PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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Comet Halley: The Gas Composition Derived from Space Missions [and Discussion]

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Comet Halley: the gas composition derived from space missions

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Important results have been obtained by the *Vega* and *Giotto* missions concerning Comet Halley's gas composition. Water vapour and carbon dioxide have been identified with respective production rates of about $10^{30}\ s^{-1}$ and $10^{28}\ s^{-1}$. In addition, there is evidence for the presence of hydrocarbons and/or carbonaceous material in large amounts in the immediate vicinity of the nucleus.

1. Introduction

Before the 1986 apparition of Comet Halley very little was known about the nature of parent molecules directly outgassed from cometary nuclei. Visible and ultraviolet spectra of various comets had given a large amount of information upon the nature and relative abundance of secondary products – ions, radicals and daughter molecules – which come from the dissociation of the parent molecules by the solar flux. In contrast, very little was known about the parent molecules because their observation is very difficult. First, they have a limited lifetime, so that they can be found only in the immediate surrounding of the nucleus, in a region corresponding to a few seconds of arc in diameter as observed from the Earth. Secondly, the strongest transitions expected for the candidate parent molecules occur in the infrared or millimetric range, where observations are more difficult.

On the basis of indirect arguments, as well as marginal detections, a few molecules had been selected as best candidates. The first one is H_2O because of: (1) the amount of OH and H, the most abundant radicals observed in comets; (2) the presence of the H_2O^+ ion; (3) the tentative detection of H_2O in the radio range, on Comet IRAS–Araki–Alcock (Altenhoff *et al.* 1983). HCN was considered as a possible parent of the CN radical, observed on all comets; it was also tentatively detected (Huebner *et al.* 1974), as well as CH_3CN (Ulich & Conklin 1974), on Comet Kohoutek. S_2 was also detected as a minor parent molecule on the UV spectrum of Comet IRAS Araki-Alcock (A'Hearn *et al.* 1983). The abundance of carbon and the form in which it is incorporated (gas or grains) is a major puzzle for cometary research. Although CO_2^+ was observed in many cases, CO_2 was never observed before 1986; CO, in contrast, was observed on several comets, as well as CO^+, but in very variable amounts, and it was not clear whether CO was a parent or a daughter molecule. More generally, the presence of parent carbonaceous molecules were needed to explain the abundances of CN, CH, C_2 and C_3 regularly observed in the visible spectra of all comets.

Ground-based observations of Comet Halley during the 1986 apparition already provided some new results for this research. First, the H_2O molecule was unambiguously detected, thanks to the progress of infrared airborne astronomy (Mumma *et al.* 1986), with an abundance comparable to the expected value. Water vapour has thus been confirmed as one of the most (if not the most) abundant parent molecules in comets. The second important result came from the detection of HCN, obtained in the millimetric range (Despois *et al.* 1986). The derived mixing ratio HCN/H_2O, in the order of 10^{-3}, is also in agreement with previous expectations. These discoveries have provided a major step in cometary research, with the first non-ambiguous detection of two parent molecules, but, very clearly, there were still other abundant parent molecules which remained to be found.

2. The space missions

Among the five space missions devoted to the study of Comet Halley, three had experiments to determine the gas composition of the coma: *Vega* 1, *Vega* 2 and *Giotto*. The two *Vega* probes encountered Comet Halley on 6 March 1986 and 9 March 1986, with respective miss distances of 8890 km and 8030 km. The instruments for gas analysis were two spectrometers, a neutral-mass spectrometer and an ion-mass spectrometer. The *Giotto* probe was somewhat more ambitious, in that it encountered Comet Halley on 14 March 1986 with a miss distance of only 605 km. Instrumentation directly devoted to *in situ* gas measurements consisted of ion- and neutral-mass spectrometers; an optical photopolarimeter was also included in the payload. In addition, several instruments were added on the three probes for the study of dust (dust-impact analysers, dust-mass spectrometers) and plasma (ion and electron analysers, magnetometers).

For the study of gas composition, information of different kinds was obtained. First, data were obtained on the spatial distribution of radicals in the inner coma; these results come from the trichannel spectrometer of *Vega* 2 (TKS) and the *Giotto* optical photopolarimeter (OPE). Second, information on parent molecules was obtained by the infrared spectrometer IKS aboard *Vega* 1; third, direct information on the gaseous constituents was derived from the *Vega* and *Giotto* mass spectrometers (ING aboard *Vega*, NMS and IMS aboard *Giotto*).

3. Spatial distribution of radicals

The TKS spectrometer on Vega was designed to record the spectrum of the comet in three channels (UV, visible and near IR) with one spatial dimension; the other spatial dimension is achieved by scanning, so that monochromatic images can be obtained in the central coma. The spatial resolution is about 20 km at the fly-by point. The instrument operated successfully on *Vega* 2, except in the UV channel, during the encounter sequences and during two other sequences, one day before and after encounter.

By integrating the signal in the near infrared channel, during 10 mn, at the time of encounter, the H_2O $\nu_1+\nu_3$ band at 1.38 μm has been detected. The (0–0) band of the CN red system seems to be present at 1.1 μm, as well as some structure due to the OH $\Delta V = 2$ band between 1.5 and 1.8 μm. In the visible range, a large number of spectra were recorded, at a rate of 1 every 5 s, between 2800 and 7000 Å†, with a spectral resolution of ~ 25 Å and a very high signal: noise ratio. The following bands are easily identifiable: OH (3090 Å), NH (3360 Å), CN (3883 Å), C_3 (4040 Å), C_2 ($\Delta V = 0$, -1 and -2 at about 5100 Å, 5600 Å and 6100 Å, respectively) and NH_2 (6000–7500 Å). The S_2 signature is possibly present below 3000 Å. At a few hundred kilometres from the nucleus, the continuum increases very strongly following the solar continuum; this effect is due to the rapid increase of the dust distribution, more peaked than the distribution of radicals, towards the nucleus. The first results of the TKS

† 1 Å = 10^{-1} nm = 10^{-10} m.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

experiment can be found in Krasnopolsky *et al.* (1986). We extract from this study the table of production rates for the most abundant species (table 1).

The OPE experiment aboard *Giotto* was built on a very different principle. The instrument was a photopolarimeter which operated in seven different visible filters; three in the dust continuum and four in selected emission bands corresponding to different cometary species: OH, C_2, CN and CO^+ (see figure 1). The instrument was oriented backwards and measured the integrated number density of each species along the line of sight. By difference, it is possible to retrieve the density distribution of each constituent as a function of the distance to the nucleus. The instrument operated successfully until the time of miss distance, and data were recorded every 4 s in each filter. The first results are presented in Levasseur-Regourd *et al.* (1986).

For nucleus distances ranging between 5×10^3 and 10^5 km, the dust density is found to follow

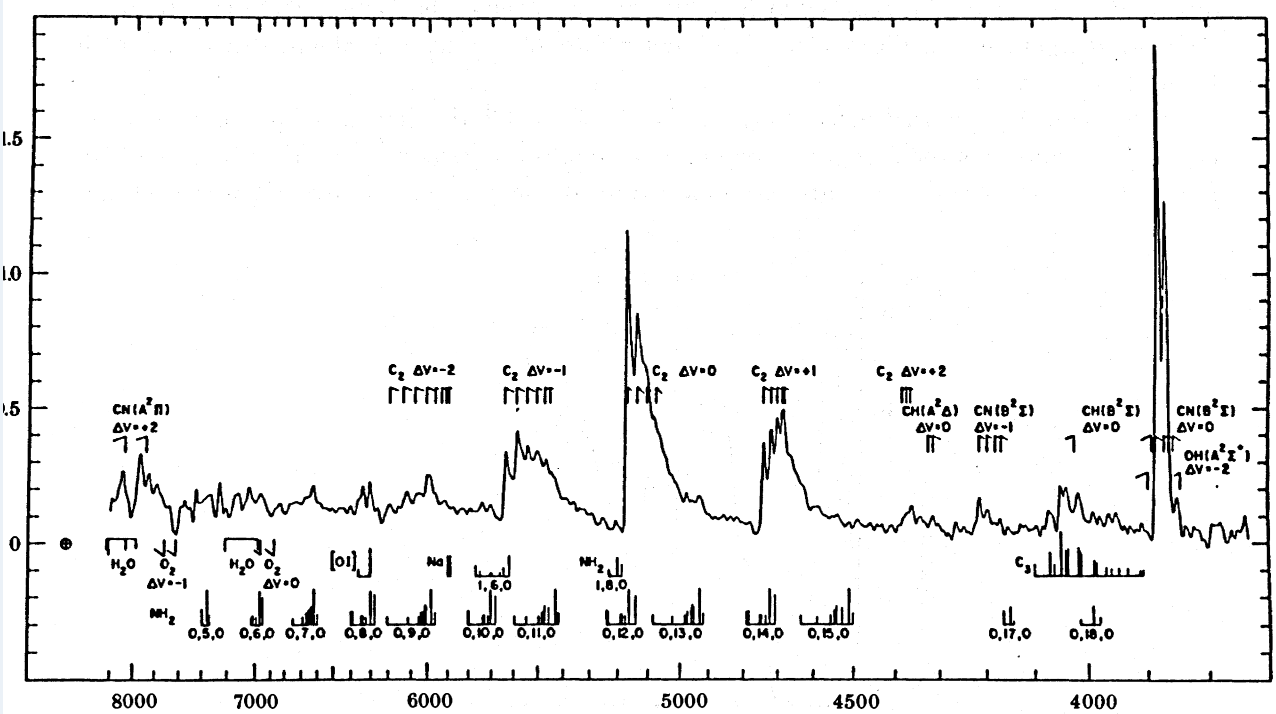

FIGURE 1. The visible spectrum of Comet Kohoutek (1973 XII) (A'Hearn 1983). Above the dust continuum are superimposed emission features due to fluorescence of cometary species: C_2, CN, NH_2 in the visible region, OH in the UV region (3090 Å).

TABLE 1. GASEOUS PRODUCTION RATES DERIVED FROM THE TKS EXPERIMENT (9 MARCH 1986)

(Krasnopolsky *et al.* (1986).)

molecule	production rate/s^{-1}
H_2O	4×10^{29}
OH	2×10^{30}
C_2	6×10^{27}
C_3	3×10^{27}
CN	10^{27}
NH	2×10^{26}

a r^{-2} distribution (where r is the distance to the nucleus). This result is consistent with the assumption of expansion at constant velocity, currently admitted in the vicinity of the nucleus. Below 5×10^3 km, the dust distribution increases faster than r^{-2} as the nucleus distance decreases; this is in agreement with the TKS result. The density distributions of the radicals follow a slope that is not as steep as in the case of the dust; this is as expected for secondary products.

4. The parent molecules

The IKS experiment aboard *Vega* was especially designed to search for parent molecules in the vicinity of the coma. The cometary flux was recorded in two spectroscopic channels, in the 2.5–5 μm range and 6–12 μm range with a resolving power of 40; the field of view was 1°. In addition, an 'imaging channel' was designed to modulate the infrared signal of the nucleus by two perpendicular grids, to recover the diameter of the nucleus along two perpendicular directions; the signal was recorded at two different IR wavelengths (8 μm and 12 μm) to derive a colour temperature of the nucleus. The first results of the IKS experiment can be found in Combes *et al.* (1986).

The instrument operated successfully on *Vega* 1; on *Vega* 2, the detectors could not be cooled because of a failure of the cryogenic system. Results of the *Vega* 1-IKS experiment are shown on figure 2. To remove the background signal due to the instrument itself, it was necessary

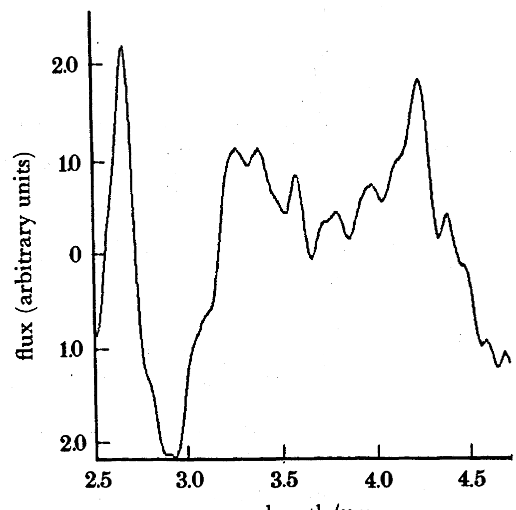

FIGURE 2. The 2.5–5 μm spectrum of P/Halley recorded by the IKS-*Vega* experiment. The spectral signature of H_2O (2.7 μm), CO_2 (4.25 μm) in emission, and H_2O ice (2.9 μm) in absorption, are easily identified. The broad feature centred at 3.3–3.4 μm is attributed to hydrocarbons (from Combes *et al.* 1986).

to take differences of spectra recorded at different distances from the nucleus; by this method, the spectrum obtained is representative of the cometary signal. Additional filtering is used to remove the remaining background. Figure 2 shows the filtered cometary signal between 2.5 and 4.7 μm obtained as the difference of two spectra recorded at 40000 km and 90000 km, respectively, from the nucleus. The spectrum is dominated by the ν_3 band of H_2O at 2.7 μm and the ν_3 band of CO_2 at 4.25 μm excited by fluorescence. These two signatures have the widths expected from theoretical calculations, and correspond to production rates of about

10^{30} s^{-1} and 10^{28} s^{-1} for H_2O and CO_2, respectively (Crovisier & Encrenaz 1983; Crovisier 1984; Bockelée-Morvan & Crovisier 1986). In addition, there is a broad emission centred at 3.3–3.4 μm, which apparently cannot be interpreted by fluorescence of a single molecule, for example CH_4. It is more likely that different species could contribute to give the broad feature. Because the 3.3–3.4 μm signature is typical of C—H bonds, it can be suggested that the feature observed on the cometary spectrum could be due to the presence of hydrocarbons. Finally, we also note that the absorption signature of ice seems to be present at 2.9 μm.

The 13.3 μm emission could be the signature of hydrocarbonaceous grains; these grains could be on the nucleus or in its surrounding; with their very low albedo, they could be at a temperature higher than the surrounding. It is also interesting to note the analogy between the cometary features and the emissions observed in the interstellar medium (figure 3); in the 3 μm regions. A preliminary conclusion is that there seems to be some evidence for carbonaceous material in the immediate vicinity of the nucleus, in the form of hydrocarbons, either in the gaseous or the solid phase.

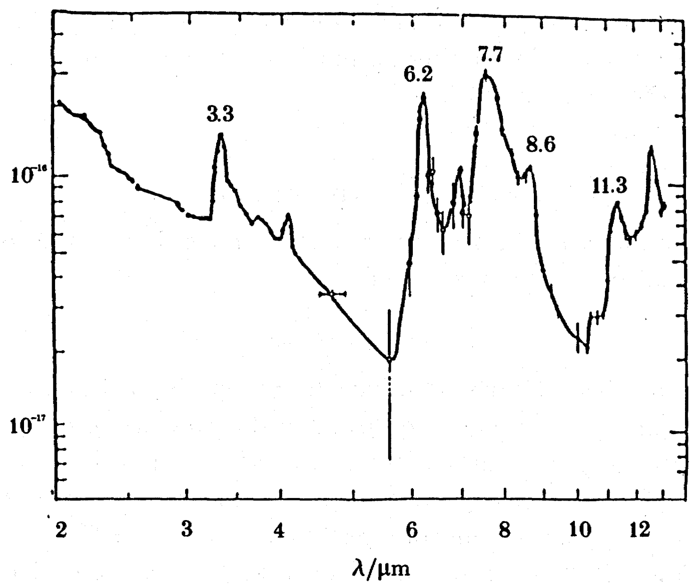

FIGURE 3. The spectrum of M82 between 2 and 14 μm (Willner *et al.* 1977).

5. *In situ* measurements

Additional information upon the composition of cometary gas and dust has been provided by mass spectrometers for both neutrals and ions. Two instruments have to be especially mentioned: the PUMA experiment, aboard the two *Vega* probes and *Giotto*, and the NMS aboard *Giotto*.

The PUMA experiment (Kissel *et al.* 1986) obtained most of its results from the *Vega* 1 encounter, which corresponded to the maximum dust-ejection rate. The PUMA experiment recorded the impacts of about 40000 grains, and recorded 4000 mass spectra. These spectra show evidence for several very distinct classes of particles: (1) the silicate particles either the 'olivine' type (including Mg, Si, Fe) or the 'pyroxene' type (including Mg, Si, Ca, Na); (2) the 'light element' particles dominated by the elements H, C, O and N, these particles being especially abundant (60%); (3) the intermediate particles, with all possible compositions between the two extremes (1) and (2). An additional important result is that the 'light-element' particles have a remarkably low density (0.1 g cm^{-3}) implying some kind of porous material. The unexpectedly large abundance of these 'light-element' particles, rich in carbon and with relative abundances close to the solar abundances, seems to be a good indicator of primordial Solar System matter in Comet Halley.

The NMS experiment aboard *Giotto* recorded mass spectra of neutrals and ionic species at distances ranging from 920000 to 350000 km to the nucleus, and mass spectra of neutrals from 350000 to 750 km to the nucleus (Krankowsky *et al.* 1986). For neutral particles, strong peaks occur around atomic masses of 18 (H_2O group), 28 (CO group), 32 (C_2) and 44 (CO_2); we have to note that the 44 peak may be partly due to the presence of CS. The speed of the species was measured to be 900 ± 200 m s^{-1}. The production rate of H_2O was found to be 6.9×10^{29} s^{-1}, with a R^{-2} density distribution between 10^3 and 10^4 km. The CO_2 production rate was found to be up to 2×10^{28} s^{-1} (the upper limit comes from a possible contribution from CS). The ion mass spectra also show a strong maximum in the H_2O group, with a strong amount of H_3O^+. The same result was obtained by the ion-mass spectrometer (Balsiger *et al.* 1986). This preliminary result is interesting in that H_3O^+ could be observed from the ground by radioastronomy in the millimetric range.

6. Discussion and conclusion

From a comparative analysis of all results reported above, important conclusions can be drawn about the composition of the inner coma.

6.1. *Water vapour*

The H_2O molecule has been clearly identified by the IR channel of TKS, and by IKS. The H_2O signature of ice is also present on IKS spectra, and the presence of H_2O (ice or gas) is also obvious from mass spectrometer analyses (PUMA and NMS). There is a slight disagreement, which may not be significant, between the deduced production rates of H_2O: 10^{30} s^{-1} at the time of *Vega* 1 (IKS) 4×10^{29} s^{-1} at the time of *Vega* 2 (TKS) and 5.5×10^{29} s^{-1} at the time of *Giotto* (NMS). However, we know that the dust production rate decreased by a factor of about four between *Vega* 1 and *Vega* 2 and by another factor of about 4 between *Vega* 2 and *Giotto*; it is likely that the gas production rate also decreased during the same period; it is worth noting that IUE observations derived a H_2O production rate of 8×10^{29} s^{-1} at the time of *Vega* 2 and 5×10^{29} s^{-1} at the time of *Giotto* (M. Festou personal communication 1986).

6.2. *Carbonaceous material*

The first carbonaceous material unambigously identified is CO_2, with a CO_2/H_2O ratio of about 10^{-2}; this result obtained by the IKS-*Vega* experiment, is also confirmed by the NMS-*Giotto* measurements. This result, expected from theoretical calculations, shows that CO_2 is a possible parent for CO, but other carbonaceous parent molecules still have to be found. It is interesting to note that CO was not observed in large amounts with IKS, although IUE spectra, recorded in a much larger field of view seem to indicate a CO/H_2O ratio of about 0.1. This result might imply that CO is probably not a parent molecule, so that its amount would be very low in a sphere of a few hundred kilometres around the nucleus.

The detection of carbonaceous material in the vicinity of the nucleus is probably the most

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

important result of the space mission concerning the gaseous phase of P/Halley. The result is deduced from, or confirmed by many different experiments: (1) the TV cameras of *Vega* and *Giotto* measured a very low albedo, 4 % or less, implying that the surface of the nucleus is covered by some strongly absorbing material (Keller *et al.* 1986; Sagdeev *et al.* 1986); (2) the imaging channel of IKS measured a high temperature (higher than 300 K) for the surface of the nucleus or its immediate environment (Combes *et al.* 1986); this result is fully compatible with the low albedo of the surface; (3) as mentioned above, the mass spectrometers of *Giotto* and *Vega* detected the presence of carbonaceous particles in large amounts; (4) as mentioned above also, the IKS experiment detected spectroscopic signatures which are likely to be due to hydrocarbons.

It is interesting to compare the infrared signatures of IKS with the spectra obtained at the same wavelengths from ground-based observations. The 3.3–3.4 μm spectral range has been studied in several occasions by a large number of observers. In December 1985 and January 1986, results seem to have been negative (Tokunaga *et al.* 1986), whereas in March and April 1986, an emission feature centred at 3.4 μm was definitely reported by several authors from IRTF, UKIRT, AAT and ESO (Wikramasinghe & Allen 1986). This latter result seems to imply that the hydrocarbons presumably responsible for this emission could have a lifetime of at least 10^3 km so that they could be observable in a field of view of a few seconds of arc from the Earth. The absence of any feature before perihelion is puzzling; the only possible explanation that we see now is a temporal variation.

In conclusion, it can be said that the space missions devoted on Comet Halley have significantly changed our conception of the cometary nucleus. Carbon has been found to be present in large amounts, probably on the surface itself; if the 'dirty snow ball' model of F. Whipple is still valid, the cometary nucleus has to be very dirty: on most of the surface, the ice is covered by (or mixed with) a layer of absorbing material, and water vapour is outgassed from sporadic areas. The exact nature of carbonaceous material has still to be determined. Most likely these preliminary results will open a new field of research in cometary physics.

References

A'Hearn, M. F., Feldman, P. D. & Schleicher, D. G. 1983 *Astrophys. J.* **274**, L99.

Altenhoff, W., Huchtmeier, W., Schmidt, J., Stumpff, P. & Walmsley, M. 1983 *Astron. Astrophys.* **125**, L19.

Balsiger, H., Altwegg, K., Bühler, F., Geiss, J., Ghielmetti, A. G., Goldstein, B. E., Goldstein, R., Huntress, W. T., Ip, W.-H., Lazarus, A., Meir, A., Neugebauer, M., Rettenmund, U., Rosenbauer, H., Schwenn, R., Sharp, R. D., Shelley, E. G., Ungstrup, E. & Young, D. T. 1986 *Nature, Lond.* **321**, 330.

Bockelée-Morvan, D. & Crovisier, J. 1986 In *Asteroids, comets, meteors, II* (ed. C. Lagerkvist *et al.*). Uppsala University.

Combes, M., Moroz, V. I., Crifo, J. F., Lamarre, J. M., Charra, J., Sanko, N. F., Soufflot, A., Bibring, J. P., Cazes, S., Coron, N., Crovisier, J., Emerich, C., Encrenaz, T., Gispert, R., Grigoryev, A., Guyot, G., Krasnopolsky, V. A., Nikolsky, Yu. V. & Rocard, F. 1986 *Nature, Lond.* **321**, 266.

Crovisier, J. 1984 *Astron. Astrophys.* **130**, 361.

Crovisier, J. & Encrenaz, T. 1983 *Astron. Astrophys.* **126**, 170.

Despois, D., Crovisier, J., Bockelée-Morvan, D., Schraml, U., Forveille, T. & Gérard, E. 1986 *Astron. Astrophys.* **160**, L11.

Huebner, W. F., Snyder, L. E. & Buhl, D. 1974 *Icarus* **23**, 580.

Kaminski, C. & Griep, D. 1985 IAU circ. no. 4154.

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., Schmidt, H. U., Schmidt, W. K. H., Seige, P., Whipple, F. & Wilhelm, K. 1986 *Nature, Lond.* **321**, 320.

Kissel, J., Sagdeev, R. Z., Bertaux, J. L., Angarov, V. N., Audouze, J., Blamont, J. E., Büchler, K., Evlanov, E. N., Fechtig, H., Fomenkova, M. N., Von Hörner, 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. & Zubkov, B. V. 1986 *Nature, Lond.* **321**, 280.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Krankowsky, D., Lämmerzahl, P., Herrwerth, I., Woweries, J., Eberhardt, P., Dolder, U., Herrmann, U., Schulte, W., Berthellier, J. J., Illiano, J. M., Hodges, R. R. & Hoffman, J. H. 1986 *Nature, Lond.* **321**, 326.
Krasnopolsky, V. A., Gogoshev, M., Moreels, G., Moroz, V. I., Krysko, A. A., Gogosheva, Ts., Palazov, K., Sargoichev, S., Clairemidi, J., Vincent, M., Bertaux, J. L., Blamont, J. E., Troshin, V. S. & Valníček, B. 1986 *Nature, Lond.* **321**, 269.
Levasseur-Regourd, A. C., Bertaux, J. L., Dumont, R., Festou, M., Giese, R. H., Giovane, F., Lamy, P. Le Blanc, J. M., Llebaria, A. & Weinberg, J. L. 1986 *Nature, Lond.* **321**, 341.
Mumma, M. J., Weaver, H. A., Larson, H. P., David, D. S. & Williams, M. 1986 *Science, Wash.* **232**, 1523,
Sagdeev, R., Blamont, J., Galeev, A., Moroz, V. I., Shapiro, V. D., Shevchenko, V. & Szegö, K. 1986 *Nature, Lond.* **321**, 259.
Tokunaga, A. T., Smith, R. G., Nagata, T., Deloy, D. & Sellgren, K. 1986 *Astrophys. Lett.* **310**, L45.
Ulich, B. L. & Conklin, E. J. 1974 *Nature, Lond.* **248**, 121.
Willner, S. P., Soifer, B. T., Russell, R. W., Joyce, R. R. & Gillett, F. C. 1977 *Astrophys. J.* **217**, L121.
Wickramasinghe, D. & Allen, D. 1986 *Nature, Lond*, **323**, 44.

Discussion

W. K. H. Schmidt (*MPI für Aeronomie, Lindau, F.R.G.*). I was a bit surprised about the figure of $T = 330$ K that seemed to refer to the dark part of the nucleus. Where did this figure come from?

Thérèse Encrenaz. The temperature of the nucleus derived by the IKS-*Vega* instrument is actually a colour temperature, derived from the ratio of the infrared flux in two channels (7–10 μm and 9–15 μm). The result is that the temperature of the central emissive region is higher than 300 K.

D. T. Wickramasinghe (*Australian National University, Canberra, Australia*). Was there any evidence of water ice in the *Vega* infrared spectra between 3 and 4 μm?

Thérèse Encrenaz. As mentioned in Combes *et al.* (1986) water ice seems to be present in absorption at 2.9 μm. However, we have to be careful, because the spectrum had to be filtered (to remove the internal background emission) so that the continuum level of the cometary signal is lost. Thus, there is some uncertainty in the definition of the zero level, and in the assignment of emission and absorption features.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES