Reprinted from Nature, Vol. 321, No. 6067, pp. 266-268, 15 May 1986

Infrared sounding of comet Halley from Vega 1

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The IKS instrument carried by the Vega 1 spacecraft performed infrared sounding of the inner coma and nuclear region of comet Halley. An emissive centre, a few kilometres in size, was detected with a temperature significantly in excess of 300 K. In the surrounding central coma, hydrocarbon species or other carbonaceous material seem to be present. The fluorescence signatures of H_2O and CO_2 were identified.

The IKS instrument was designed to record spectra of the inner part of the coma in the spectral ranges 2.5-5 and 6-12 μm ('spectroscopic channels'), and to measure the temperature of the nucleus and its dimensions in two perpendicular directions ('imaging channel'). The instrument is described in ref. 1. The infrared detectors had to be cooled down to ~80 K to detect the expected weak signals. An active cryogenic system was used, based on the expansion of pressurized gaseous nitrogen.

On Vega 1, the IKS instrument operated successfully. The last available cometary data from the imaging channel were obtained a few minutes after closest approach. For the preliminary analysis of data from the spectroscopic channels, we have used only spectra obtained a few minutes before closest approach, when the distance to the comet was 43,000 km. Near closest approach the data flow was interrupted for ~30 min, due to an erroneous command received by the instrument. No results were obtained from Vega 2 because of failure of the cryogenic system.

Spectroscopy is achieved in two spectral bands by using two circular variable filters (CVF) located on two tracks of the encoding wheel. Each track is divided into two halves to duplicate the spectrum and avoid discontinuities. The resolving power of the CVF is $\lambda/\Delta\lambda = 40$, and the field of view is 1° in diameter. The large apparent size of the source during the fly-by prevented the use of sky chopping to eliminate the large instrument background; the signal is only spectrally modulated by the rotation of the wheel. The cometary signal is superimposed on the background due to the emission of the instrument itself, most of which is eliminated by taking the difference between spectra obtained at different times. Because the cometary signal is expected to vary approximately as r^{-1} (where r is the distance to the nucleus) this difference is, to first order, proportional to the cometary spectrum. After the subtraction, a small residual background signal remains which is due to temperature variations of the instrument. It can be removed using laboratory calibration data and accurate monitoring of the instrument temperature. The minimum detectable intensity is $\sim 5 \times 10^{-8}$ W μm^{-1} cm^{-2} sr^{-1} at 3 μm, and 6×10^{-7} W μm^{-1} cm^{-2} sr^{-1} at 6 μm. Spectra are added over 18-s intervals, each corresponding to 128 rotations of the filter wheel. An internal black body is used for calibration.

Figure 1 shows a representative spectrum of the 2.5-μm region, obtained at a distance of 43,000 km from the comet. The continuum signal was eliminated by filtering out the low frequencies in the power distribution of the spectrum. The spectrum shows narrow emission features at 2.70 and 4.25 μm which may be attributed to the ν_3 bands of H_2O and CO_2. A broad emission feature at 3.2-3.4 μm might be due to the C-H vibration of hydrocarbon molecules (an alternative explanation will be given below), and the water-ice absorption signature seems to be present at ~3 μm. The presence of other molecular emissions is not excluded, but further analysis is needed.

According to fluorescence excitation models[2,3], the 2.7-μm feature corresponds to a water production rate of $\sim 10^{30}$ molecules s^{-1}, and the 4.25-μm feature to a CO_2 production rate ~100 times lower.

Figure 2 shows a spectrum of the cometary flux between 6 and 12 μm. A strong and broad emission centred at 7.5 μm

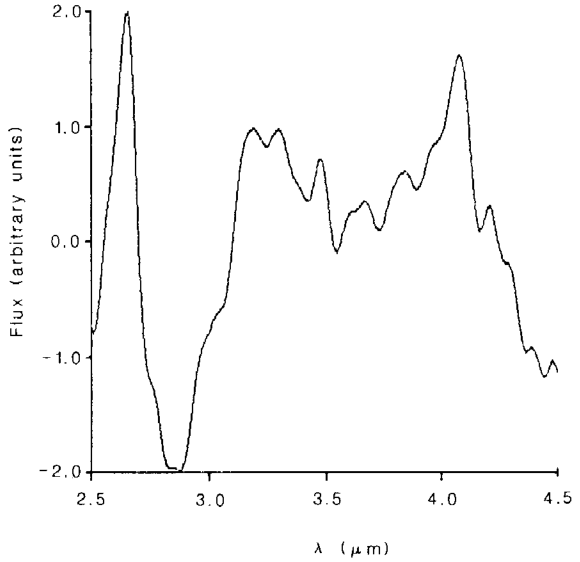

Fig. 1 Spectrum of comet Halley's central region at wavelength $2.5 \leq \lambda \leq 5$ μm, obtained from the difference between spectra recorded at distances of 43,000 and 90,000 km from the comet, in order to remove the instrumental background. Low frequencies have been filtered out of the power spectrum to remove the residual background signal. At a distance of 43,000 km, the observed coma has a diameter of 770 km (or 1 arc s, as seen from the Earth). The mean standard deviation of the data is 0.3 units.

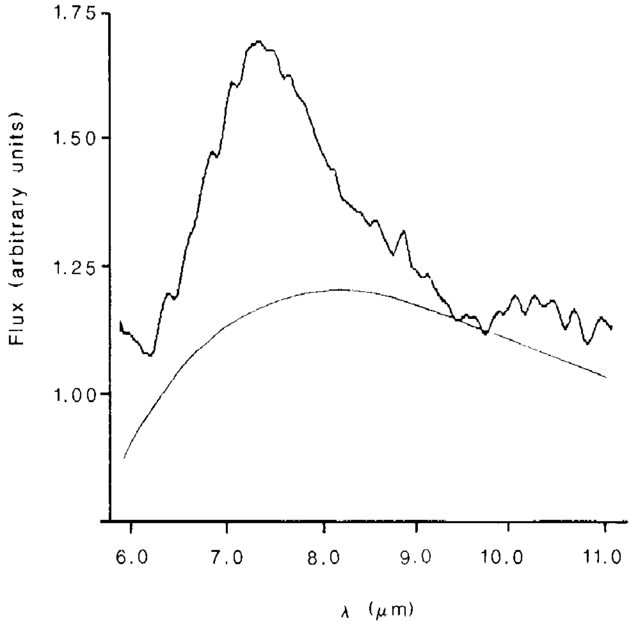

Fig. 2 Spectrum of comet Halley's central region at wavelengths between 6 and 12 μm, obtained from the difference of two spectra acquired at 43,000 and 60,000 km, in order to remove the instrumental background. The smooth line is the spectrum of a black body at 350 K. The mean standard deviation of the data is 0.05 units.

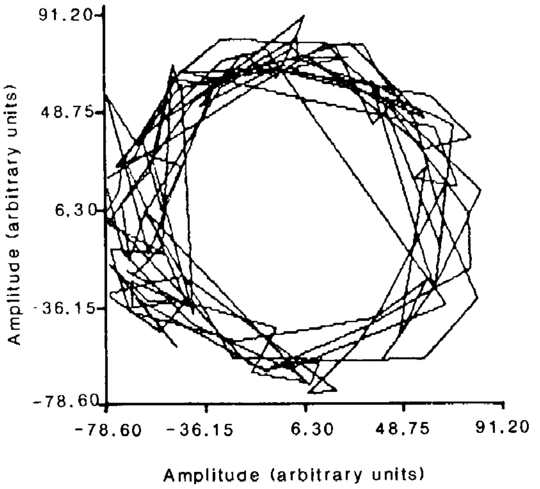

Fig. 3 Phase diagram of the output of one image channel during an 18-s interval. The axes are signal amplitudes. Changes in the position of the nucleus image in the field of view appear as rotations of the phase of the modulated signal. The data points accumulate on a ring, the centre of which is determined by the instrument background and the average radius of which is proportional to the cometary signal.

extends from 6.5 to 9 μm, and a second weaker emission may be present between 9 and 11 μm. We tentatively interpret the 9-11-μm band as being due to silicates and the 7.5-μm emission (not seen from the ground) as representative of the presence of C-C bonds in the nuclear region.

It seems unlikely that the 7.5-μm feature could be due to fluorescence excitation of a gaseous molecule. Indeed, the expected fluorescence rates of all possible molecules are quite low at this wavelength[2]. We note that both the 3.3- and 7.5-μm features are present in interstellar medium emission spectra. These features of the comet spectrum could be related to the presence of carbonaceous material including C-H and C-C bonds.

In the IKS imaging channel[1,4] the image of the comet is formed on a moving grid with an angular period of one minute of arc. The flux emitted by a point-like source is 100% modulated, but when the dimensions of the source image become nearly equal to the period of the grid, the modulation may vanish. Because of variations in the apparent dimensions of the nuclear region during the fly-by, the measured signal should show a succession of maxima and minima, from which one can find the source dimensions in the two directions of analysis of the grid, which are approximately parallel and perpendicular to the comet's orbital plane. These measurements are performed in two infrared bands: 7-10 and 9-14 μm. Comparisons of the two spectral densities give the colour temperature of the source. Thus, the signal is split into four channels: I (long wavelength, perpendicular), II (long wavelength, parallel), III (short wavelength, parallel) and IV (short wavelength, perpendicular).

As explained in detail in ref. 4, the residual pointing platform jitter produces some randomization of the phase of the modulated signal, whereas the instrument calibration and background signal are unaffected. Therefore, on a phase diagram of each channel output (see Fig. 3), the points of the cometary signal acquired over a short time period must lie on a circle (see Fig. 3 of ref. 4 obtained during ground tests). The data were therefore reduced by plotting phase diagrams of the data, locating the centres of the circles, and computing every 4 s the mean of their radii. The signal emerged clearly from the noise only 5 min before closest approach. Figure 3 shows one of the obtained phase diagrams and Fig. 4 presents the four channel signals.

There is a marked difference between the time variation of signals I and IV and that of II and III (Fig. 4), indicating a non-spherical source. This fact, combined with the rapid variation of the line-of-sight orientation during the encounter, limits the utility of a preliminary analysis based on simple simulation. It is nevertheless possible to interpret the results given by channels I and IV by comparison with simulations of the fly-by using uniformly bright sources of simple shapes[4]. The positions of the first small maximum (M_1 in Fig. 4*a*), the well-marked minimum and the large maximum (M_2) correspond to an emissive region with an effective dimension of 5.5 ± 1 km perpendicular to the comet orbit plane. To explain the ratio of the two maxima, we must assume some strong effect of the quickly changing phase angle and/or a double structure in the emitting source. Such effects must also be taken into account in interpreting the data from channels II and III: this will be done in future, using more realistic and sophisticated models and inversion procedures.

The ratios of signals I/IV and II/III were very similar, indicating that the colour temperature is not a function of the direction of analysis. These ratios are also constant throughout the period when the signal-to-noise ratio is good. The measured values of 0.85 ± 0.02 (I/IV) and 0.83 ± 0.03 (II/III) indicate, on the basis of pre-flight calibration data, a colour temperature of 420 ± 60 K. However, if the strong spectral features observed by the spectroscopic channels of IKS near 7 μm are also present in the small region detected by the image channel, the derived temperature of this region will be ~300-400 K. In any case, the absolute

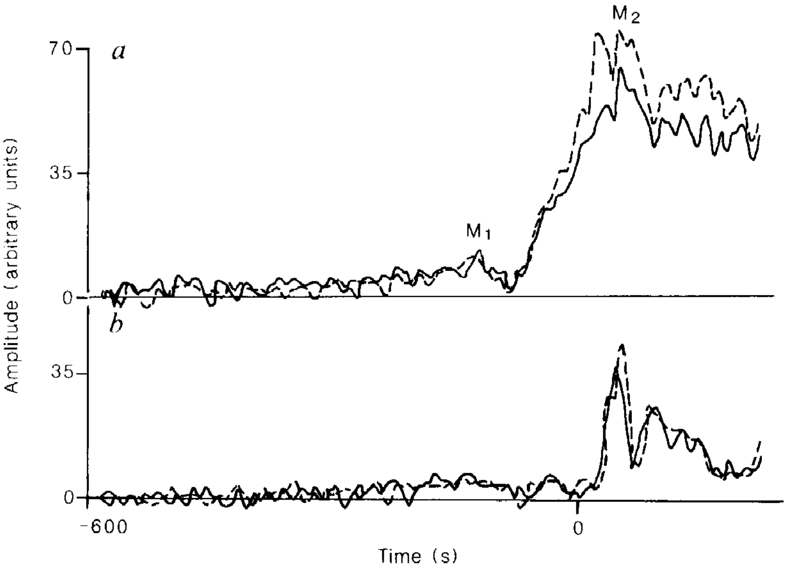

Fig. 4 Outputs of imaging channels I (——) and IV (- - -) (*a*) and II (——) and III (- - -) (*b*). The time is expressed relative to an arbitrary zero time, which is within 20 s of the time of closest approach. Signals I and IV exhibit two maxima (M_1 and M_2), separated by a well-marked minimum from which the source dimension can be estimated (see text).

value of the flux measured by channels I and IV requires a minimum physical source temperature of 300 K (for unit emissivity). These temperatures are well in excess of the sublimation temperature of bare ice; they lie in the range appropriate for absorbing dust, or the surface of a dark body, at a distance of 0.8 AU from the Sun. However, this observation alone does not exclude the presence of subliming ice, the thermal radiation of which would be masked by the higher-temperature contribution[5]. A surface layer of a porous dark substance with a low thermal conductivity, covering the ice, could explain the high measured temperature.

We thank the French and Soviet technical team members who have developed a highly efficient cooperative effort. Financial support was provided by the Centre National d'Etudes Spatiales.

Received 3 April; accepted 11 April 1986.

1. Arduini, M. *et al. Adv. Space Res.* **2,** 113-122 (1983).
2. Crovisier, J. & Encrenaz, T. *Ast. Astrophys.* **126,** 170-182 (1983).
3. Bockelée-Morvan, D. & Crovisier, J. in *Asteroids, Comets, Meteors II* (eds Lagerkvist, C.-I. *et al.*) 279-282 (Uppsala University Press, 1986).
4. Lamarre, J. M., Gondet, B., Gispert, R., Emerich, C. & Rocard, F. *Adv. Space Res.* **4,** 277-281 (1984).
5. Crifo, J. F. *Adv. Space Res.* **2,** 203-206 (1983).