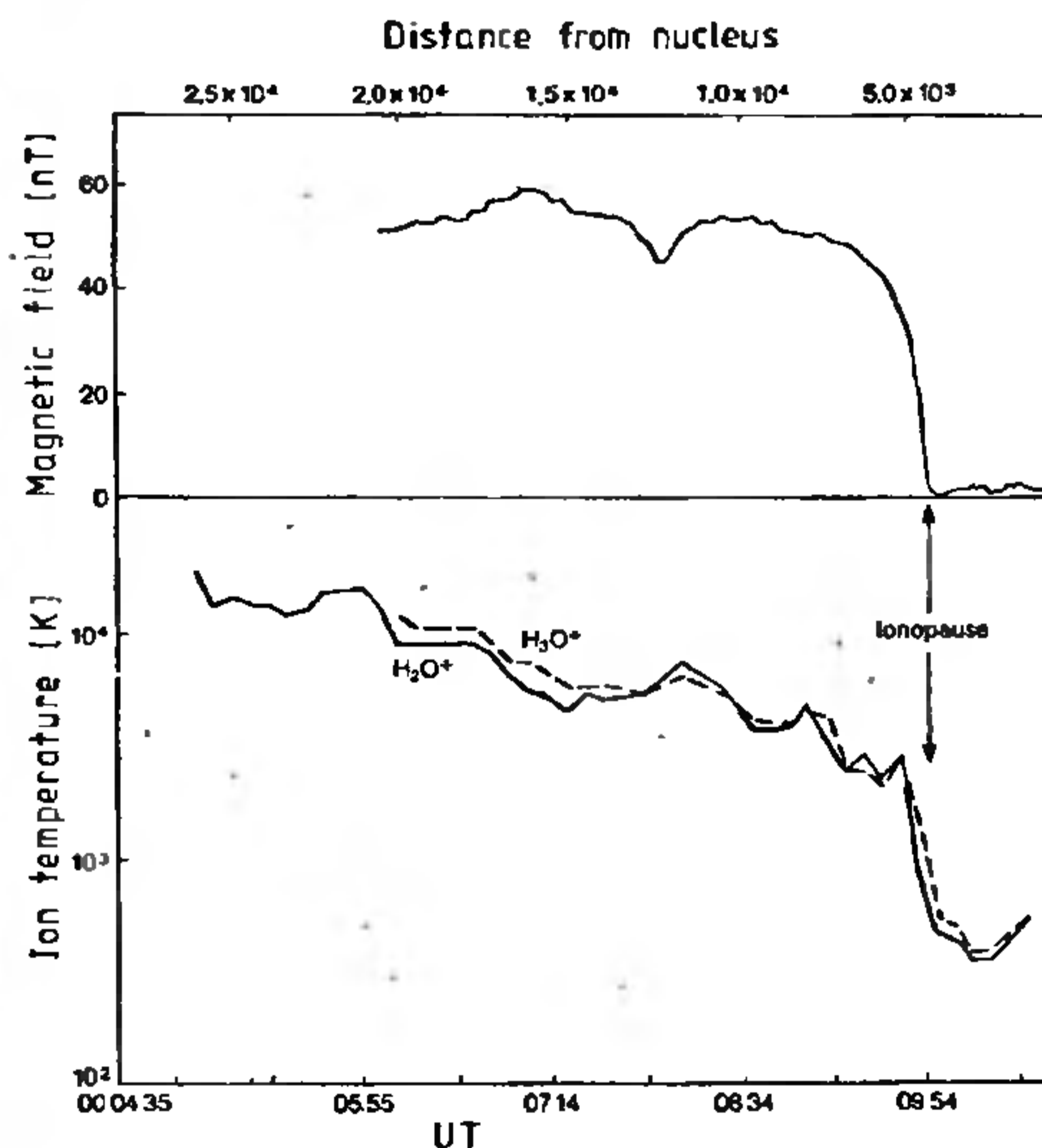


Figure 4. The piled up magnetic field drops to zero within less than 30 km at the contact surface or ionopause (upper graph<sup>42</sup>). The ion temperature shows also a strong discontinuity (lower graph<sup>43</sup>).

zero within a fraction of a second. Such a sharp discontinuity was not expected. The size of this cavity came also as a surprise. The large stand-off distance could be explained by taking the pressure of the neutrals into account to balance the magnetic field force. The ions were still collisionally coupled to the neutrals at distances of several thousand kilometers. The importance of this coupling has not been appreciated.

The ion temperature dropped strongly inside the cavity. Here were only cometary ions, the solar wind could not penetrate. The ion mass spectrometer received high resolution data as close in as 1500 km from the nucleus.

Several layers and discontinuities in the ion distribution have been detected and discussed during the analysis of the data. They are less marked and also less well understood in their significance when compared to the contact surface and the bow shock (see ref. 6) for a review).

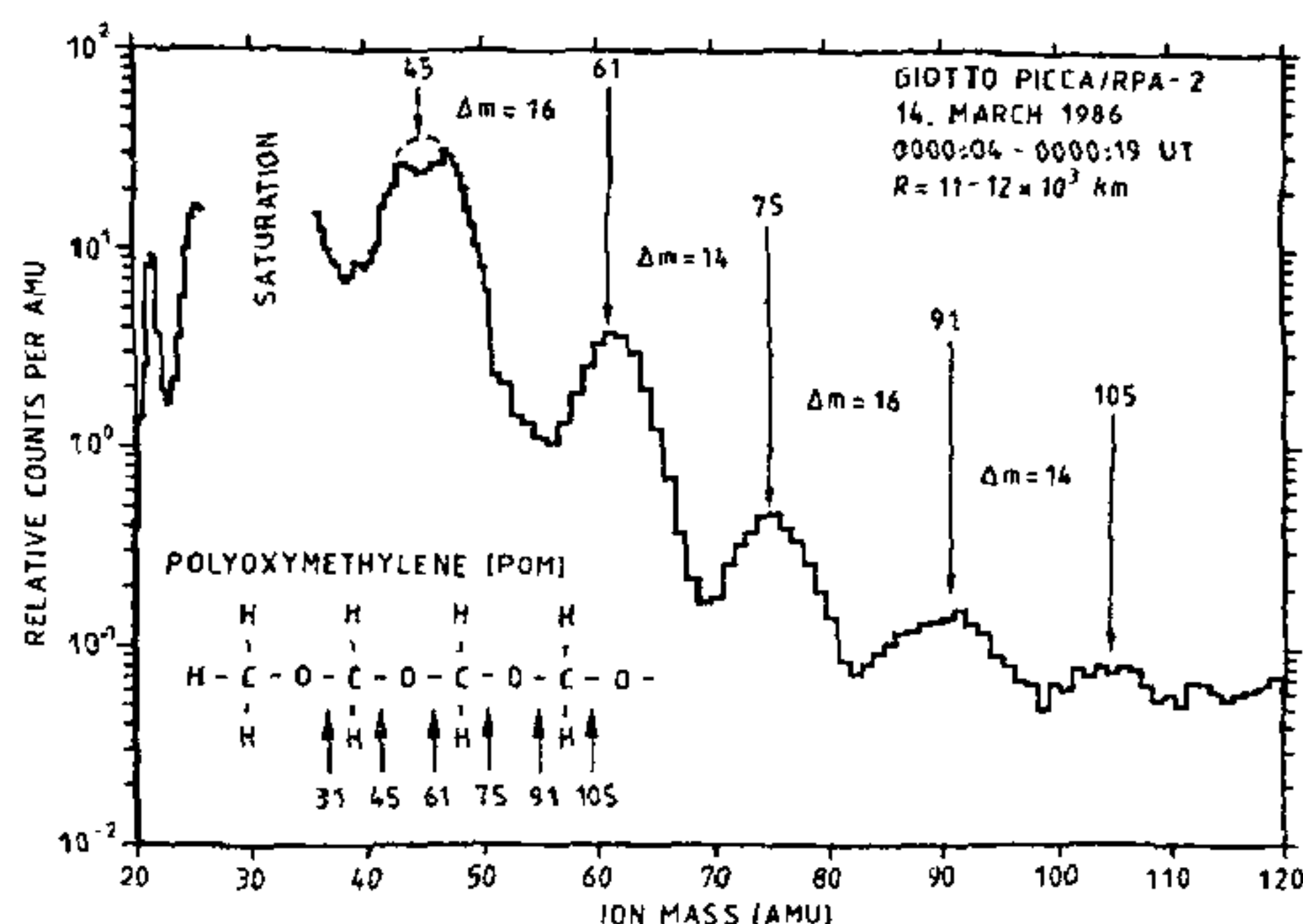
### The cometary coma

The composition of the coma revealed little surprise. The dominating parent molecule (80%) was water  $H_2O$ , CO followed with 5–15% and then  $CO_2$  with 3.5%. All other species were in the range of one per cent and below. Often only upper limits were determined. A major part of the observed CO probably came from dust grains that formed an extended source around the nucleus<sup>7,8</sup> (see Table 1). Very volatile compounds such as  $N_2$ ,  $CH_4$ , and also CO (if only the fraction in the ice is considered) were underrepresented. There are several possible explanations:

- (i) The temperature during formation of the nucleus (condensation of the volatiles and coagulation of the grains) was too high to freeze these highly volatile species.
- (ii) They did not exist in the solar nebula.
- (iii) They had been depleted in the external layers of the nucleus. The temperature of an ice covered surface reaches about 200 K and the gradient into the nucleus causes heat transport into the nucleus. Therefore the outer layers will be much warmer than the temperature in the Oort cloud ( $\approx 10$  K). If

**Table 1.** Abundances of probable parent molecules in the coma of comet Halley<sup>44</sup>. The data were obtained by the Neutral Mass Spectrometer (NMS)<sup>44</sup> on board Giotto, 1986, at heliocentric distances of 0.89 AU

Species	Gas production rate relative to $H_2O$	Remarks
CO	0.05...0.15	Also rocket UV observations
$CO_2$	$\leq 0.035$	
$CH_2$	$\leq 0.07$ $\approx 0.02$	Giotto ion mass spectrometer
$NH_3$	$\leq 0.1$ 0.01...0.02	Gas spectra Ion spectra
$N_2$	$\leq 0.02$ $< 0.02$	Gas spectra Ion spectra



**Figure 5.** Ion mass spectrum<sup>45</sup> at a distance between 11 and 12.10<sup>6</sup> m. The repetitive peaks could be interpreted as dissociation production of the chain molecule polyoxymethylene.

the nucleus structure is porous enough diffusion, and with it depletion, of highly volatile compounds seems plausible.

Case (iii) also sets a big caveat. The composition observed in the coma at a certain point on the orbit and in time does not necessarily reflect the average or original composition of the nucleus.

Heavy molecular ions were detected ranging beyond 100 AMU<sup>9</sup>. Relative density maxima were found at alternate mass differences of 14 and 16 AMU (Figure 5). Interpreting these differences as  $CH_2$  and O splitting alternatively from a chain molecule leads to polyoxymethylene as large parent molecule<sup>10</sup>. Other interpretations are possible, even invoking ring structures<sup>11</sup>. Compounds in question are not easy to sublime and need higher temperatures than that of subliming water ice. These organic tar-like materials probably sublime from the non-volatile dust component either from the grains or to a lesser degree from the hot (otherwise inert) surface.

### Dust

The result of the dust grain observations returned very exciting data both from the measurements of the grain size distribution as well as from the determinations of the composition. For the first time it was possible to measure the grain size distribution within the coma directly rather than to infer it from the scattering properties. And sure enough new particles too tiny to reflect the light in the visible were detected. Rather than peaking around a radius of about 0.1  $\mu m$  the number of small particles kept increasing beyond the limit of the measurements at the very low value of  $10^{-16}$  g (Figure 6)<sup>12</sup>. There was a fluid transition from large

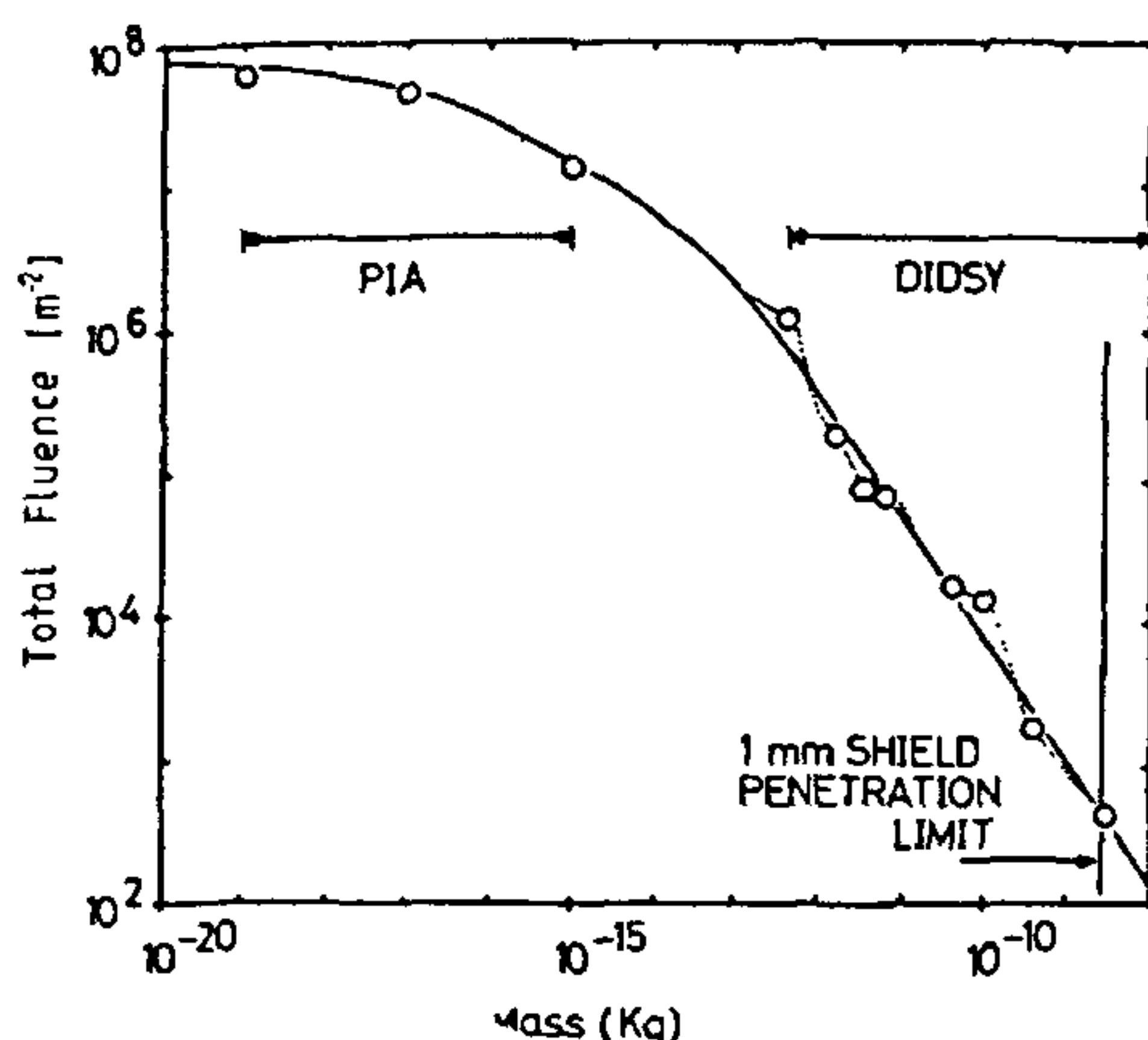


Figure 6. Fluences derived from  $-5$  min to  $+5$  min around Giotto closest approach. Data were taken by the instruments PIA and DIDSY<sup>12</sup>

centimeter size grains to molecular clusters. The main mass of the dust was contained in the large particles that could not be observed because of the poor statistics and the masking by impacts of the numerous small grains. In fact the largest impact (about 100 mg) was recorded by the Halley Multicolour Camera registering an attitude change of the Giotto spacecraft.

The spatial dust distribution was not isotropic but concentrated in jets, therefore it was difficult to extrapolate from measurements along the spacecraft trajectories to the total dust production. The dust to gas ratio by mass was estimated<sup>13</sup> to lie between 0.2 and 6. This value is higher than those assumed in the past. A 1:1 ratio seems plausible and also supported by arguments based on the overall element abundances in comets<sup>14</sup>.

Some of the most exciting results came from the *in situ* measurements of the composition of dust grains. The sophisticated Particulate Impact Analyzer (PIA called PUMA on board the Vega spacecraft) analysed thousands of particles<sup>15, 16</sup> mainly of small sizes in the range below  $10^{-12}$  g. The composition of the grains was found to be highly variable<sup>17</sup> ranging from mineral type grains to mass spectra only showing the volatile elements H, C, O and N (Figure 7). These CHON particles, contributing one third of the dust mass, constituted one of the biggest surprises. Cometary dust grains contained a large component of organic material that did not vaporize at the sublimation temperature of water around 200 K. However, when the dust grains left the matrix of the nucleus, the small particles were heated to temperatures up to 500 K and the semi-volatile molecules transgress into the gas phase. The high mass

ions of organic material found in the inner coma and the appearance of CN and C<sub>2</sub> jets in ground-based observations of the coma<sup>18</sup> as well as the inferred extended source for CO molecules<sup>19</sup> support the idea that the dust grains contribute substantially to the gas component of the cometary coma. The dust grains did not only show a continuous transition from large centimeter size grains to dimensions of molecular clusters but also from non-volatile to volatile material.

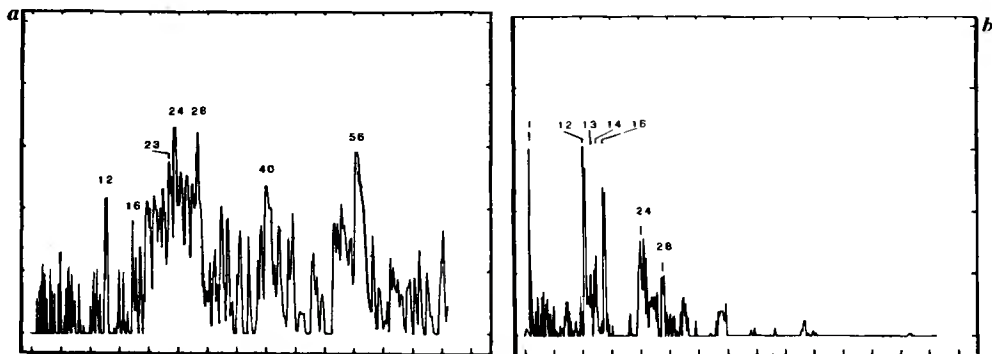
## Nucleus

The nucleus of comet Halley was observed by cameras on board the Vega<sup>20</sup> and Giotto<sup>21</sup> spacecrafts. Only the Giotto Halley Multicolour Camera (HMC) revealed details of the surface morphology and topography. The Giotto spacecraft passed the nucleus at a distance of 596 km in the first few minutes on 14 March 1986<sup>22</sup>. It lost contact with the earth shortly before closest approach. Therefore, the images taken by HMC during the fly-by covered a distance range from 770,000 down to 1600 km (Figure 8). The best resolution was about 40 m per picture element ( $22 \mu\text{rad}/\text{pixel}$ ). The phase angle during approach was  $107^\circ$  and changed only by a few degrees as long as HMC operated. The camera and its operation were described by Keller *et al.*<sup>23</sup>.

Not surprisingly, comet Halley was found to have *one* solid nucleus. It was rather irregularly shaped and appreciably larger than expected. Its dimensions are about  $16 \text{ km} \times 8 \text{ km} \times 8 \text{ km}$ , highly elongated. It had a uniformly dark surface with a geometric albedo of less than 4%. The dark surface showed only localized activity of dust production (jets). Its temperature ( $> 300 \text{ K}$ ) was markedly higher than the equilibrium temperature for sublimating water ice<sup>24</sup>. The total surface of the nucleus was about  $400 \text{ km}^2$  and its volume about  $550 \text{ km}^3$  with an uncertainty of 30%<sup>25</sup>. The mass of the nucleus can be estimated from the effect of the 'non-gravitational forces' caused by the non uniform sublimation of the ice near the Sun (see ref. 26 for a discussion). The derived density of the body is rather low,  $\leq 0.5$ .

## Shape of nucleus

The whole outline of the nucleus was visible (Figure 9); the major part (75%) as dark silhouette against the scattered light of the dust in the background. The highly elongated shape (2:1) of the nucleus of comet Halley may not be uncommon for comets (e.g. comet Iras-Araki-Alcock<sup>27</sup>). The sublimation rate (see below) is too small to yield such an irregular body starting from an approximate sphere. Therefore the nucleus of comet Halley was formed as a highly elongated body. This and the observed coarse roughness support the assumption



**Figure 7.** Two very different dust composition spectra achieved during the Vega 1 fly-by: *a*, spectrum closely related to a particle of type C1 carbonaceous chondrite; *b*, spectrum dominated by light elements, a so-called CIION particle<sup>15</sup>



**Figure 8.** Six examples of images of comet Halley in original frame sizes taken by the Halley Multicolour Camera on board the Giotto spacecraft. Image # 3056 (distance to nucleus 124,000 km) was taken 1814 s and image # 3502 31 s (2200 km) before closest approach

that the nucleus was formed from rather large subnuclei (dimensions 1/2 to 1 km).

A (relatively recent) break-up of a much larger body could also yield this strongly elongated shape. The almost straight limb on the dark side is suggestive for such an interpretation.

### Surface properties

The reflectivity of the surface was uniform. Variations observed at the phase angle of 107° were about  $\pm 50\%$

of the extremely low value of 0.4%. Images of the Vega 2 fly-by taken at low phase angles (about 20°) showed no identifiable variability of the surface reflectivity either. One has to conclude that the active areas (about 10% of the total surface as judged from the dust activity during the fly-by, see below) were only insignificantly brighter than the inactive majority of the surface. Probably the interior of the nucleus was not physically different from its outer surface. There was no ice (in the classical sense) visible. The comet did not look differentiated.



Figure 9. A composite of 6 HMC images ranging in resolution from 320 m to 60 m per pixel. Some of the contributing single images are displayed in Figure 8

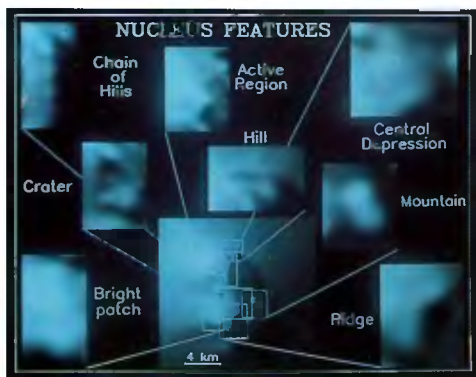


Figure 10. Several surface features of the nucleus of comet Halley from images taken by the Halley Multicolour Camera. The features are individually stretched in contrast and three-fold enlarged compared to the central composite image.

The temperature of the dark surface (directly measured during the Vega 2 fly-by) was so high that water ice

could not exist on it<sup>24</sup>. Therefore most of the nucleus was covered by a mantle. This surface mantle could well be a matrix of dust similar to the interior but simply depleted of water ice and other volatiles. It did not have to be a crust of regolith or debris left over from the sublimation activity. The thermal inertia of the surface layers seemed to be rather low, too low to keep activity going beyond the dusk terminator as witnessed by the dust distribution close to the nucleus<sup>28</sup>.

### Topography

Many features on the surface manifested themselves not as much by variation of the surface reflectivity but by their imprints on the outline of the nucleus and of the terminator (Figure 10). Only 25% of the visible surface was illuminated by the Sun. The contributions of scattered light from dust in the very vicinity of the surface masked the light being scattered directly from the surface.

The most prominent feature directly visible was the 'crater', a roundish structure of about 2000 m in diameter, rather shallow 150 to 200 m in depth<sup>29</sup>. High resolution images showed structures of less than 400 m within the crater. Similar scales or slightly larger ones could be found in the undulation of the terminator north of the crater towards the northern tip of the nucleus. Here the strongest visible activity was located. Some of the very fine structures (filaments less than 500 m across) in the dust emission could be related to somewhat brighter spots on the surface. A very prominent feature was the bright spot within the dark section of the surface. The strong gradient in brightness was unresolved (less than 200 m). It could be the Sun illuminated tip of a 'mountain'. This interpretation implies a rise to about 1 km above the ellipsoidal shape. A similarly accentuated feature was the 'duck tail', the southern rather sharp 90° corner of the nucleus seen in projection.

The coarse roughness of the nucleus implied a certain amount of tensile strength although gravity was very low. It also indicated that the sublimation did not equalize features. There were areas where the amount of volatiles within the surface region was depleted so that no sublimation could take place.

### Rate of sublimation

It could be estimated that the loss of surface layer per revolution was about 6 m at active areas. For this estimate water sublimating unrestricted from a dark surface had been assumed and a density of the material of 1/3 g cm<sup>-3</sup> (ref. 30). If, for example, the 'crater' was an area of enhanced and steady activity it would have been visible at the time of the first recorded apparition of comet Halley more than 2000 years (30 orbits) ago.

It would take about another several 1000 revolutions of comet Halley around the Sun for its nucleus to vanish completely if the level of activity could be maintained. Investigations of meteor streams associated with the orbit of comet Halley show that the evolution of meteorite population has taken at least 2000 orbits of comet Halley around the Sun on its present orbit<sup>31</sup>. This makes comet Halley a rather old comet and indicates that the size of its nucleus was originally even larger, possibly twice its present linear dimension.

It also means that a possible alteration of the nuclear surface during the storage of the nucleus in the Oort cloud caused by cosmic rays for over  $4 \cdot 10^9$  yr could not be found today. The thickness of such a layer is estimated<sup>32</sup> to be substantially less than 100 m.

### Rotation of nucleus

A period of rotation of 52 to 54 h was derived from comparison of images taken during the three fly-bys<sup>33, 34</sup>. Since it has not been possible to identify specific features on the Vega images a considerable uncertainty remains in the orientation of the spin axis<sup>35</sup>. The situation is further complicated by nutation of the body. The variability of gas and dust production with a period of 7.3 or 14.6 d (ref. 36, 37) is generally related to nutation<sup>38, 39</sup>. The rotation of about two days is also reflected in the curvature of dust jets.

The rather long rotation period (if compared to the mean period of asteroids) may be physically required for the nucleus to survive. Due to its elongated shape the velocity of rotation of the tips (8 km from the centre) is comparable to the orbital velocity around the nucleus if the average density of the nucleus is about  $1/3 \text{ g cm}^{-3}$ .

### Activity of the nucleus

One of the most unexpected results from the imaging was the strong concentration of dust jets emanating from limited areas only comprising about 10 to 20% of the total surface. This concentration of activity makes plausible the often observed rather strong variability of the cometary production within hours, short compared to the duration of a 'day'. It has not been possible to discern areas of activity clearly from those dormant.

Within these active areas (typical diameter about 3 km) a certain degree of inhomogeneity was visible expressed in the fine filaments of dust jet structure. These structures are strongly confined with opening angles of a few degrees. They could be caused by variation of the (visible) dust to gas ratio within the active area or by enhanced sublimation caused either by variation of physical properties or of chemical composition or indicate enhancement in the boundary layers of colliding jets.

Several faint dust jets (filaments) pointed in antisolar direction on images taken by HMC. They could still emanate from the area near the evening terminator. However, on Vega images at least one jet could be traced back to the dark side of the nucleus<sup>40</sup>. Some places on the nucleus might have stored enough energy to support limited activity even on the nightside.

### Conclusions

The observations revealed the heart of a comet for the first time. The volatile component was dominated by water as predicted. However, the appearance of the nucleus did not resemble a 'snow ball'. Its surface was extremely dark and can be heated up to temperatures far beyond the sublimation temperature of water ice. The morphology and topography did not support a crust of left-over regolith of dust particles. The reflectivity varied little. The nucleus was not covered by a crust that is substantially different from the interior. Possible alterations due to high energy radiation have been lost on comets such as Halley.

The elongated and irregular shape of the cometary nucleus leads to the presumption that the nucleus was formed out of large subnuclei of kilometre size. This assumption is also supported by the typical scale size of surface structures in the range of 1/2 km. However smaller scale features were also observed as expected from a body size distribution.

The surface of the nucleus appeared uniform. Similarly, there was little variation within its active areas implying that the interior and the surface were of the same physical quality. No 'icy' surface was visible. The rather large topographic features (in particular the height of the mountain) eliminate the picture of a shrinking ice ball covered by regolith of larger dust particles. All this supports the picture of a nucleus, the physical structure of which is dominated by the matrix of the non-volatile (dust) rather than by the volatile material (ice). Large parts of the surface were depleted of volatiles and could reach high temperatures. The depth of this layer of depletion is unknown but does not have to be thick. The surface texture was probably very fluffy as witnessed by the observed dust particles. This explained the extremely low reflectivity. The heat conduction by the solid material will be low. However, heat could be transported by the sublimated gas inside the fluffy surface which could recondense further inside.

The scenario of the formation of cometary nuclei could be as follows. Ice covered dust particles (not only silicates but rather condensates of non-volatile (compared to water) material including organic substances) form fluffy structures. The ice is predominantly preserved within the cavities. Cometary nuclei may have been formed out of dust particles rather than of 'snow

flakes'. The ice filled dust particles clump together to form larger grains and bodies. Collisions even at low relative speeds lead to strong perturbations of the contact areas. The bodies are so fluffy (but still stiff) that they can penetrate each other during the collisions. These contact zones may show up as inhomogeneities leading to changes in the rate of sublimation. The requirement of non-catastrophic collisions restricts the formation of the nuclei to a region with low relative velocities near the limits of the present planetary system. Not only the sizes of the nuclei but also their masses ( $\sim 10^{17}$  g) are rather large.

- 1 Kaneda, E., Hirao, K., Takagi, M., Ashihara, O., Itho, T. and Shimizu, M., *Nature*, 1986, **320**, 140
- 2 Kaneda, E., Ashihara, O., Shimizu, M., Takagi, M. and Hirao, K., *Nature*, 1986, **321**, 297
- 3 Sekanina, Z. and Larson, S. M., *Astron J*, 1986, **92**, 462
- 4 Gringauz, K. I., Gombosi, T. I., Remizov, A. P., Apathy, I., Szemerey, I., Verigin, M. I., Denchikova, L. I., Dyachkov, A. V., Keppler, F., Klimenko, I. N., Richter, A. K., Somogyi, A. J., Szego, K., Szendrő, S., Tatrallyay, M., Varga, A. and Vladimirova, G. A., *Nature*, 1986, **321**, 282
- 5 Johnston, A., Coates, A., Kellock, S., Wilken, B., Jockers, K., Rosenbauer, H., Studemann, W., Weiss, W., Formisano, V., Amata, E., Cerulli-Irelli, R., Dobrowolny, M., Terenzi, R., Egidio, A., Borg, H., Hultquist, B., Winningham, J., Gurgiolo, C., Bryant, D., Edwards, T., Feldman, W., Thomsen, M., Wallis, M. K., Biermann, L., Schmidt, H., Lust, R., Haerendel, G. and Paschmann, G., *Nature*, 1986, **321**, 344
- 6 Galeev, A. A., *Astron Astrophys*, 1987, **187**, 12
- 7 Krankowsky, D., Lämmerzahl, P., Herrwerth, I., Woweries, J., Eberhardt, P., Dolder, U., Herrmann, U., Schulte, W., Berthelier, J. J., Illiano, J. M., Hodges, R. R. and Hoffman, J. H., *Nature*, 1986, **321**, 326
- 8 Eberhardt, P., Krankowsky, D., Schulte, W., Dolder, U., Lämmerzahl, P., Berthelier, J. J., Woweries, J., Stubbemann, U., Hodges, R. R., Hoffman, J. H. and Illiano, J. M., *Astron Astrophys*, 1987, **187**, 481
- 9 Korth, A., Richter, A. K., Loidl, A., Anderson, K. A., Carlson, C. W., Curtis, D. W., Lin, R. P., Reme, H., Sauvaud, J. A., d'Uston, C., Colin, F., Cros, A. and Mendis, D. A., *Nature*, 1986, **321**, 335
- 10 Huebner, W. F., *Science*, 1987, **237**, 628
- 11 Korth, A., Marconi, M. L., Mendis, D. A., Krueger, F. R., Richter, A. K., Lin, R. P., Mitchell, D. L., Anderson, K. A., Carlson, C. W., Reme, H., Sauvaud, J. A. and d'Uston, C., *Preprint*, 1988
- 12 McDonnell, J. A. M., Alexander, W. M., Burton, W. M., Bussoletti, F., Evans, G. C., Evans, S. T., Firth, J. G., Gard, R. J. L., Green, S. F., Grün, E., Hanner, M. S., Hughes, D. W., Igenbergs, E., Kissel, J., Kucsera, H., Lindblad, B. A., Langevin, Y., Mandeville, J.-C., Nappo, S., Pankiewicz, G. S. A., Perry, C. H., Schwehm, G. H., Sekanina, Z., Stevenson, T. J., Turner, R. I., Weishaupt, U., Wallis, M. K. and Zarnecki, J. C., *Astron Astrophys*, 1987, **187**, 719
- 13 Crifo, J. F., *Xth European Regional Astronomy meeting of the IAU*, 1987
- 14 Jessberger, E. K., Christofilidis, A. and Kissel, J., *Nature*, 1988, **332**, 691
- 15 Kissel, J., Sagdeev, R. Z., Bertaux, J. L., Angarov, V. N., Audouze, J., Blamont, J. F., Büchler, K., Evlanov, E. N., Fechtig, H., Iomchenkova, M. N., von Hoerner, H., Inogamov, N. A., Khromov, V. N., Knabe, W., Krueger, F. R., Langevin, Y., Leonas, V. B., Levasseur-Regourd, A. C., Managadze, G. G., Podkolzin, S. N., Shapiro, V. D., Tabaldyev, S. R. and Zubkov, B. V., *Nature*, 1986, **321**, 280
- 16 Kissel, J., Brownlee, D. E., Büchler, K., Clark, B. C., Fechtig, H., Grün, E., Hornung, K., Igenbergs, E. B., Jessberger, E. K., Krueger, F. R., Kucsera, H., McDonnell, J. A. M., Morfill, G. M., Rahe, J., Schwehm, G. H., Sekanina, Z., Utterback, N. G., Völk, H. J. and Zook, H. A., *Nature*, 1986, **321**, 336
- 17 Clark, B. C., Mason, L. W. and Kissel, J., *Astron Astrophys*, 1987, **187**, 779
- 18 A'Hearn, M., Hoban, S., Birch, P. V., Bowers, C., Martin, R. and Klinglesmith, D. A., *Nature*, 1986, **324**, 649
- 19 Eberhardt, P., Krankowsky, D., Schulte, W., Dolder, U., Lämmerzahl, P., Berthelier, J. J., Woweries, J., Stubbemann, U., Hodges, R. R., Hoffman, J. H. and Illiano, J. M., *Symposium on the Exploration of Halley's Comet*, 1986, ESA-SP 250, 383
- 20 Sagdeev, R. Z., Szabo, F., Avanesov, G. A., Cruvellier, P., Szabó, L., Szegő, K., Abergel, A., Balazs, A., Barinov, I. V., Bertaux, J.-L., Blamont, J., Dettaille, M., Demarelis, E., Dul'nev, G. N., Endroczy, G., Gardos, M., Kanyo, M., Kostenko, V. I., Krasikov, V. A., Nguyen-Trong, T., Nyitrai, Z., Reny, I., Rusznyak, P., Shamus, V. A., Smith, B., Sukhanov, K. G., Szabó, F., Szalai, S., Tarnopolsky, V. I., Toth, I., Tsukanova, G., Valnicek, B. I., Varhalmi, L., Zaiko, Yu. K., Zatsepin, S. I., Ziman, Ya. L., Zsenczi, M. and Zhukov, B. S., *Nature*, 1986, **321**, 262
- 21 Keller, H. U., Arpigny, C., Barbieri, C., Bonnet, R. M., Cazes, S., Coradini, M., Cosmovici, C. B., Delamere, W. A., Huebner, W. F., Hughes, D. W., Jamar, C., Malaise, D., Reitsema, H. J., Schmidt, H. U., Schmidt, W. K. H., Seige, P., Whipple, F. L. and Wilhelm, K., *Nature*, 1986, **321**, 320
- 22 Curdt, W., Wilhelm, K., Craubner, H., Krahn, E. and Keller, H. U., *Astron Astrophys*, 1988, **191**, L1
- 23 Keller, H. U., Schmidt, W. K. H., Wilhelm, K., Becker, Ch., Curdt, W., Engelhardt, W., Hartwig, H., Kramm, J. R., Meyer, H. J., Schmidt, R., Gliem, F., Krahn, E., Schmidt, H. P., Schwarz, G., Turner, J. J., Boyries, P., Cazes, S., Angrilli, F., Bianchini, G., Fanti, G., Brunello, P., Delamere, W. A., Reitsema, H., Jamar, C. and Cucciato, C., *J Phys E Sci Instrum*, 1987, **20**, 807
- 24 Emerich, C., Lamarre, J. M., Moroz, V. I., Combes, M., Sanku, N. F., Nikolsky, Y. V., Rocard, F., Gispert, R., Coron, N., Bibring, J. P., Encrenaz, T. and Crovisier, J., *Astron Astrophys*, 1987, **187**, 839
- 25 Keller, H. U., Delamere, W. A., Huebner, W. F., Reitsema, H. J., Schmidt, H. U., Whipple, F. L., Wilhelm, K., Curdt, W., Kramm, J. R., Thomas, N., Arpigny, C., Barbieri, C., Bonnet, R. M., Cazes, S., Coradini, M., Cosmovici, C. B., Hughes, David, W., Jamar, C., Malaise, D., Schmidt, K., Schmidt, W. K. H. and Seige, P., *Astron Astrophys*, 1987, **187**, 807
- 26 Whipple, F. L., *Symposium on the Exploration of Halley's Comet*, ESA-SP 1986, **250**, 281
- 27 Sekanina, Z., *Astron J*, 1988, **95**, 1876
- 28 Thomas, N. and Keller, H. U., *Proceedings of the Symposium Dust in the Universe* (1988), p. 540
- 29 Schwarz, G., Craubner, H., Delamere, W. A., Goebel, M., Gonano, M., Huebner, W. F., Keller, H. U., Kramm, J. R., Mikusch, E., Reitsema, H., Whipple, F. L. and Wilhelm, K., *Astron Astrophys*, 1987, **187**, 847
- 30 Huebner, W. F., Delamere, W. A., Reitsema, H., Keller, H. U., Wilhelm, K., Whipple, F. L. and Schmidt, H. U., *Symposium on the Exploration of Halley's Comet*, 1986, ESA-SP 250, vol. II, 363
- 31 Hajduk, A., *Symposium on the Exploration of Halley's Comet*, 1986, ESA-SP 250, 239
- 32 Johnson, R. E., Cooper, J. F., Lanzerotti, L. J. and Strazula, G., *Astron Astrophys*, 1987, **187**, 889
- 33 Wilhelm, K., Cosmovici, C. B., Delamere, W. A., Huebner, W. F., Keller, H. U., Reitsema, H., Schmidt, H. U. and Whipple, F. L., *Symposium on the Exploration of Halley's Comet*, 1986, ESA-SP 250, 367

34. Sagdeev, R. Z., Krasikov, V. A., Shamis, V. A., Tarnopolski, V. I., Szegő, K., Tóth, I., Smith, B., Larson, S. and Merényi, E., *Symposium on the Exploration of Halley's Comet*, 1986, ESA-SP 250, 335.
35. Keller, H. U. and Thomas, N., *Nature*, 1988, 333, 146.
36. Millis, R. L. and Schleicher, D. G., *Nature*, 1986, 324, 646.
37. Festou, M. C., Drossart, P., Lecacheux, J., Encrenaz, T., Puel, F. and Kohl-Moreira, J. L., *Astron. Astrophys.*, 1987, 187, 575.
38. Sekanina, Z., *Nature*, 1987, 325, 326.
39. Julian, W. M., *Nature*, 1987, 326, 57.
40. Smith, B., Szegő, K., Larson, S., Merényi, E., Tóth, I., Sagdeev, R. Z., Avanesov, G. A., Krasikov, V. A., Shamis, V. A. and Tarnopolsky, V. I., *Symposium on the Exploration of Halley's Comet*, 1986, ESA-SP 250, vol. II, 327.
41. Mukai, T., Miyake, W., Terasawa, T., Kitayama, M. and Hirao, K., *Nature*, 1986, 321, 299.
42. Neubauer, F. M., Glassmeier, K. H., Pohl, M., Raeder, J., Acuna, M. H., Burlaga, L. F., Ness, N. F., Musmann, G., Mariani, F., Wallis, M. K., Ungstrup, E. and Schmidt, H. U., *Nature*, 1986, 321, 352.
43. Balsiger, H., Altwegg, K., Bühler, F., Geiss, J., Ghielmetti, A. G., Goldstein, B. E., Goldstein, R., Huntress, W. T., Ip, W.-H., Lazarus, A. J., Meier, A., Neugebauer, M., Rettenmund, U., Rosenbauer, H., Schwenn, R., Sharp, R. D., Shelley, E. G., Ungstrup, E. and Young, D. T., *Nature*, 1986, 321, 330.
44. Krankowsky, D. and Eberhardt, P., *Comet Halley 1986: World-Wide Investigations, Results and Interpretations*, Ellis Horwood, Chichester, 1989, p. 273.
45. Huebner, W. F., Boice, D. C., Sharp, C. M., Korth, A., Lin, R. P., Mitchell, D. L. and Rème, H., *Symposium on the Diversity and Similarity of Comets*, 1987, ESA-SP 278, 163.

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