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The Nature of Comets [and Discussion]

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The nature of comets

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[Plates 1–4]

The vast scientific campaign associated with the 1986 return of Halley's Comet has greatly improved and expanded our knowledge of comets. An overview of the first results is presented here with emphasis on the large-scale structure, the chemistry, and the nucleus.

Biermann and Alfvén's basic large-scale picture involving the interaction with the solar wind was confirmed. The interaction extends over very large distances and involves the draping of magnetic field lines from the solar wind around the head region. The near-nuclear region is essentially free of magnetic field. The cometary environment is a rich plasma physics laboratory as well as the site of spectacular disconnection events.

As Whipple proposed, the chemical composition of the nucleus is largely water, and the breakup of the water molecule produces the large hydrogen-cloud surrounding the comet. Minor constituents with high molecular mass have been observed in the comet. The composition of the dust generally resembles carbonaceous chondrites enriched in the elements H, C, N and O. The interest in the cometary chemistry stems from the belief that cometary material is probably the best remnant of the solar nebula's original composition.

The nucleus is monolithic, as predicted by Whipple's icy-conglomerate model. Far from spherical, the nucleus is irregular and peanut- or potato-shaped. The surface is very dark, and the emission of gas and dust occurs in jets on the sunward side. Irregular erosion of the surface, which is covered by a dust crust, could lead to many interesting possibilities for outbursts or splitting.

Even with our current enhancement of knowledge, comets will continue to excite scientific curiosity. Future research on comets should be very fruitful.

INTRODUCTION

The sight of a bright comet in the sky, such as the view shown in figure 1, plate 1, is fascinating to scientists and non-scientists alike. A tail tens of millions of kilometres long stretching many degrees requires explanation. Such explanation is being supplied through a massive group enterprise.

This enterprise, which culminated during 1985 and 1986, has resulted in a fundamental change in the field of cometary research. The standard bearer of the change was, of course, the direct exploration of comets by spacecraft. These are indicated in table 1. Six spacecraft were involved; five were probes for Halley and the sixth probed Comets Halley and Giacobini–Zinner. Roughly 50 experiments aboard these spacecraft gathered information

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Table 1. Space missions to comets

spacecraft	comet	approximate distance at closest approach/km	date of closest approach	imaging of nucleus?
ICE (NASA)	Giacobini–Zinner	8000, tailward	11 September 1985	no
Vega 1 (U.S.S.R.)	Halley	9000, sunward	6 March 1986	yes
Suisei (Japan)	Halley	150000, sunward	8 March 1986	no
Vega 2 (U.S.S.R.)	Halley	8000, sunward	9 March 1986	yes
Sakigake (Japan)	Halley	7000000, sunward	11 March 1986	no
Giotto (ESA)	Halley	600, sunward	14 March 1986	yes
ICE (NASA)	Halley	28000000, sunward	25 March 1986	no

ranging from images of the nucleus to plasma waves far from the nucleus. We should note our extreme good fortune for the successful launches of all the comet missions and the proper functioning of nearly all the scientific instruments.

As impressive as the direct exploration has been, our progress in understanding comets does not rest solely on these missions. Very important data have been obtained from spacecraft in orbit around the earth (the *International Ultraviolet Explorer*, the *Solar Maximum Mission*, and the *Dynamics Explorer* 1) and around Venus (*Pioneer Venus Orbiter*), from rocket flights, from the *Kuiper Airborne Observatory*, and from the vast ground-based networks of the *International Halley Watch*.

Current preliminary reports involve a considerable amount of 'cream skimming'. Our definitive model will ultimately involve compatibility with all data gathered regardless of method. The goal is a complete observational effort for a highly variable object that leads to a detailed synthesis. Successful completion will surely take several more years.

This paper is organized into three general sections: (1) large-scale structure–plasma physics; (2) chemistry and (3) the nucleus.

LARGE-SCALE STRUCTURE–PLASMA PHYSICS

The view that the solar-wind interaction is important in the large-scale structure of comets stems from the work of L. Biermann in the early 1950s and from H. Alfvén's elaboration founded on the importance of the magnetic field. The physical picture is based on the idea that a strong interaction occurs when sublimated neutral molecules stream away from the nucleus and are ionized and trapped onto the solar-wind magnetic-field lines. The field lines are decelerated by the additional mass from the 'pickup ions' and wrap around the comet. This process produces the plasma tails of comets, which are seen when the trapped ionized molecules fluoresce when illuminated by the sun. The tail structure is normally attached to the comet's head region and has a bi-lobed magnetic configuration. The regions of opposite polarity should be separated by a current sheet. In addition, the comet is an obstacle in the solar-wind flow (which is supersonic and superalfvénic) and, hence, a bow shock was expected.

For Comet Giacobini–Zinner, the *International Cometary Explorer* (ICE) established that our ideas were basically correct, as summarized in figure 2. Magnetic field draping was confirmed. Dust impacts were recorded and the mass spectrometer showed that the principal ions were from the water group (HO^+, H_2O^+, H_3O^+). The plasma tail was dense and cold.

Some results were not expected. The reversal of the magnetic polarity was detected as the

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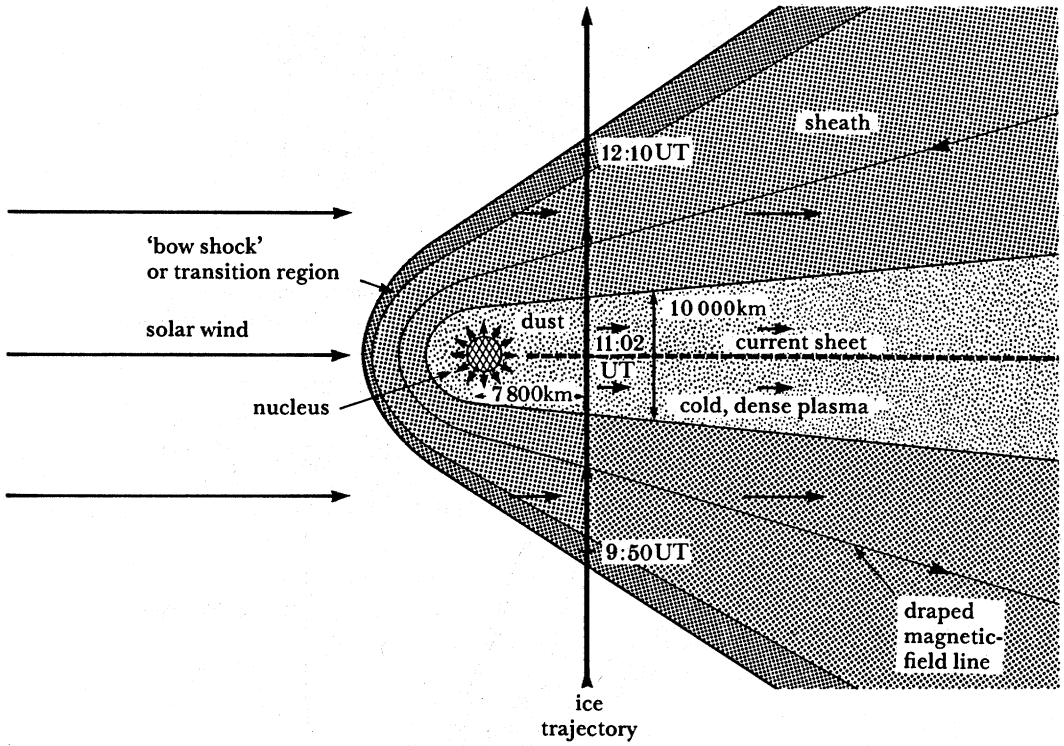

FIGURE 2. Summary schematic for the *International Cometary Explorer* encounter with Comet Giacobini–Zinner, not to scale. The vertical line represents the spacecraft trajectory marked with times on 11 September 1985. See text for discussion.

spacecraft crossed the current sheet. The surprise here exists because of expected unfavourable geometry. Both the normal orientation of the current sheet and the ICE trajectory were approximately perpendicular to the ecliptic. Solar-wind conditions rotated the current sheet and facilitated detection. The size of the interaction region was immense as evidenced by magnetic-wave activity and the measurement of pickup ions. A major (but not universal) surprise was the nature of the bow wave. The classical, abrupt changes associated with a bow shock were not observed. Rather, the deceleration is gradual and takes place over a considerable distance. The function of the expected bow shock or its surrogates is the same in any case, namely to slow the solar wind so that it can flow around the obstacle. This function is achieved for Comet Giacobini–Zinner and Comet Halley in a manner different from other Solar System bodies.

The large interaction region for Comet Giacobini–Zinner gave reason to expect a very large one for Comet Halley. In the range of total gas production rates applicable to these comets, large-scale plasma structures have dimensions that scale linearly with the production rate (*not* the square root). This feature may arise from the collective nature of the solar-wind interaction. Thus, both *Sakigake* at 7 M km sunward and ICE at 28 M km sunward were expected to directly detect Comet Halley, and they did. The results for Comet Halley are illustrated in figure 3. As a rough approximation, the Halley results are similar to the results for Comet Giacobini–Zinner scaled up by a factor of 7. The shock is diffuse, and the total interaction region extends to about 35 M km from the nucleus. The flow speed of the plasma measured by the

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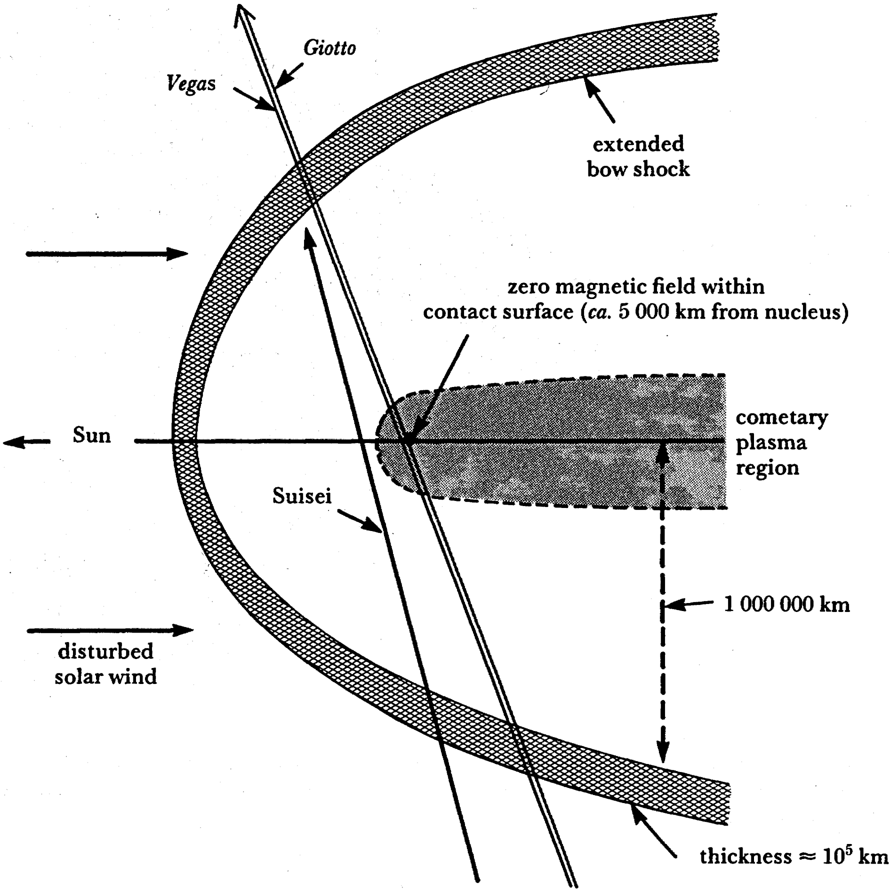

Figure 3. Summary schematic for plasma structures in Halley's Comet drawn approximately to scale. The trajectories of *Giotto* and the *Vegas* are displaced for clarity. Cometary ions dominate in the cometary plasma region and *Giotto* found an apparently magnetic-field-free cavity around the nucleus.

various spacecraft varies from the solar-wind speed well away from the comet to much lower speeds of not more than about 10 km s^{-1} near the nucleus. Near the nucleus of Halley's Comet, the measurement showed H_3O^+ to be the most abundant ion.

In addition, *Giotto* passed sufficiently close to the nucleus to verify the existence of the nearly field-free region (where the solar-wind magnetic field is excluded). Measurements at both comets showed the existence of ions at energies of *ca.* 500 keV. At these energies, acceleration processes other than the pickup of cometary ions by the solar wind flow are required.

Ground-based data have recorded some dramatic examples of large-scale phenomena, and correlations of imaging with the *in situ* data are in progress. The images in figure 4, plate 1, show an example of a disconnection event (DE) occurring in Comet Halley. In this event, the entire plasma tail disconnects from the comet, moves in the antisolar direction, and the comet begins to form a new tail. The leading model by Niedner and Brandt predicts that DEs should occur at the sector boundaries in the solar wind where the magnetic polarity reverses. Evidence available until now indicates that this model is holding up well.

Much of this discussion has focused on the plasma-physics aspects of comets. This subject is important to understanding comets and, conversely, comets are beautiful plasma-physics

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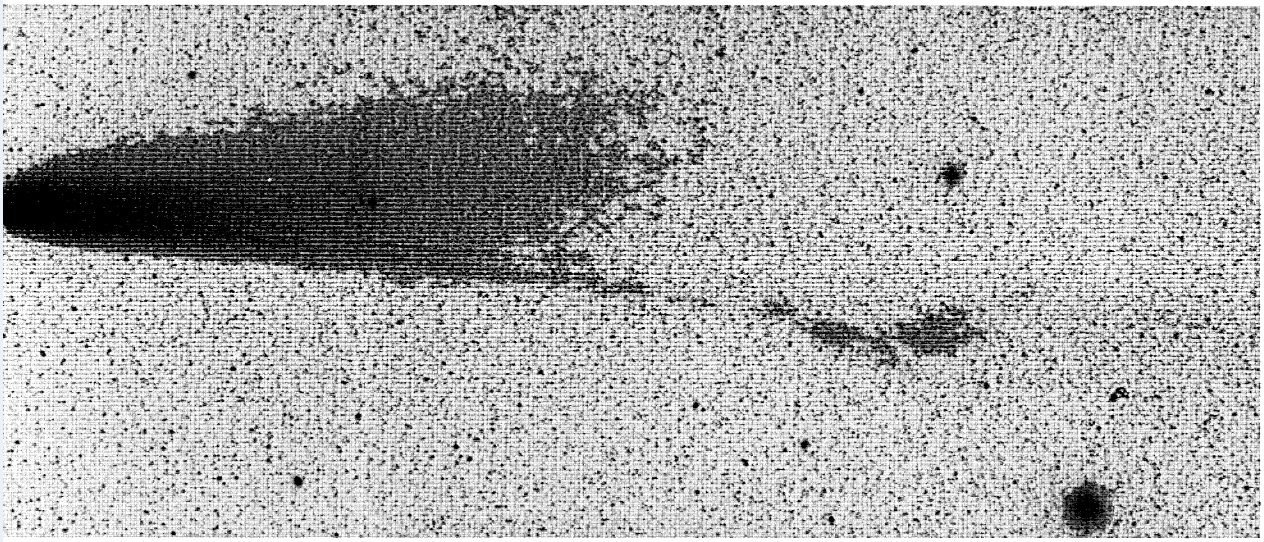

FIGURE 1. Comet Halley as photographed on 22 March 1986 showing the dust tail (above) and the plasma tail (below) with a bend caused by a disturbance in the solar wind. The tail stretches approximately 8° across the sky, or some 20×10^6 km. (Photograph taken by E. P. Moore at the Joint Observatory for Cometary Research, operated by the Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center and the New Mexico Institute of Mining and Technology.)

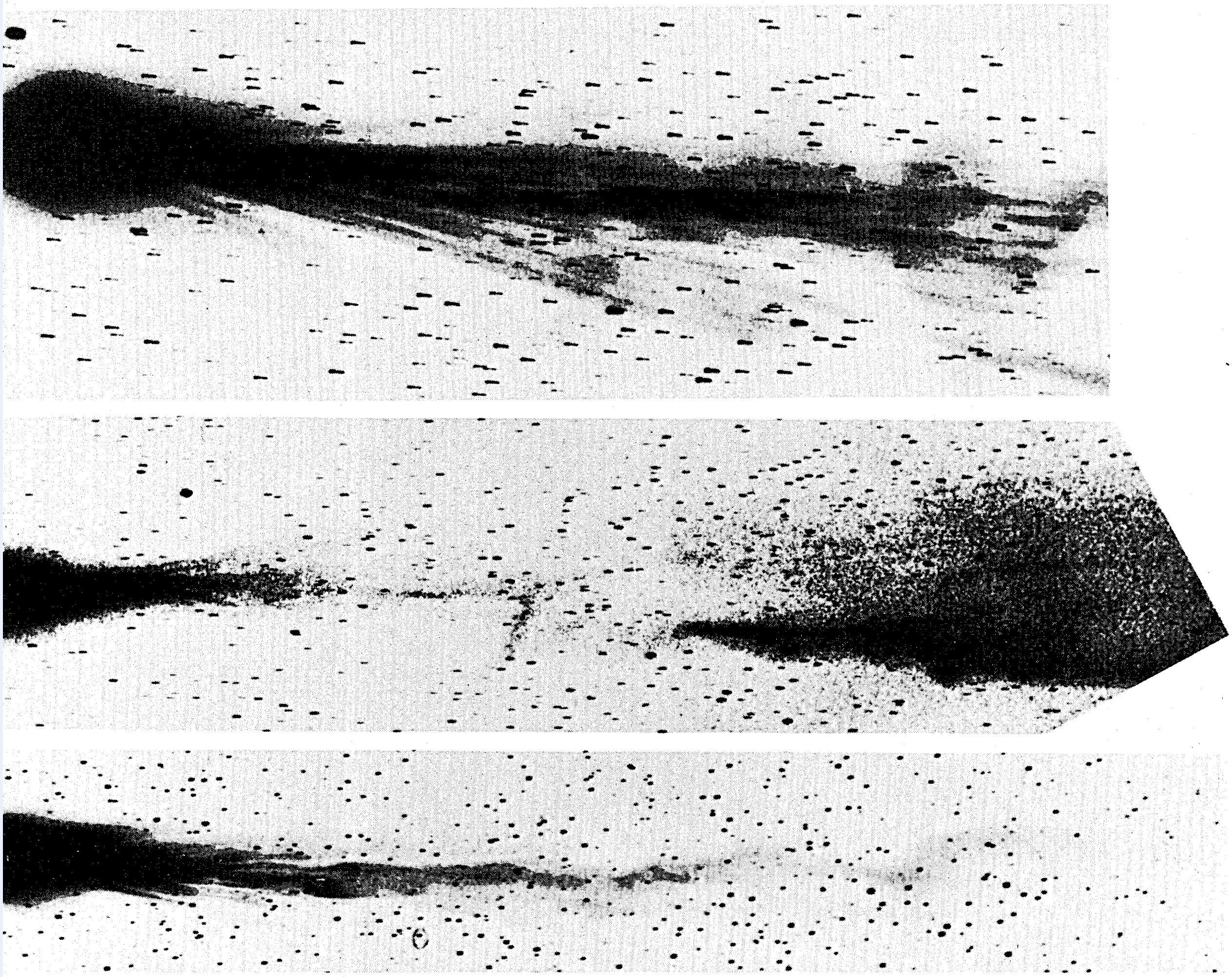

FIGURE 4. Disconnection event in Comet Halley. The individual photographs are: (*a*) 9 January 1986, Calar Alto Observatory, Spain (Max-Planck-Institut für Astronomie, Heidelberg); (*b*) 10 January 1986, Calar Alto Observatory, Spain (Max-Planck-Institut für Astronomie, Heidelberg and (*c*) 11 January 1986, Haute-Provence Observatory (C.N.R.S. – University of Liège). The disconnected tail is clearly shown on 10 January (*b*) along with the usual tail the day before and the day after. Full tail length shown is approximately 15×10^6 km.

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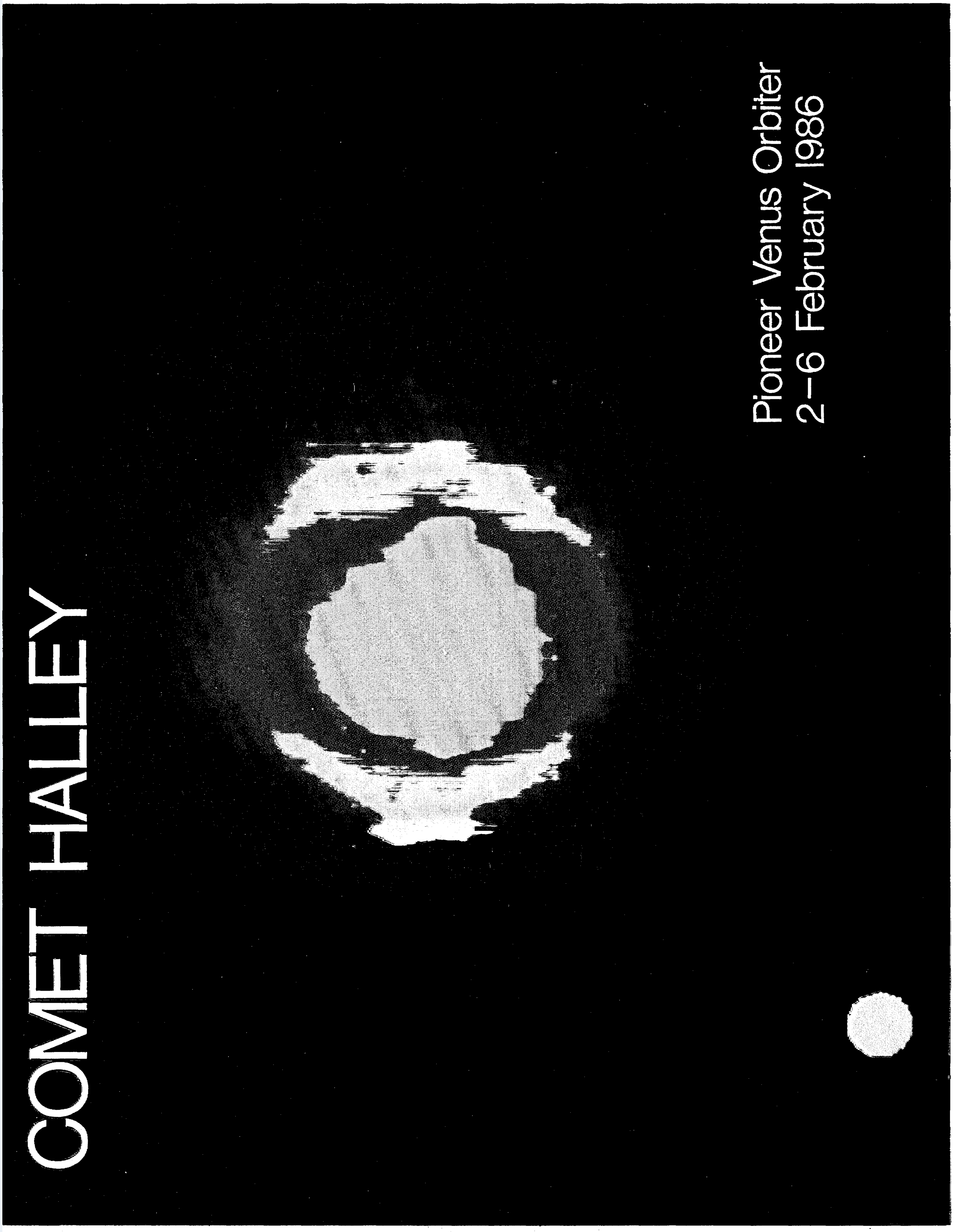

FIGURE 5. The hydrogen cloud of Comet Halley in early February 1986 as observed from the *Pioneer Venus Orbiter*. The false-colour image is based on brightness contours in hydrogen Ly-α at 1216 Å (121.6 nm). The image covers an area 20×10^6 km by 23×10^6 km, and the white disc in the lower left corner is the size of the Sun. (I. A. F. Stewart, University of Colorado.)

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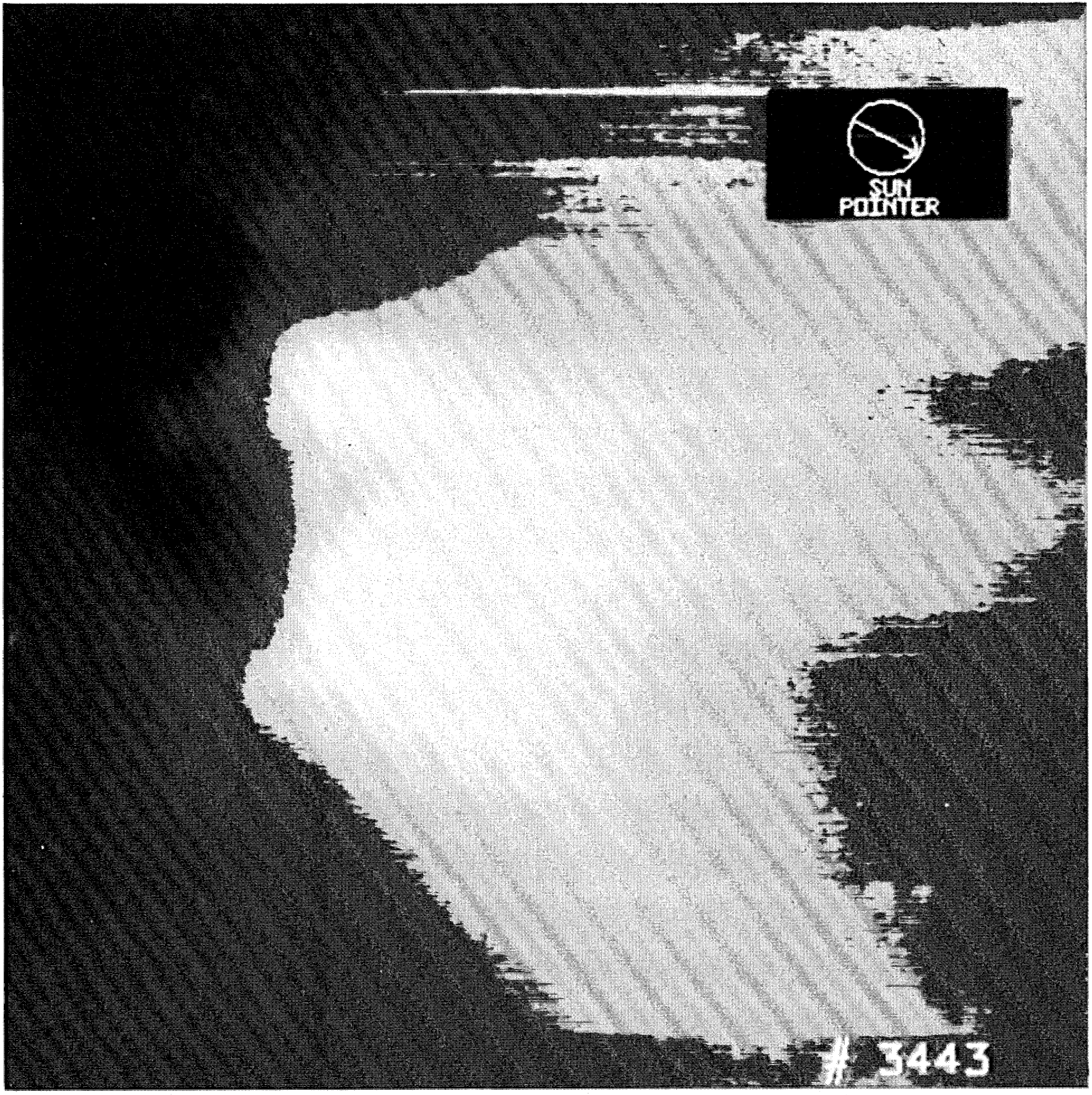

FIGURE 7. Pseudocolour or false-colour (but not contour) image of the nucleus of Halley's Comet obtained by *Giotto* at a distance of 18270 km. The frame is 30 km by 30 km. The nucleus is the dark object at upper left seen in silhouette against the bright background. The bright jets point toward the Sun (as indicated by the sun pointer). The bright feature in the centre of the nucleus could be due to an elevated feature on the night side of the terminator that is illuminated by sunlight. On images taken closer to the nucleus, a crater-like circular feature is clearly seen. Compare with figures 6 and 8. (Halley Multicolor Camera, Giotto Project, Max-Planck Institut für Aeronomie.)

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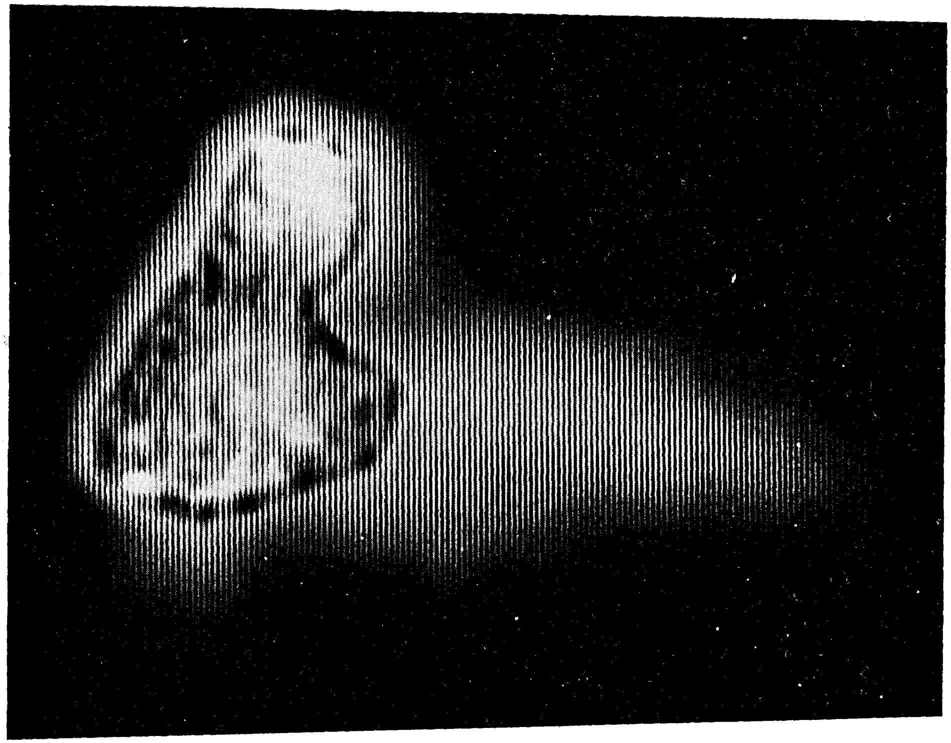

FIGURE 6. Enhanced, grey-scale image of the nucleus of Halley's Comet obtained by *Vega 2* at a distance of 8030 km showing the solid body and a prominent jet. Compare with figures 7 and 8. Note that the jet shown is sunward as are nearly all the near-nuclear structures (figures 6 and 7). The appearance contrasts with views of the entire comet (figures 1, 4 and 9) where the structures (e.g. the tail) are antisunward. (*Vega* Project.)

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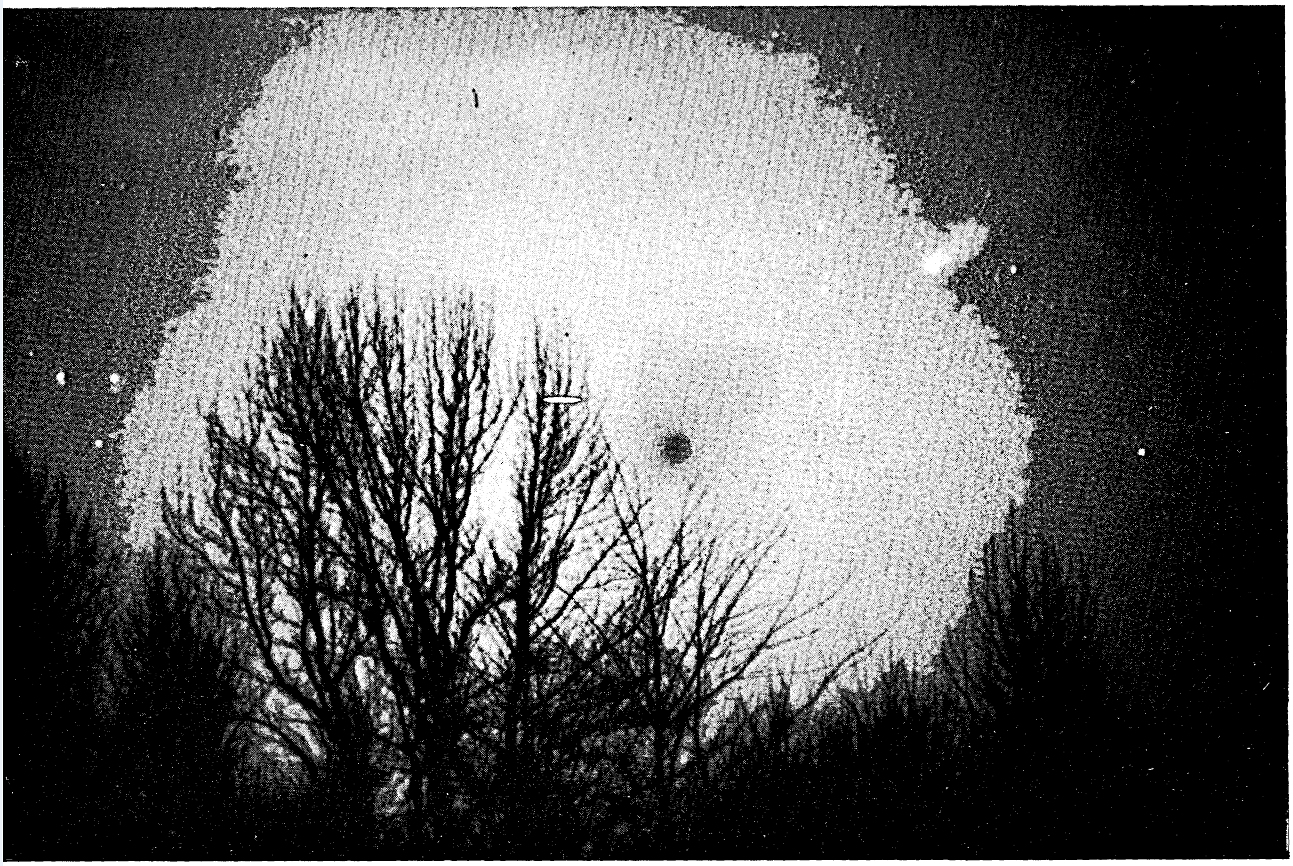

FIGURE 9. Halley's Comet on 16 March 1986 from a site near Washington, D.C. Approximately 5° of tail is shown. This bittersweet photograph was obtained by E. Grayzeck with the flight spare Wide Field Camera for the *Astro 1* Mission (which was scheduled for launch on 6 March 1986). The dark spot at the centre is a blemish on the photocathode of the image intensifier.

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laboratories. Approximately half the experiments sent to comets in 1985–1986 have related to plasma physics. This aspect of cometary physics provides unique opportunities to obtain knowledge of cosmic plasmas, which, after all, constitute the state of the overwhelming majority of matter in the Universe.

CHEMISTRY

The large-scale structure discussion is briefly continued to introduce a topic in chemistry. The icy-conglomerate model of the nucleus is based on water ices as the major volatile constituent. All relevant evidence, whether remote or *in situ*, confirms this view; the ices are at least 80% water. A spectacular manifestation of this composition is the hydrogen cloud consisting of H atoms from H_2O molecules that have been torn apart. The dimensions of the cloud are large, as illustrated in figure 5, plate 2. Monitoring of Comet Halley's hydrogen cloud has been carried out from *Suisei*, *Pioneer Venus Orbiter*, and from *Dynamics Explorer* 1, and the data are extensive. The record contains evidence for major changes in size and scale height. These variations have been described as 'breathing'. Observations from *Suisei* found brightness fluctuations with a period of 2.2 d. This value has been interpreted as the rotation period of the nucleus and, indeed, the value is consistent with the aspect of the nucleus as recorded by the *Vega*s and *Giotto*.

The water vapour from the nucleus has been unambiguously detected by infrared observations at 2.65 μm from the *Kuiper Airborne Observatory*, by Mumma and his associates. These observations are important for at least two reasons. (1) They provide a straightforward way to routinely detect gaseous water in comets and to determine the production rate. (2) They provide a measurement of the temperature of the comet's interior because the ratio *ortho*:*para* water – an observable – is temperature-dependent. Although the water is observed in vapour form, the ratio *ortho*:*para* reflects the temperature of the ice in the interior because the time scale for changing the spin states is very long. For Halley's Comet, the temperature is *ca.* 35 K. The origin of the temperature is unclear. It could be approximately the black-body equilibrium temperature around aphelion or it could have some other explanation. We need a larger base of data for more comets that the relative ease of these observations makes possible.

The second most abundant species in the atmosphere is carbon monoxide (CO). The abundance is in the range 10–15%, a fact established by Feldman and his associates from ultraviolet spectra obtained on rocket flights.

Clearly, there are minor constituents in the cometary composition. Carbon dioxide (CO_2) is present at the 3.5% level and HCN among others has been reported. Detailed results and models are required to proceed. The reason for this is simple. *In situ* composition measurements with mass spectrometers give densities at a particular mass unit. For example, at atomic mass 16, the measurements could refer to O, CH_4, NH_2, etc. The interpretation requires detailed models and synthetic spectra.

In addition, ions in the range up to 200 u have been reported. Here our imagination may be strongly stimulated. The possibility that the interiors of comets are the ultimate storehouse of unprocessed material from the formation of the Solar System has intrigued scientists for years. Included in this interest is the hope that molecules sufficiently complex to encourage evolutionary processes leading to life might be found. The high mass observations might have several causes: (1) metals, these would be relatively uninteresting in this context; (2) cluster

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ions, these would be of the form $I^+(H_2O)_n$ and should indicate conditions in the region of formation; (3) complex organics, these would be of interest for their evolutionary possibilities and again a detailed analysis is required to proceed.

The albedo of the nucleus (see next section) may support the existence of organic molecules in the nucleus, but they need not have high molecular masses. If the low albedo values *ca.* 0.02 are correct, they may not be explainable by a surface created by vacuum welding of chondritic powers, even though the albedos of the powders of some carbonaceous chondrites are quite dark. Lower albedos could be obtained by polymerization, a process well known to investigators working in the vacuum ultraviolet region. Many simple molecules polymerize easily, including formaldehyde (H_2CO) which is an important minor constituent in some models of the nucleus (e.g. those of Delsemme). Of course, other chemistries such as the ones studied by Greenberg could be responsible for the low albedo. A rough surface could also help to lower the albedo because 'reflection' would involve multiple scattering in a (say) porous surface structure.

The composition of the dust has been reported to resemble carbonaceous chondrites. This result was not unexpected, but the situation is actually somewhat complex. The dust particle compositions have been divided into three groups: (1) particles composed predominantly of H, C, N and O; (2) particles with a silicate composition and (3) particles with compositions that are a mixture of groups (1) and (2). Cosmic ray irradiation may play a role in the chemistry of these particles. Group (3) is the largest. Their compositions could be considered to be like carbonaceous chondrites enriched in light elements, and they would resemble the Brownlee particles collected in the earth's atmosphere. A possible clue to the dust particle composition and origin may be the measured distribution of masses. Contrary to expectations, there was no peak in the number density with decreasing mass. Rather, the number density with decreasing mass increased down to the measurement limit of 10^{-17} g.

Note, however, that there is no conflict between the low albedo of the surface of the nucleus and the high scattering efficiency of the dust after it leaves the surface. The diffraction part of the scattering coefficient does not depend on the composition.

NUCLEUS

The confirmation of the existence of a monolithic nucleus, even though assumed by almost all contemporary cometary scientists, is a major triumph of the missions to Halley's Comet. Images (figure 6, plate 4, and figure 7, plate 3) from the *Vega*s and *Giotto* clearly show an irregular, very dark central body with very bright jets largely confirmed to the sunward side. We can look forward to construction of a three-dimensional model of Halley's nucleus from all available aspect data. A schematic summary is shown in figure 8. Note that the surface temperature was measured to be *ca.* 330 K. This value is compatible with the equilibrium temperature of a slowly rotating blackbody at the distance of the *Vega 1* encounter (0.8 AU). The standard formula $T = 289\ \text{K}/r^{\frac{1}{2}}$, r in AU, gives $T = 325$ K.

Some of the false-colour contour displays used to present the initial imaging results were confusing and lead to some erroneous reports (e.g. that the nucleus was double). Although such displays can be useful and attractive in many applications (see figure 5), their use in displaying the first images of a very dark object of unknown shape and orientation can be misleading. The brightness contours draw attention to the jets, not the nucleus. Surprisingly, we make relatively minor use of brightness information in our mental processing of scenes. Rather, the

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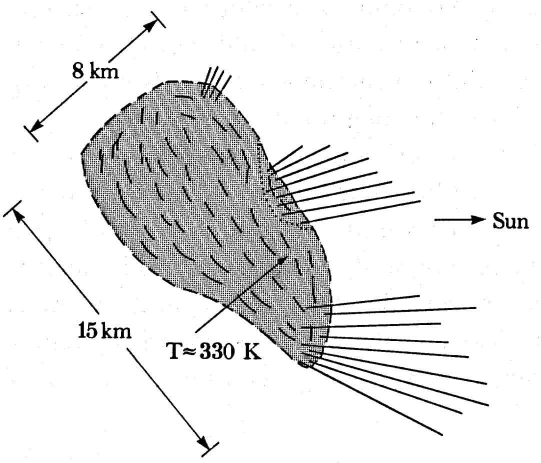

Figure 8. Schematic drawing of the nucleus with dimensions and some jets indicated. The dotted line records the fact that in some views the *Vega* interpretation has a narrower waist than the *Giotto* interpretation. Compare with figures 6 and 7.

brain makes maximum use of edges and their orientation to construct a visual image containing sizes, shapes, and spatial orientations. Grey-scale renditions present the data in readily processable form.

The dimensions of the nucleus are roughly 15 km × 8 km, and the shape has been compared to a peanut or potato. The smaller dimension of 8 km could be larger, say 10 km, because of uncertainties on the night side of the nucleus. The surface has been described as darker than coal or black velvet. The geometric albedo has been quoted in the range 0.02–0.05. These values make the nucleus of Halley's Comet one of the darkest objects in the Solar System. Even though some chondritic powders are very dark and the surface is probably porous, some other process such as polymerization may be needed. Clearly, a critical evaluation of the albedo determination needs to be undertaken before further progress can be made.

The low albedo and the high temperature for the surface lead immediately to the conclusion that most of the comet is covered by a dust crust. Such a crust is a feature of many previously published models of comets. The time scale for heat conduction inward must be much less than the rotation period (to explain the relative lack of nightside sublimation seen in the *Giotto* and *Vega* imagery). Initial estimates for the crust thickness are *ca.* 1 cm, but larger values are also possible. Some previously published models featured an extensive dust cloud that heated all sides of the nucleus by infrared radiation. The concentration of the gas and dust emission on the sunward side calls such models into question.

The overall picture of sublimation in Halley's Comet involves sunlight heating the dark surface to temperatures of *ca.* 330 K, conduction through the crust to the ices, sublimation beneath the surface, and escape of the gases and dust usually in jets covering *ca.* 10% of the surface. The collimation of the jets as seen in sunlight scattered by dust particles (the gas does not remain collimated) requires that the width be approximately equal to the depth.

The evolution of the pits as sublimation continues could easily produce the Brownlee-type particles as the crust at the pit edges breaks away. On a larger scale, it is easy to see how the irregular shape of the nucleus could have been produced. Indeed, after a little reflection, we realize that the spherical nucleus seen so often in our models cannot exist. Even if the shape

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is initially spherical, it cannot remain so. Evolution of the shape of the nucleus may offer possibilities for brightness enhancements and splitting. Dynamical instabilities could also be important. Note, however, that the rotation of Halley's nucleus is now stable, with rotation about an axis perpendicular to the long dimension.

The nature of the gas and dust emission, i.e. from a few jets comprising *ca.* 10% of the surface and active only on the sunward side of the nucleus, may lead to a mystery. The reaction force on the nucleus from the dust and gas emission has been known for years, and has been accurately determined. These so-called non-gravitational forces are important in orbit calculations and have been nearly constant for centuries, for example, in the work by Yeomans. Because of the discrete nature of the mass loss and the constant switching on and off of the jets as the nucleus rotates, the history of nearly constant non-gravitational forces is difficult to understand.

DISCUSSION

Because of their diverse physical processes, wide ranges in energy and dimensions, and important impacts on other fields of study, comets continue to excite many investigators' scientific curiosity. Some of these processes, dimensions and impacts are summarized in table 2; the lists are not intended to be complete.

TABLE 2. THE NATURE OF COMETS

	energy	
	T/K	T/eV
nucleus (interior)	35	3×10^{-3}
nucleus (surface)	330	3×10^{-2}
ions	6×10^{9}	5×10^{5}

processes	dimensions/km	impacts
condensation	nucleus, 10	cosmic chemistry
sublimation	coma, 10^5	origin of solar system
complex chemistry–gas phase reactions	plasma tail, interaction region 3×10^7	origin of life
fluid flows		meteoritics
solar-wind interaction		meteors
		plasma physics–solar wind

Many of our fundamental ideas for understanding comets date from the 1950s. These are: the Biermann–Alfvén view of the solar-wind interaction and the large-scale plasma structure; the icy-conglomerate model of the nucleus proposed by Whipple; and the storage of comets in the Oort cloud. Only the latter has not been directly and severely tested by the investigations in 1985 and 1986.

Despite the intrinsic interest in the study of comets, the general euphoria over the recent activities, and the anticipation of analysis and intercomparison over the next few years, there may be a tendency toward post-encounter melancholy. Currently, there is no approved comet mission anywhere on Earth, although a retargeted Halley spacecraft may encounter another comet or an asteroid. Yet this depression will probably not last long. The next good comet will

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cure us. As long as scientists and non-scientists are motivated to obtain images like the one shown in figure 9, plate 4, all is well.

Dr William Butler centuries ago said of strawberries:

> 'Doubtless God could have made a better berry, but doubtless God never did.'

Comet scientists now might summarize their feelings by paraphrasing Dr Butler:

> 'Doubtless God could have made a better celestial object, but doubtless God never did.'

I am indebted to Dr A. Delsemme, Dr M. B. Niedner, Professor D. Brownlee and Professor F. Whipple for conversations and clarifications during the preparation of this paper.

Further reading

Our understanding of comets is evolving from the picture presented here. The literature and recent reviews should be consulted. In particular, a controversy has developed over the true rotation period of the nucleus of Halley's Comet. Both a 2.2 d and a 7.4 d period are now (December 1986) being advocated. A comprehensive pre-1985–1986 view of the subject is contained in J. C. Brandt & R. D. Chapman 1981 *Introduction to Comets*. Cambridge University Press (1981). The first spacecraft results for Comet Giacobini–Zinner are in the 18 April 1986 issue of *Science* (vol. 232, pp. 353–385), and for Comet Halley in the 15 May 1986 issue of *Nature* (vol. 321, pp. 259–366). Also see E. Grün (ed.) Comets Halley and Giacobini–Zinner. *Adv. sp. Res.* **5** (1986).

The major presentation of results was in *Exploration of Halley's Comet* (20th ESLAB Symposium). A preliminary proceedings has been published by ESA as *Proc. 20th ESLAB Symposium on the Exploration of Halley's Comet* (in three volumes) ESA SP-250 (1986) and a final proceedings will be published in *Astron. Astrophys.* (scheduled for late summer 1987).

Discussion

E. Anders (*University of Chicago, The Enrico Fermi Institute, Chicago, U.S.A.*). Has anyone tried, by computer modelling, to reproduce the elongated shape of Halley's nucleus? I think this shape – with an axial ratio of 2 – is a potentially significant clue to the origin of Halley. Of the three possible mechanisms – cratering, coalescence and sublimation – the first seems unlikely, as comets probably always existed in places where impact rates, or at least impact velocities, were low. Coalescence, by low-velocity collisions, seems more likely, and has actually been proposed for the Trojan asteroid 624 Hektor, with an axial ratio of 3.4 (Dunlap & Gehrels 1969). Sublimation at locally higher rates can also do it, either by a self-accelerating process (such as the preferential evaporation from hollows mentioned by Whipple this symposium), or by some initial compositional heterogeneity (which itself would need to be explained).

Reference

Dunlap, J. L. & Gehrels, T. 1969 *Astron. J.* **74**, 796–803.

J. C. Brandt. I know of no detailed computer models attempting to reproduce the shape of Halley's nucleus, but I am sure that they will follow. The connection between the present

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nuclear shape and the comet's origin should be investigated, but convincing or unique results may be difficult to obtain. The nuclear mass now is estimated at roughly one-half the original mass. The shape now, which involves evolution from an unknown original shape, reflects structure and processes in material already lost.

J. A. M. McDonnell (*Unit for Space Sciences, University of Kent at Canterbury, U.K.*) Concerning the shape of Comet Halley's nucleus, and the suggestion that it might have been modified by impact processes, I would like to remind the meeting that by all current evidence Halley has certainly lost a mass equal to its present mass since injection, based even on a 20000 year existence near its present orbit. Therefore its present shape – be it a potato or a peanut – does have to be ascribed to the ablation by solar radiation perhaps reflecting inhomogeneity of internal structure. At each perihelion passage it loses an average of some 0.5–1 m over the whole surface – perhaps 5 m in active regions – and therefore impact erosion, which corresponds to a rate of 10^{-6} mm a^{-1} at 1 AU as derived from lunar data, is a negligible force in determining its morphology now.

M. K. Wallis (*Department of Applied Mathematics and Astronomy, University College, Cardiff, U.K.*). From Dr Brandt's conception of the jet-emitting regions, I estimate roughly five craters of 1 km radius and depth. At an erosion rate of 10 m per orbit, such craters must be pretty stable. Yet he conceives the surface between them as consisting of 1 cm deep crust over ice, which is rather unstable under sublimation (Shul'man 1972). Are these two scales for evolution of the nucleus surface not contradictory?

Reference

Shul'man 1972 In *Motion, evolution of orbits and origins of comets* (IAU Symp. no. 45), p. 271.

J. C. Brandt. We are all in the position of attempting to synthesize vast quantities of new data into a coherent picture. The roughly 1 cm crust thickness refers to the active (gas and dust-emitting) regions; the crust between the active regions is expected to be thicker. This clarification may resolve the contradiction in time scales.

J. A. M. McDonnell (*Unit for Space Science, University of Kent at Canterbury, U.K.*). How can the 2.2 μm observation of the two water states be inferred as indicative of the interior temperature of Halley, when the major cross section of Comet Halley resides in the surrounding dust coma?

J. C. Brandt. The water observations at 2.65 μm refer to vapour that has already sublimated and left the nucleus. Because alteration of the spin state of the water molecules takes a very long time, the water vapour retains the signature of the interior temperature through the *ortho*:*para* ratio.

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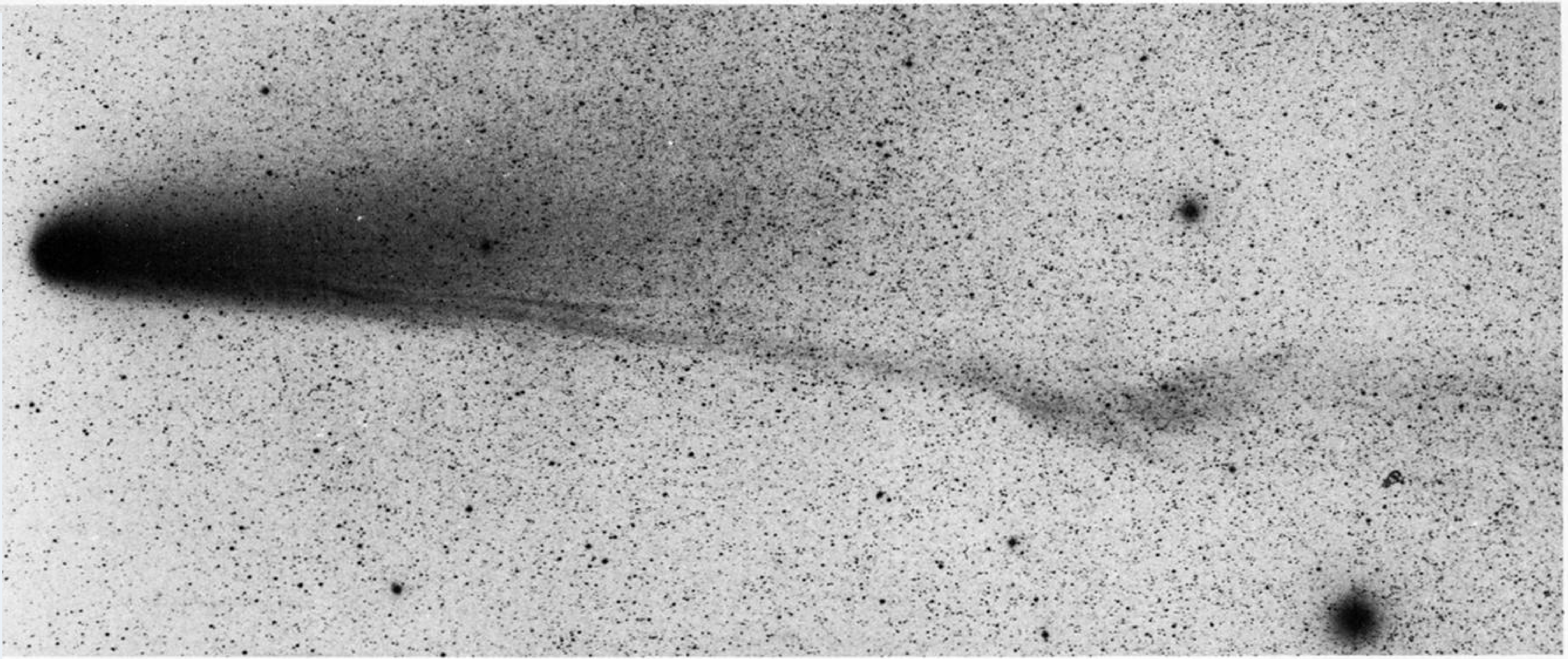

FIGURE 1. Comet Halley as photographed on 22 March 1986 showing the dust tail (above) and the plasma tail (below) with a bend caused by a disturbance in the solar wind. The tail stretches approximately 8° across the sky, or some 20×10^6 km. (Photograph taken by E. P. Moore at the Joint Observatory for Cometary Research, operated by the Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center and the New Mexico Institute of Mining and Technology.)

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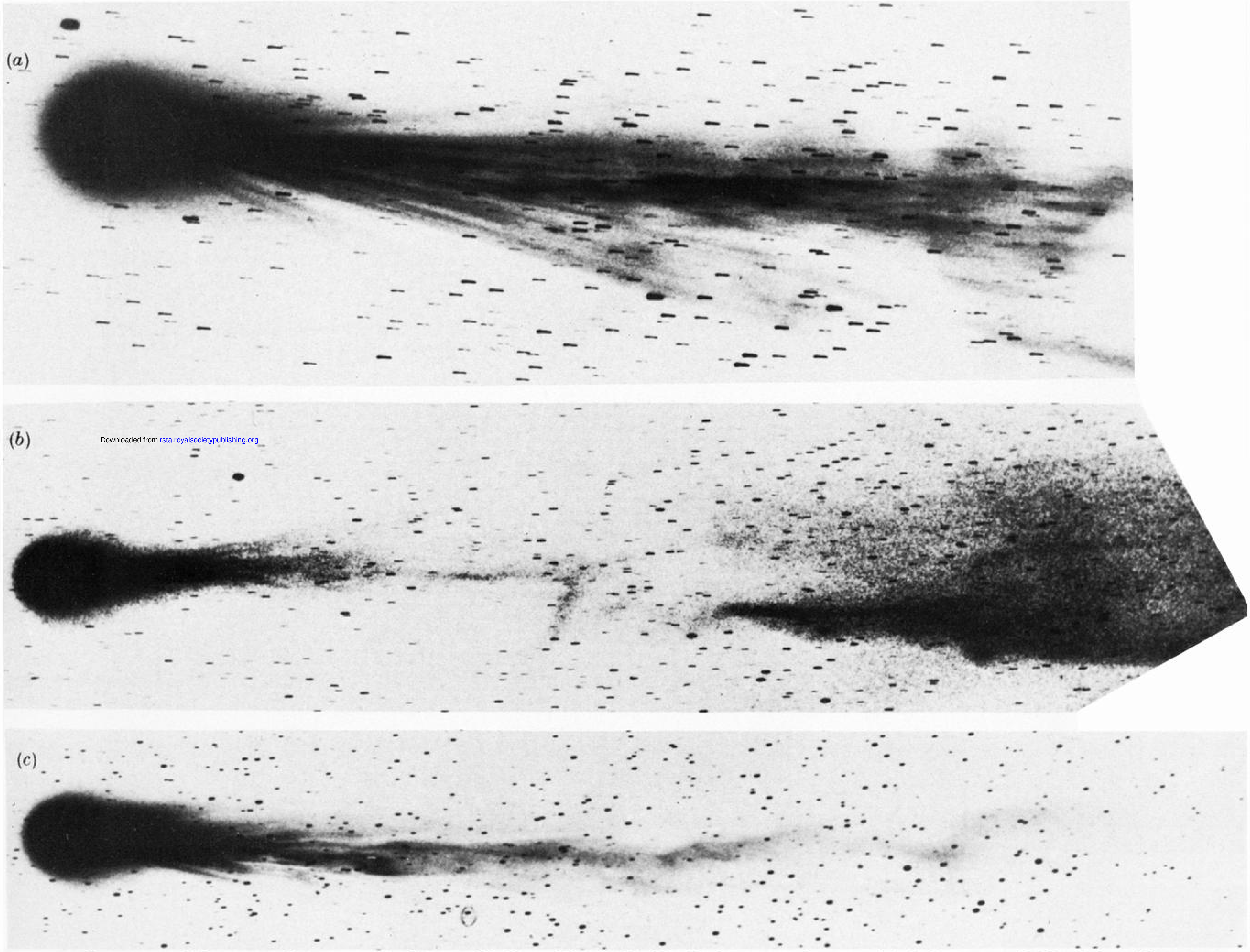

FIGURE 4. Disconnection event in Comet Halley. The individual photographs are: (*a*) 9 January 1986, Calar Alto Observatory, Spain (Max-Planck-Institut für Astronomie, Heidelberg); (*b*) 10 January 1986, Calar Alto Observatory, Spain (Max-Planck-Institut für Astronomie, Heidelberg and (*c*) 11 January 1986, Haute-Provence Observatory (C.N.R.S. – University of Liège). The disconnected tail is clearly shown on 10 January (*b*) along with the usual tail the day before and the day after. Full tail length shown is approximately 15×10^6 km.

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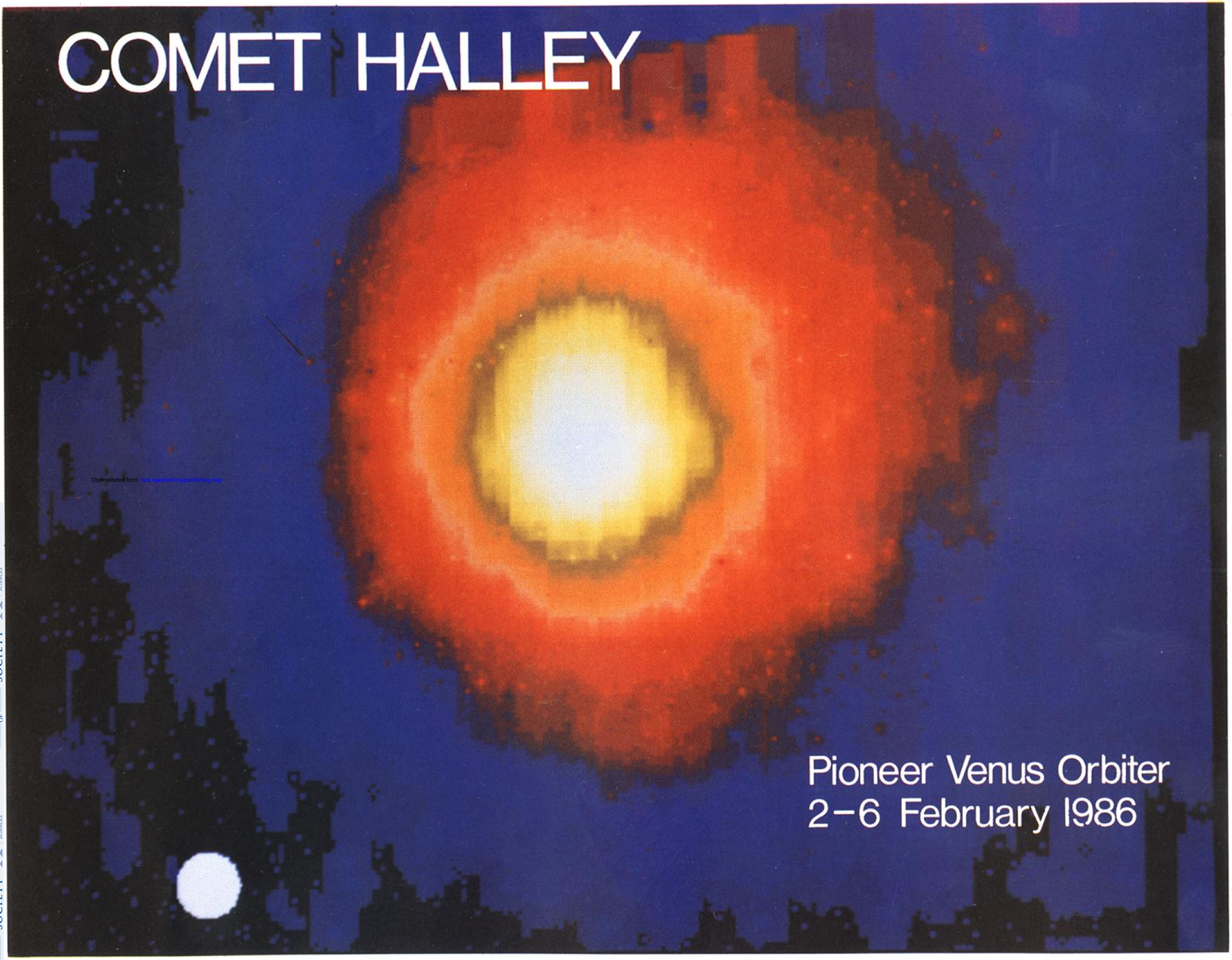

IGURE 5. The hydrogen cloud of Comet Halley in early February 1986 as observed from the *Pioneer Venus Orbiter*. The false-colour image is based on brightness contours in hydrogen Ly-α at 1216 Å (121.6 nm). The image covers an area 20×10^6 km by 23×10^6 km, and the white disc in the lower left corner is the size of the Sun. (I. A. F. Stewart, University of Colorado.)

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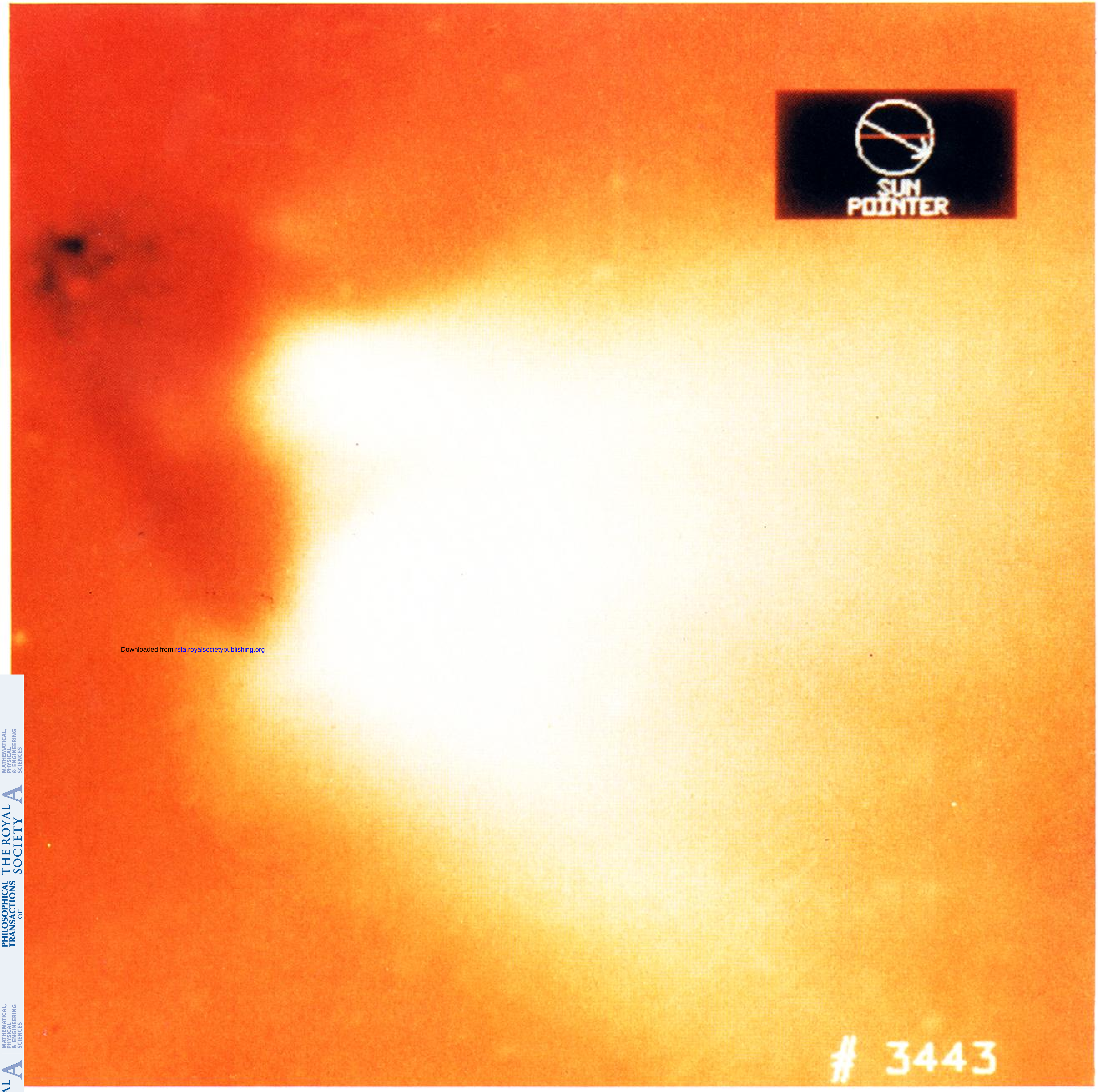

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FIGURE 7. Pseudocolour or false-colour (but not contour) image of the nucleus of Halley's Comet obtained by *Giotto* at a distance of 18270 km. The frame is 30 km by 30 km. The nucleus is the dark object at upper left seen in silhouette against the bright background. The bright jets point toward the Sun (as indicated by the sun pointer). The bright feature in the centre of the nucleus could be due to an elevated feature on the night side of the terminator that is illuminated by sunlight. On images taken closer to the nucleus, a crater-like circular feature is clearly seen. Compare with figures 6 and 8. (Halley Multicolor Camera, Giotto Project, Max-Planck Institut für Aeronomie.)

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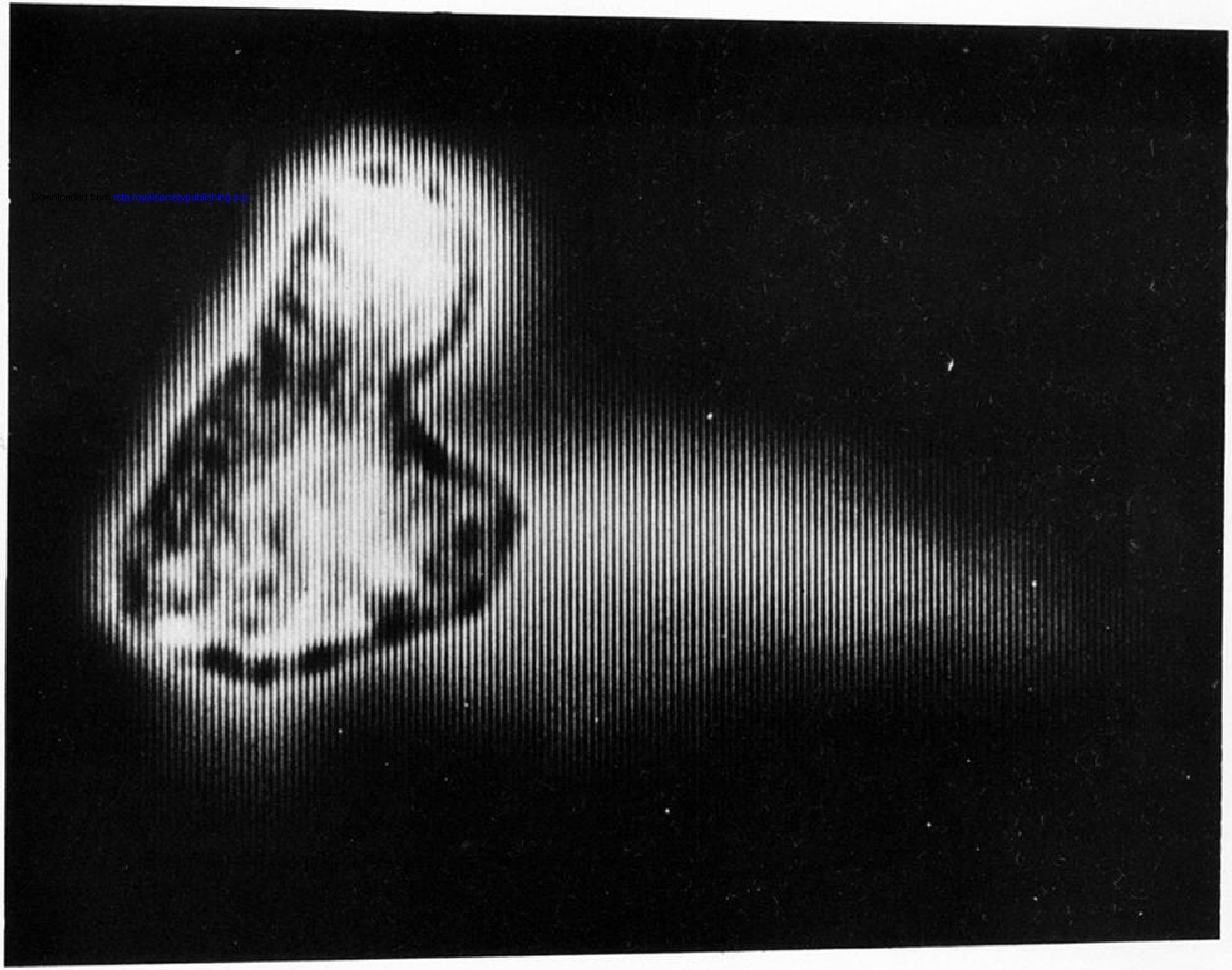

IGURE 6. Enhanced, grey-scale image of the nucleus of Halley's Comet obtained by *Vega 2* at a distance of 8030 km showing the solid body and a prominent jet. Compare with figures 7 and 8. Note that the jet shown is sunward as are nearly all the near-nuclear structures (figures 6 and 7). The appearance contrasts with views of the entire comet (figures 1, 4 and 9) where the structures (e.g. the tail) are antisunward. (*Vega* Project.)

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FIGURE 9. Halley's Comet on 16 March 1986 from a site near Washington, D.C. Approximately 5° of tail is shown. This bittersweet photograph was obtained by E. Grayzeck with the flight spare Wide Field Camera for the *Astro 1* Mission (which was scheduled for launch on 6 March 1986). The dark spot at the centre is a blemish on the photocathode of the image intensifier.

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