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Earth-Based Observations of Comet Halley Dust and Gas [and Discussion]

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Earth-based observations of Comet Halley dust and gas

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[Plate 1]

Very extensive ground-based observations of P/Halley have now been made, both to provide a standard cometary archive and to help interpret data from the Halley space probes. A number of new results are reported here, of which the most important is probably the major role played by sporadic activity of the nucleus in the development of the comet.

Introduction

From the viewpoint of the ground-based observer, P/Halley has the virtue that it is a bright comet with a very accurately determined orbit. An observational programme can therefore be planned well beforehand, and can include a more detailed examination of cometary properties than is possible with fainter periodic comets.

P/Halley was first observed at this apparition on 16 October 1982 (which led to its current designation as 1982i), when it was still some 11 AU from the Sun (Jewitt *et al.* 1982). Observations over the following months were consistent with the assumption that sunlight was being reflected from an irregularly shaped, slowly rotating body a few kilometres across.

This estimate of size depended on the value assigned to the albedo, which was highly uncertain. Figures of 0.1–0.2 have often been used for comets, but it has been clear that both higher and lower albedos might be possible. A higher figure would be reasonable if the nucleus had a clean surface made of ice, perhaps reaching the 0.6 achieved by the jovian satellites. However, if loss of volatiles has led to the formation of a 'crust' on the nucleus, the albedo could be very low: less than 0.05 to judge from the values for the darkest asteroids. Interestingly, the observations of the satellites of Uranus by the *Voyager* fly-by mission in January 1986 indicated another reason for expecting a low albedo for cometary nuclei. The lower albedo of these satellites as compared with those of Jupiter and Saturn has been attributed tentatively to the presence in their icy surface of volatiles containing carbon. The influence of solar ultraviolet radiation can convert these volatiles into polymers of low albedo. Such volatiles (e.g. methane) are certainly present in comets.

The problem was that some ground-based observations of P/Halley were taken to imply a higher (0.2–0.3), rather than a lower albedo for its nucleus. Infrared measurements of the nucleus could, in principle, have resolved the uncertainty, but the infrared instruments were too insensitive to detect the comet until it had already become active.

Comets tend to brighten from 6 AU inwards as the solar heat input becomes large enough for water ice to sublime. The first near-infrared measurement was made when P/Halley was at 5.4 AU from the Sun, at which time a small dust coma already appeared to be present (Birkett *et al.* 1985). Measurements in the thermal infrared, initially by the University of Kent and UKIRT staff, came later, when a dust coma was certainly observed. Consequently, direct estimates of the nuclear albedo had to await the *Giotto* fly-by.

Observations of dust

Observations of P/Halley have clearly shown that the emission of dust from its nucleus tends to be sporadic and localized, rather than continuous and from the whole surface. The dust often appears to be thrown out in relatively short-lived jets from restricted regions of the nucleus. The forces leading to this emission presumably arise from the rapid sublimation of volatiles, so that the dust is carried along with the outflowing gas. Whereas the gas expands in all directions, the dust tends to continue along its original direction, so forming a definable envelope which, under favourable circumstances, can be observed from the ground. Recent image-enhancement of photographs of P/Halley taken in 1910 has shown that the tracing of such jets is feasible (Larson & Sekanina 1985). The appearance of the envelope produced by a jet depends on the rotational period of the nucleus and the position of the observer relative to the rotational axis. Hence, it is possible, in principle, to deconvolve the observations to provide information on these. The ground-based data from 1910 have suggested a rotational period of 52 h and an obliquity of some 30°. Large numbers of images providing information on dust have been obtained at this apparition. Schmidt plates (exposures of a few seconds) of P/Halley taken for astrometric purposes can apparently provide unexpectedly useful information on jets (see figure 1). Hence, data on this type of activity are currently increasing rapidly.

Jet formation may be limited to specific areas covering less than 10% of the nuclear surface. There is even a suspicion from a preliminary comparison of 1910 data with some from the present apparition that the surface localities concerned may be similar in both. Activity from

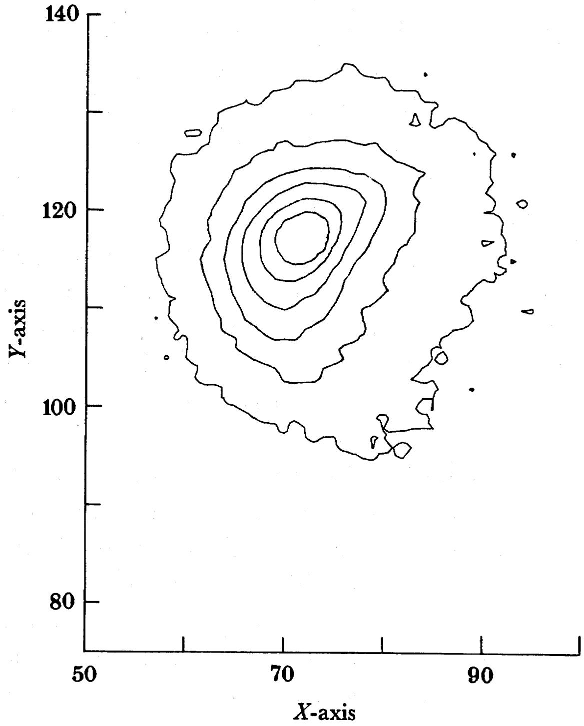


Figure 1. Intensity contours of P/Halley obtained from a U.K. Schmidt plate taken for astrometric purposes. The exposure of a few seconds was expected to produce a point image, but the actual image is extended and slightly asymmetrical.

these spots seems to switch on and off at intervals. It might be expected that near-nuclear variations would show some sign of the period of rotation of 52 h. At this apparition, the first signs of activity occurred in 1984 as the comet came within 7 AU from the Sun. Variations in brightness by a factor of up to six were observed over periods of a day or so. These were mainly random in time, but a more detailed analysis has suggested that an underlying two-day period may be present (Morbey 1985). In January 1986, jets were particularly frequent, and were found to have an approximately two-day cycle of activity (Larson 1986).

The dust ejected from the nucleus is acted on by solar radiation, so leading to the formation of an extended dust trail. The first attempt to discuss this theoretically was actually made by Bessel on the basis of observations of P/Halley at its 1835 apparition. Basically, a dust particle takes up an orbit round the Sun that depends on the balance between the solar gravitational attraction (F_G) and the solar radiation pressure (F_R). For a spherical dust particle of radius, a, and density, ρ, at a heliocentric distance, r, we have

$$F_G = (GM_{\odot}/r^2)\,\tfrac{4}{3}\pi a^3 \rho; \quad F_R = (\phi/c)\,[L_{\odot}/4\pi r^2]\,\pi a^2,$$

where $M_{\odot}$ is the mass of the Sun; $L_{\odot}$ is the solar luminosity; c is the velocity of light; ϕ is the radiation pressure efficiency (i.e. the ratio of the radiation pressure cross section to the geometrical cross section of the particle). Both F_G and F_R are radial and vary as r^{-2}, but act in opposite directions. Hence, the dust particle follows a keplerian orbit under a reduced effective gravitational force, $(1-\beta)F_G$, where β (the acceleration ratio) is given by

$$\beta = F_R/F_G = \text{const.} \times (\phi/\rho a).$$

It is convenient to use this parameter β in considering the formation of a dust tail. Suppose a cometary nucleus continuously releases dust particles with a given value of β. The particles are repelled successively by radiation pressure, and so become strung out along a locus called a syndyne. In reality, cometary dust particles will have a distribution of sizes and may have more than one density. Consequently, particles will have different values of β, and will move along different syndynes. Under these circumstances, it may be more convenient to consider the trajectories followed by dust particles with different β values, all released at the same time. The locus of the corresponding envelope is called a synchrone. Calculation of typical synchrones shows that, for large particles (greater than 0.01 cm), the motion is so slow they can remain in the vicinity of the cometary nucleus for several hundred days. If the particles are released with non-zero velocities, both syndynes and synchrones will be spatially blurred. When cometary dust is produced continuously and isotropically, the resultant dust tail is therefore spread out into a broad fan. We have seen, however, that this has not been the typical form of dust production in P/Halley: one result of its sporadic activity has been the production of a number of distinct dust tails visible simultaneously. It should be added that P/Halley was better placed for observing its dust tails after perihelion, at which time a distinct antitail was noted.

Ground-based infrared observations of P/Halley dust have allowed short-term changes in its amount to be monitored quantitatively and for the changing temperature of the dust to be measured. Dust production after perihelion was up by a factor of 2–4 as compared with amounts before perihelion: this was presumably connected with the increased jet activity seen. There were indications that the dust size distribution also changed with time. One interesting point emerged from radio observations of high spatial resolution of OH emission made in November

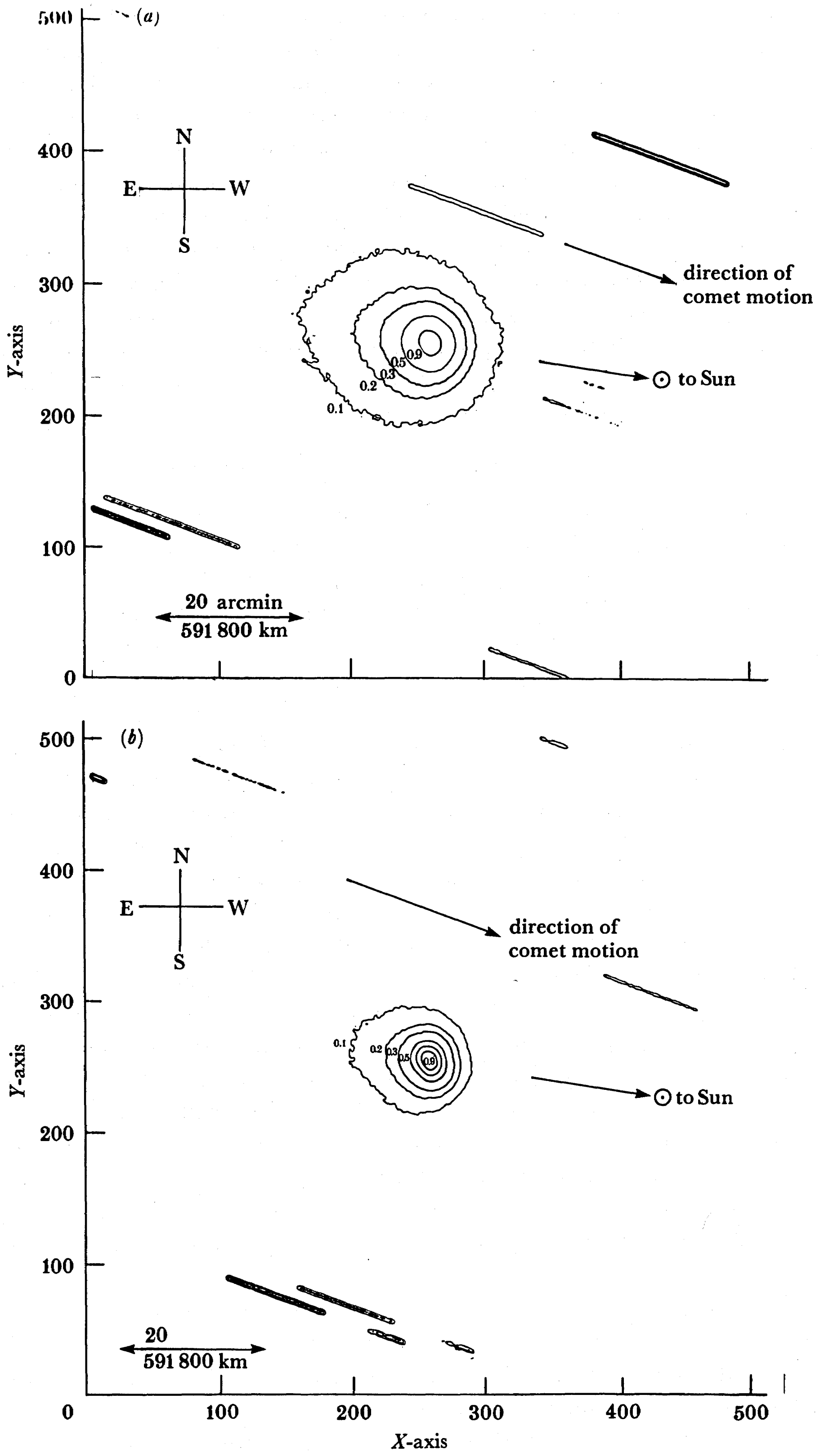


FIGURE 2*a*, *b*. For description see opposite.

1985. These indicated that OH, instead of decreasing smoothly in amount away from the nucleus, appeared to be concentrated into clumps. A possible explanation (though not the only one) is that large fragments of ice broke off from the nucleus and began to sublime as they separated. An infrared absorption feature due to water ice was observed in November (Bregman *et al.* 1985). Emission features corresponding to the C–H bond and to silicates have also been identified.

It is of interest to compare the parallel changes in the gas and dust content of the coma. The decrease in observed flux as a function of distance from the centre of the coma can be compared for C_2 emission and the continuum (corresponding to reflected light from dust) for two successive months, November and December 1985. The observations clearly indicate that flux from the dust is similar in both months. This flux falls off linearly with distance, implying that the mass of dust present is conserved as the emitted particles expand outwards. The C_2 fluxes do not fall off linearly with distance, and there is some difference between the two months. (Comparison of gas and dust emission is shown in figure 2*a*, *b*.)

OBSERVATIONS OF GAS

Interpretation of observations of gaseous emission from comets is more difficult than interpretation of dust observations, because photoionization and photodissociation leads to a complex mix of interrelated atomic and molecular species. Collisions in the innermost part of the coma can lead to chemical reactions, the products of which can then be acted on by solar ultraviolet radiation. Ground-based observations relate to the end-products of these interactions seen in the outer coma.

The simplest model for interpreting the gas emission is due to Haser (1957). It assumes that, in the first place, molecules evaporating from a cometary nucleus lead to a coma density given by

$$n(r) = (\phi/4\pi r^2)\exp(-r/v\tau),$$

where $n(r)$ is the number density at a distance, r, from the nucleus; ϕ is the production rate; v is the outflow velocity; τ is the mean lifetime of the molecule. The distance to which the molecule can be traced (its scalelength, γ) is equal to $v\tau$.

For daughter molecules produced from this parent, the corresponding density distribution is given by

$$n_d(r) = \frac{\phi_p \gamma_d}{4\pi v_d r^2(\gamma_p - \gamma_d)}\left[\exp-\left(\frac{r}{\gamma_p}\right) - \exp\left(\frac{-r}{\gamma_d}\right)\right],$$

where p represents parent and d represents daughter. This simple model often gives a fair approximation to the observed distribution, but needs to be replaced by more complex models when detailed studies are undertaken. However, quick-look observations of P/Halley data have typically been expressed in terms of the Haser model.

FIGURE 2. (*a*) This U.K. Schmidt narrow-band image (O I, 40 min exposure) contains gaseous emission from [O I] and NH_2 along with reflected sunlight from dust. The contours represent various light intensity levels. (*b*) This image (IF, 40 min exposure) taken on the same night (5 December 1985), consists almost entirely of reflected sunlight from dust. A comparison of parts (*a*) and (*b*) indicates both the dominance of the gaseous emission and its less rapid fall off with distance from the nucleus. The contours represent various light-intensity levels.

The development of P/Halley spectra has followed the general lines that were predictable from other cometary spectra, but a number of new, or more detailed, results have also been obtained. No significant emission was observed until February 1985, when weak CN bands were detected (Wyckoff *et al.* 1985). By September 1985, the spectrum showed strong emission from CN, C_2 and C_3. OH had by then already been detected by radio astronomy measurements (Brockelée-Morvan *et al.* 1985) and in the ultraviolet region. A month later, OH was also detected in the visible spectrum. By this time, most of the usual cometary emission features were appearing; along with carbon features (now including CH) were NH, NH_2, H_2O^+ and O I. HCN was detected subsequently (Despois *et al.* 1985), and was found to vary in intensity over periods of a day or so. HCN observations have proved particularly important because this molecule has been considered the likely parent of the common cometary radical CN. Combined observations in the visible and radio regions now show that this cannot be true for P/Halley at least. Direct measurements of the H_2O molecule for the first time (Mumma *et al.* 1985), together with OH, O and H measurements, confirm the importance of H_2O as a constituent of the nucleus of P/Halley. It has been found in previous comets where observations have been possible that radio detection of OH indicates different amounts of the radical present as compared with other methods. This has also been found for P/Halley, but the very detailed observations available offer an excellent chance of resolving the discrepancy.

Significant day-to-day variations in the intensity of OH and H have been observed, along with less obvious fluctuations in other species (CN, C_2 and C_3). These variations suggest that the rotation of the nucleus plays a larger role in the development of the gas coma than had been supposed. A surprising discovery was that the extended hydrogen coma undergoes variations with a similar period. Observations of the hydrogen coma from Ly-α images obtained by the Japanese spacecraft, *Suisei*, during November and December 1985 indicated considerable activity with a period of 2.2 d. NaI emission was detected in January 1986, when it was also found to be strongly variable (Barbieri *et al.* 1986). However, unlike the other emission features, it was found to be asymmetrically distributed relative to the nucleus.

DESCRIPTION OF PLATE 1

FIGURE 3. This print of Comet Halley, showing clearly for the first time the formation of the tail, is a constrast-enhanced photograph. It was made from plate number B10578 exposed for 25 min on the night of 9 December 1985 with the U.K. 1.2 m Schmidt Telescope at Siding Spring Observatory in Australia.

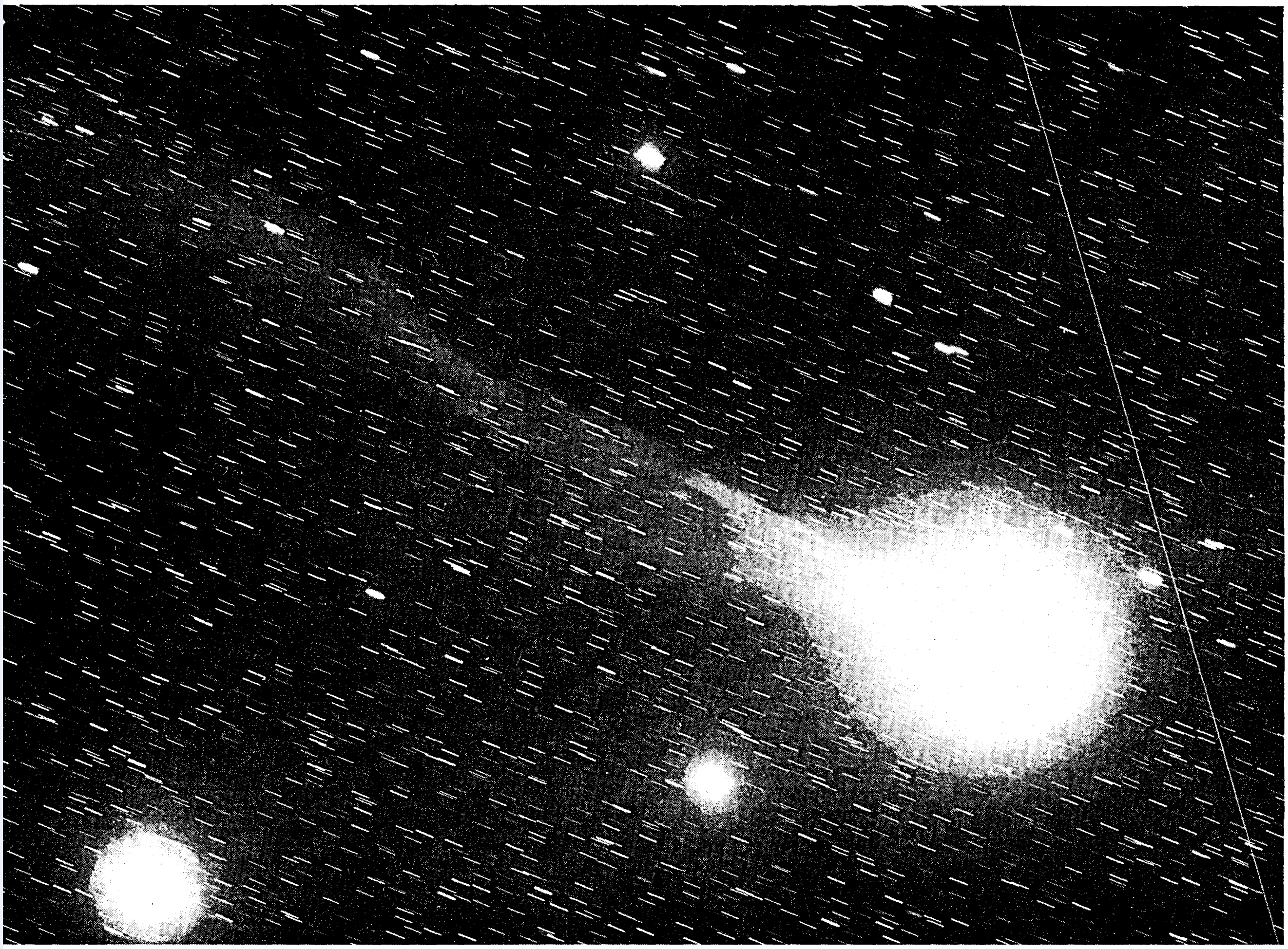
The telescope tracked the comet, which was moving relatively fast against the star background in the constellation of Pisces, resulting in the stars being trailed.

Photography by D. F. Malin from an original plate by the U.K. 1.2 m Schmidt Telescope. Reproduced with permission from the Royal Observatory, Edinburgh.

FIGURE 4. Comet Halley on 10 March 1986. This high-contrast composite positive photograph of Comet Halley is made from two exposures of ten minutes in blue light with the U.K. 1.2 m Schmidt Telescope. In this photograph the comet extends for some ten degrees across the sky covering two original photographic plates. The lower, filamentary ion tails show a disconnection about four degrees from the comet's head where material was blown away from the comet's head by the solar wind. The movement of this disconnection can be seen in comparison with a photograph taken the previous night. The smoother dust tails can be seen curving away from the comet to the north of the photograph.

This photograph complements the images obtained from various spacecraft which made their closest approaches to the comet between 6 March and 19 March.

Original plates J10830 and J10831T taken with the U.K. Schmidt Telescope in Australia. Photography by B. W. Hadley, Royal Observatory, Edinburgh. Reproduced with permission from the Royal Observatory, Edinburgh.



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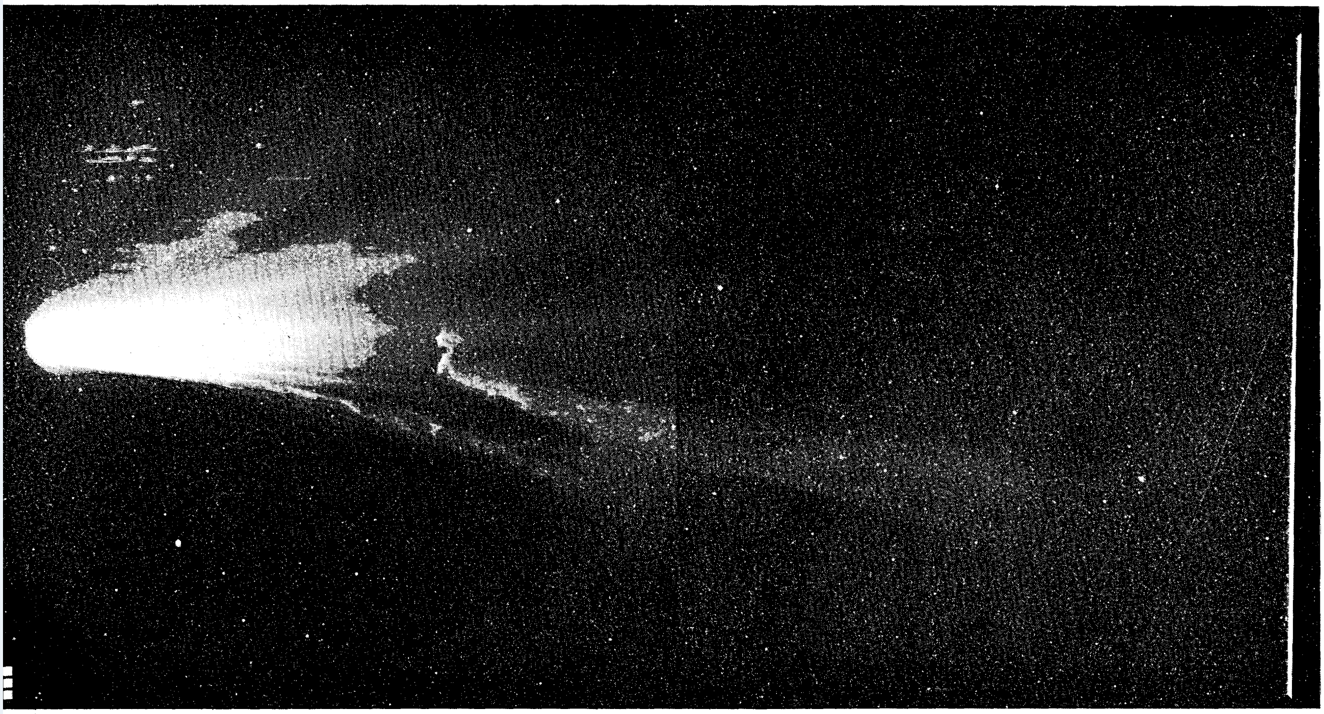

FIGURE 4. For description see opposite.

Towards the end of 1985, an extended plasma tail began to develop, and the characteristic tail emissions of N_2^+ and CO^+ were soon detected. The tail was reported to be up to 43° long in April 1986. By November 1985, the full range of plasma-tail activities were being observed. These included rays forming and changing in times of less than a day, knots moving down the tail with velocities of up to 50 km s^{-1}, and appreciable brightness changes of the whole tail from night to night. Tail oscillations with a period of 1–2 d were suspected. These might be related to the rotation of the nucleus, but could also be characteristic plasma wave velocities (Jones & Meadows 1969). The most spectacular events observed were tail discontinuities. These occurred in January and March 1986, both coinciding with reversals of the interplanetary magnetic field.

Conclusions

A major reason for the very extensive ground-based observations of P/Halley at this apparition has been to provide a standard, in whose terms observations of other comets can be interpreted, or reinterpreted. From that viewpoint, the much more detailed information now available on features commonly observed in comets will be invaluable. Inevitably, however, attention has tended to concentrate on results that are new. Here, the observations of dust development in P/Halley, and especially the frequency of jets, are notable. The most important observation concerning the gas component is probably the confirmation of the importance of H_2O. Overall, the most striking result has been the realization of the extent to which activity in P/Halley is dominated by emission from a few restricted regions of a slowly rotating nucleus.

I am grateful to members of the U.K. Schmidt Telescope Unit of the Royal Observatory Edinburgh for access to their photographic data, to Dr S. F. Green, University of Kent, for provision of infrared data and to Dr I. P. Williams for information on photometric observations. I am also grateful to Miss C. M. Birkett and Mr A. Fitzsimmons for their assistance in preparing this paper.

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Discussion

J. D. Shanklin (*British Antarctic Survey, Cambridge, U.K.*). The visual light curve (of Comet Halley) shows an approximate 2 mag brightening between 2.0 and 1.7 AU preperihelion and a corresponding fading postperihelion. Are there any comments?

A. J. **Meadows**. No; the low value of the nuclear visual albedo should imply that most of the rapid increase in brightness would occur further out.

M. K. **Wallis** (*Department of Applied Mathematics, University College, Cardiff, U.K.*). Because the emitting area at the base of the jets is rather limited, estimates that may not be conclusive give too little input of solar radiative energy into the source area to sublimate H_2O ice. Does Professor Meadows have ideas on alternative energy sources, or does he conceive that the nucleus has a substantial admixture of material other than H_2O with a much lower latent heat?

A. J. **Meadows**. Substances more volatile than H_2O may be partly contained in clathrates and partly free. The former may trap the latter below the surface of the jet-emitting area until the nucleus has approached quite closely to the Sun. Evaporation of the overlying clathrate might then lead to explosive production of the volatile. Perhaps rather less plausible is the old idea of 'unstable' molecules; unstable in the sense that they undergo strong exothermic reactions unless kept at a low temperature.

M. E. **Bailey** (*Department of Astronomy, The University, Manchester, U.K.*). Could Professor Meadows comment on the implication of the very early observed onset for sublimation (*ca.* 6 AU), together with the apparently strong domination of water ice in the nucleus, as inferred from ground-based and satellite observations? In particular, is there yet any information as to what the more volatile component is or was?

A. J. **Meadows**. The distance from the Sun at which gas first appears in appreciable quantities depends on a number of factors. For example, it can vary with nuclear albedo, and this may be important for P/Halley. Substances more volatile than water may be present in the nucleus incorporated into a clathrate structure, in which case they will tend to come off at the same distance from the Sun as water does. However, some volatiles may have condensed separately, so they can evaporate first. There are several molecules from which to choose, but because CO_2/CO seems commonest next to H_2O, this may be the most likely substance.

G. **Fielder** (*Department of Environmental Sciences, University of Lancaster, U.K.*). Professor Meadows discussed the 3.4 μm CH feature in the spectrum of Halley. Does he, or anyone else, have a laboratory material that reproduces the features?

A. J. **Meadows**. Considerable work has been done on this. Perhaps Dr Wickramasinghe would like to comment on this.

D. T. **Wickramasinghe** (*Department of Mathematics, Faculty of Science, Australian National University*). It is now well established that there is an interstellar feature near 3.4 μm due to CH stretching vibrations in organic material within interstellar dust. The characteristics of this feature are somewhat variable from one source to another depending on the astronomical environment in which the dust is found. The feature corresponding to dust in the diffuse interstellar medium is most clearly seen in observations of the Galactic-centre source IRS7 and has a central wavelength of 3.4 μm. Observations of some molecular cloud sources have shown another feature centred at 3.53 μm that is also likely to be due to organic material in the dust. The possibility that cometary dust may have properties similar to dust in the interstellar medium has been widely discussed in the literature.

On 30 and 31 March, and 1 April 1986 we obtained spectroscopic observations of Comet Halley in the wavelength region 2–4 μm with a view to search for evidence of organic material in cometary dust. The observations were carried out with the 3.8 m Anglo Australian telescope with a circular variable filter that gave a wavelength resolution $\Delta\lambda/\lambda \sim \frac{1}{100}$. Figure 1 shows the results that were obtained with a 5 in × 10 in† rectangular aperture on 31 March 1986 when the comet was at a heliocentric distance of 1.17 AU. A more detailed account of the observations will be presented elsewhere. The short wavelength region (2–3 μm) is dominated by scattered solar radiation and is essentially featureless at our resolution. Longward of 3 μm we see a sharply rising dust emission continuum on which is superimposed an emission feature peaking at 3.4 μm. The detection of this feature points to the presence of dust in the inner halo of Comet Halley that is predominantly organic in character. We note that our data do not show any evidence of a water-ice absorption feature that is expected to have a central wavelength of 3.07 μm. The band characteristics of the 3.4 μm emission feature are generally similar to those observed for the diffuse interstellar absorption feature in IRS7, but there are some differences. As in the interstellar case an identification of the 3.4 μm feature with simple organics can be excluded. Possible candidates are the non-volatile residues produced in Urey–Miller type experiments and biochemicals and organics of biological origin. It has been shown previously that the bacterial grain model of Hoyle & Wickramasinghe provides an excellent fit to the IRS7 data and it is accordingly of considerable interest to investigate whether a similar model might also fit the present data.

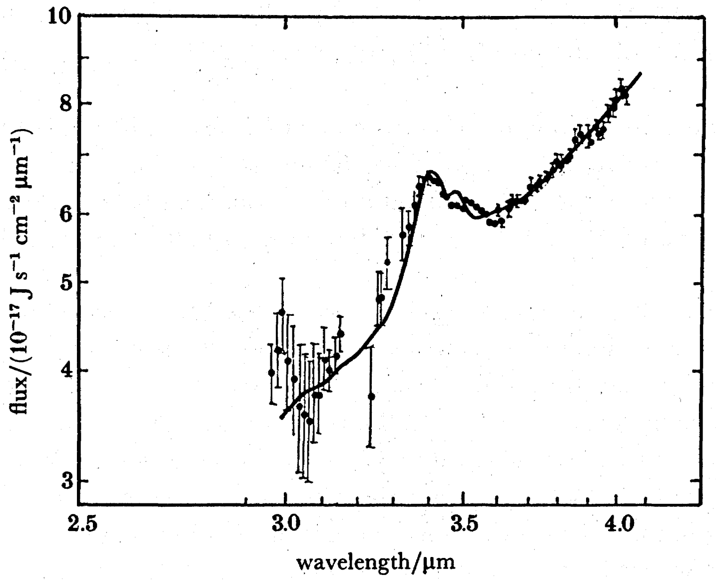

FIGURE D1. The infrared spectrum of Comet Halley on 31 March 1986. The solid curve is a fit of the cometary data with a bacterial grain model at 320 K.

The solid curve in the figure is the calculated flux representing the sum of the scattered

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† 1 in = 2.54 cm.

sunlight component and an optically thin dust emission component, which has been computed assuming a dust temperature of 320 K. The theoretical curve has been normalized to agree with the observational flux at $\lambda = 4$ μm. The observed strength and shape of the central 3.4 μm feature are in good agreement with the bacterial grain model, the two sets of data deviating from one another by no more than 5% at any wavelength. The largest significant deviation occurs near 3.5 μm. The astronomical observations show the presence of a broad secondary-emission peak extending from 3.46–3.55 μm whereas the bacterial grain model shows a sharper peak at 3.48 μm. This may indicate that there is a second independent component that contributes to this feature or that the cometary grain component is subtly different from that in the line of sight to IRS7. We note that an absorption component at 3.53 μm due to interstellar dust has been seen in ρ Oph 29 and HH100 and that a similar feature is seen in emission in HD 97048.

It may also be significant to note that spectrum of *Escherichia coli* irradiated to 1.5 Mrad† at 77 K shows a sharp absorption spike at $\lambda \sim 3.53$ μm rather than an absorption peak at 3.48 μm. A comparison of the predicted flux curve for irradiated bacteria (as would occur in a solar flare) and the observational data for Halley's comet will be published elsewhere.

H. W. Kroto (*School of Chemistry and Molecular Sciences, University of Sussex, Brighton, U.K.*). The previous discussants have juxtaposed infrared data from Halley's Comet with their own laboratory infrared data from bacteria.

As almost all organic molecules (more than 3 million known) show similar features, it is not in fact difficult to find a pure compound with a C–H stretch band that fits this resonant feature as well as do bacteria. One such compound is farnesol. If mixtures are included then the number is essentially infinite. In making the comparison it is important to separate the C–H stretch resonance of *Escherichia coli* from the extraneous, almost featureless, broad background, which comes to a peak near 3.0 μm (1). The main contributor to the background component is likely to be an opacity due to solid-particle scattering which is independent of chemical composition and perhaps also a very broad OH absorption. The separation can be achieved reasonably satisfactorily by passing a smooth curve through the *E. coli* spectrum in the regions below 3.3 μm and above 3.6 μm and interpolating over the intermediate region. The C–H stretch feature of farnesol has, according to the literature, an overall contour very closely matching that of *E. coli* and a listed wavelength maximum at 3.42 μm, together with subsidiary shoulders listed at 3.37 and 3.49 μm; wavelengths that are to be compared with the analogous features of *E. coli*. If the farnesol absorption is scaled according to Hoyle and Wickramasinghe's recipe and added to the background component of *E. coli*, the resulting curve is seen to have the same characteristic shape as *E. coli* and where the curve departs to any significant extent (between 3.30 and 3.42 μm), it matches the astrophysical data significantly better than does *E. coli*. It is to be noted that Hoyle and Wickramasinghe rest their case on the fact that the particular shape shown is unique to living matter. Unfortunately it is not, as myriads of simple compounds and an infinite number of mixtures possesses similar features.

However, the main point of this contribution is rather different and very simple. Because of the large errors that attend the measurements, even if bacteria were responsible for the observed IR flux, a perfect fit to the points cannot be expected on simple statistical grounds. Indeed any

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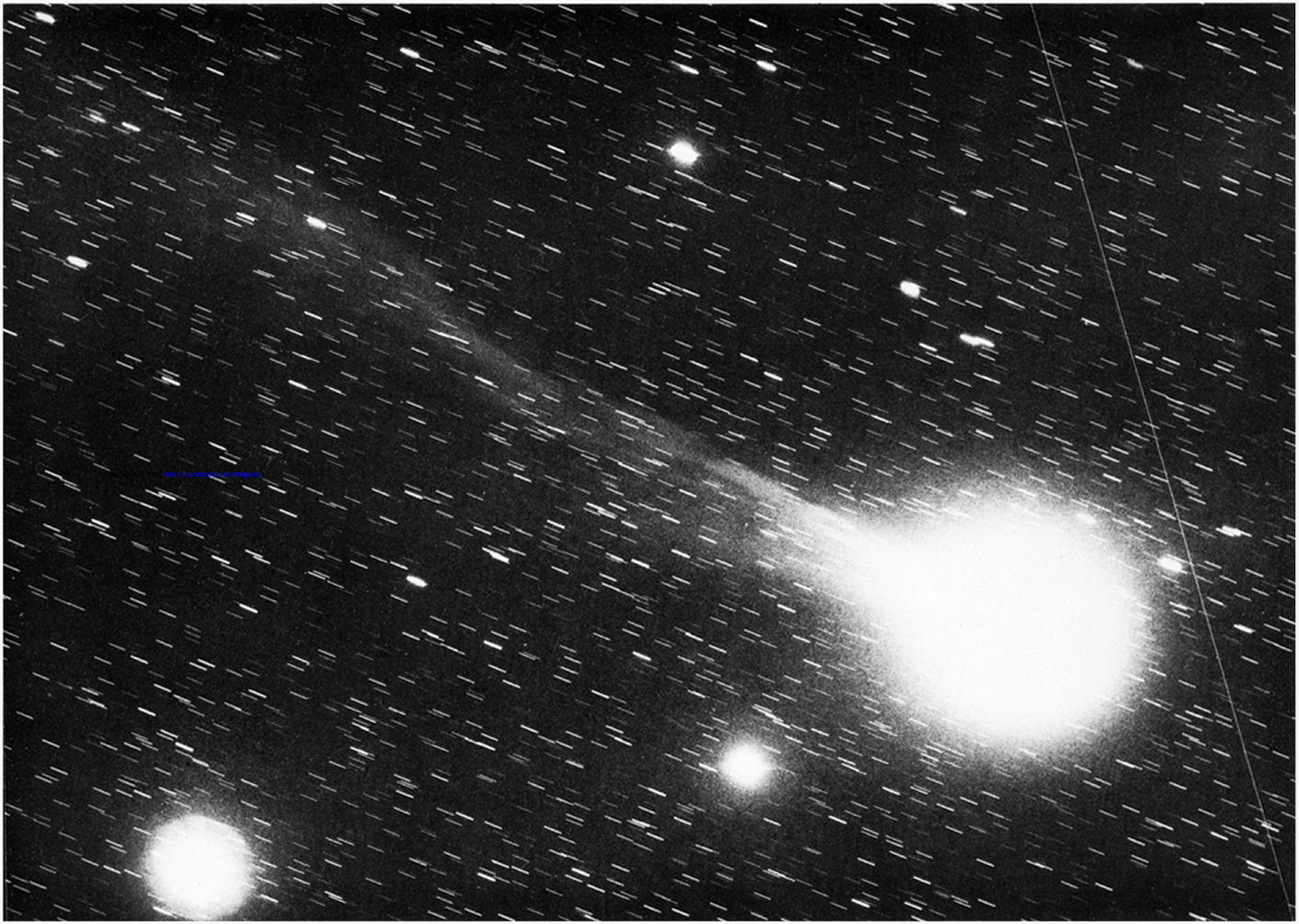
† 1 rad = 10^{-2} Gy = 10^{-2} J kg^{-1}.

curve that passes within error through the observations is as good as any other. This point is so fundamental to the fitting of experimental data that it is usually assumed to be part of basic scientific procedure.

SIR FRED HOYLE, F.R.S. (*Department of Applied Mathematics and Astronomy, University College Cardiff, U.K.*). I disagree. I have not seen a satisfactory fit arising from any abiotic model. Our laboratory spectra were all carefully calibrated to enable a calculation of the opacity function $\tau(\lambda)$ at all wavelengths over a broad band for our particular grain model. Our transmittance $T = 100\ \mathrm{e}^{-\tau}$ was presented on a graph grid from which $\tau = \tau(\lambda)$ could be read out. No such calibrated curve was shown for any of the cases that H. W. Kroto discussed. Any competing abiotic model must have a $\tau(\lambda)$ function that does not depart from the bacterial $\tau(\lambda)$ curve by more than 3% at any wavelength between 3.2 and 4 μm.



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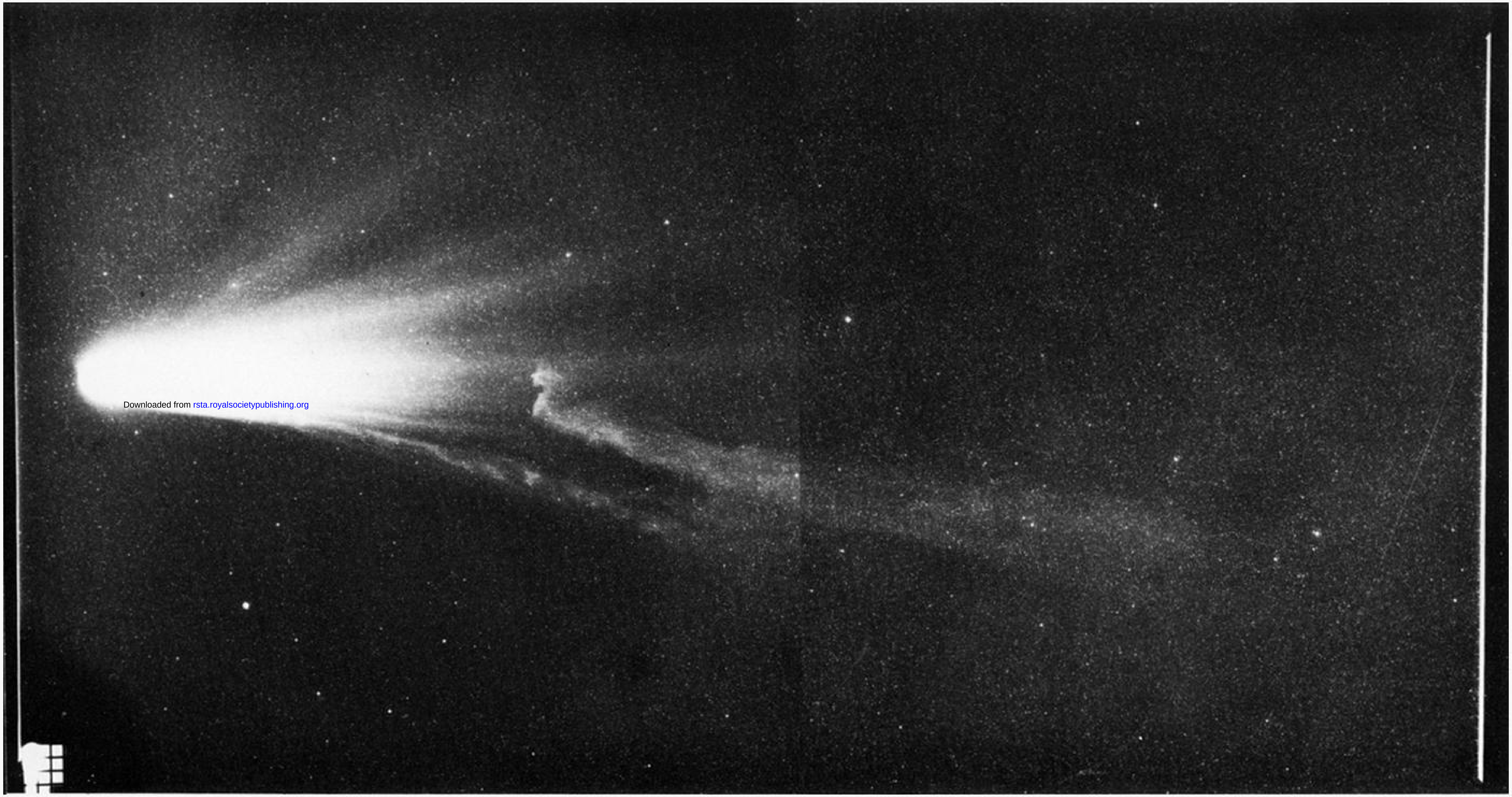

FIGURE 4. Comet Halley on 10 March 1986. This high-contrast composite positive photograph of Comet Halley is made from two exposures of ten minutes in blue light with the U.K. 1.2 m Schmidt Telescope. In this photograph the comet extends for some ten degrees across the sky covering two original photographic plates. The lower, filamentary ion tails show a disconnection about four degrees from the comet's head where material was blown away from the comet's head by the solar wind. The movement of this disconnection can be seen in comparison with a photograph taken the previous night. The smoother dust tails can be seen curving away from the comet to the north of the photograph.

This photograph complements the images obtained from various spacecraft which made their closest approaches to the comet between 6 March and 19 March.

Original plates J10830 and J10831T taken with the U.K. Schmidt Telescope in Australia. Photography by B. W. Hadley, Royal Observatory, Edinburgh. Reproduced with permission from the Royal Observatory, Edinburgh.