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Airborne and groundbased spectrophotometry of comet P/Halley from 5-13 micrometers

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Summary. Spectrophotometry from 5-10 μm ($\Delta\lambda/\lambda \approx 0.02$) of comet Halley was obtained from the Kuiper Airborne Observatory on 1985 December 12.1 and 1986 April 8.6 and 10.5, UT. 8–13 μm data were obtained on 17.2 December 1985 from the Nickel Telescope at Lick Observatory. The spectra show a strong broad emission band at 10 μm and a weak feature at 6.8 μm. We do not confirm the strong 7.5 μm emission feature observed by the Vega 1 spacecraft.

The 10 μm band, identified with silicate materials, has substructure indicative of crystalline material. The band can be fitted by combining spectral data from a sample of interplanetary dust particles. The primary component of the silicate emission is due to olivine. The 6.8 μm emission feature can be due either to carbonates or the C—H deformation mode in organic molecules. The lack of other emission bands is used to place limits on the types of organic molecules responsible for the emission observed by others at 3.4 μm.

Color temperatures significantly higher than the equilibrium blackbody temperature indicate that small particles are abundant in the coma. Significant spatial and temporal variations in the spectrum have been observed and show trends similar to those observed by the spacecraft and from the ground. Temporal variability of the silicate emission relative to the 5–8 μm continuum suggests that there are at least two physically separate components of the dust.

Key words: comets – infrared radiation

1. Introduction

The spectral region from 5.5–8 μm is unobservable from the ground and no previous data on a comet exists at these wavelengths. It is an important region to observe for several reasons. First, the 5–8 μm region contains the OH, NH, and CH deformation modes in alcohols, amines, and hydrocarbons, the CO stretching mode in carbonyl containing molecules (e.g., formaldehyde) and the important C—C stretching modes in aromatic molecules (e.g., polycyclic aromatic hydrocarbons, hereafter PAH's). Together with data from other infrared wavelength regions, this can be used as a "fingerprint" to identify the molecular subgroup in the absorbing molecules (Allamandola, 1984). The recent discovery of a 3.4 μm emission band in the spectrum of comet Halley (Combes et al., 1986; Baas et al., 1986; Wickramasinghe and Allen, 1986; Knacke et al., 1986; Danks et al., 1986) makes these observations even more important. Additionally, interplanetary dust particle (IDP) spectra sometimes show a band due to carbonates centered at 6.8 μm. If IDP's come from comets, then we might observe this band in the coma of comet Halley. Secondly, this is a good region in which to define the dust temperature as the expected peak of the thermal emission from dust in comets near 1AU from the sun occurs near this wavelength region. The continuum can also be used to constrain the particle size distribution of the dust.

In this work we present the results of a preliminary analysis of airborne and groundbased spectrophotometry of comet Halley in the 5 to 13 micrometer region.

2. Observations

Observations were obtained on 1985 Dec 12.1 UT from 5.2–9.0 μm, and 1986 April 8.6 and 10.5 UT from 5.2–10.0 μm from the Kuiper Airborne Observatory (KOA). Ground-based data were obtained on Dec 17.2 from 8.2–13.2 μm from the Lick Observatory Nickel telescope. All data were obtained with the NASA-Ames FOGS 24-channel array ($\Delta\lambda/\lambda \approx 0.02$), liquid helium cooled grating spectrometer (Witteborn and Bregman, 1984). The aperture was 21″ (FWHM), and a 100″ chop aligned approximately perpendicular to the tail was used. Spectra were obtained at various positions as shown in Table 1. All the data were divided by standard stars and multiplied by the intrinsic fluxes of the standards. The start α Tau and β Gem were used in December, while α Boo and α Hya were used in April (Gezari et al., 1984; Thomas et al., 1973). An air mass correction was computed for the April data from a model of the earth's atmosphere and applied to the data to correct for the difference since the standards were obtained at significantly different elevation angles than the comet. This procedure was not necessary for the December data. The airborne and ground-based data taken in December were combined by normalizing the ground-based data to the airborne data using the overlapping channels from 8–9 μm.

The spectra were divided by blackbody curves of different temperatures until the 5–8 μm section of the spectra were flat.

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Table 1

Date	R(AU)	Δ(AU)	Position observed	Color temp. (K ± 5)
85/12/12	1.32	0.77	Nucleus	320
85/17/12	1.32	0.77	Nucleus	—
86/08/4	1.30	0.42	Nucleus	325
			Sunward (21″ SE)	340
			Tailward (21″ NW)	335
86/10/4	1.33	0.42	Nucleus	325
			Sunward (21″ SE)	325
			Tailward (21″ NW)	325
			Up (21″ NE)	320
			Down (21″ SW)	315

This gave the color temperatures listed in Table 1. Heliocentric and geocentric distances are also given in Table 1.

Figures 1–3 show the spectra of the central condensation on the three dates while Figures 4–6 show the same spectra after division by the appropriate blackbody.

3. Results

After division of our data by blackbodies, there are residual features left in the spectra, the most obvious one being the silicate emission in the 10 μm region. Additionally, there is a weak emission feature at 6.8 μm (especially obvious in the December data) possibly due to carbonates or the C—H deformation mode of organic molecules. Also, there is an unidentified upturn (relative to a blackbody) at the shortest wavelengths.

There is no evidence for an emission feature in the 7–8 μm region as reported by Combes et al. (1986) from the IKS spectrograph on the Vega 1 spacecraft. The IKS instrument observed a much smaller central part of the coma than our instrument, and it is possible that the emission close to the nucleus is different

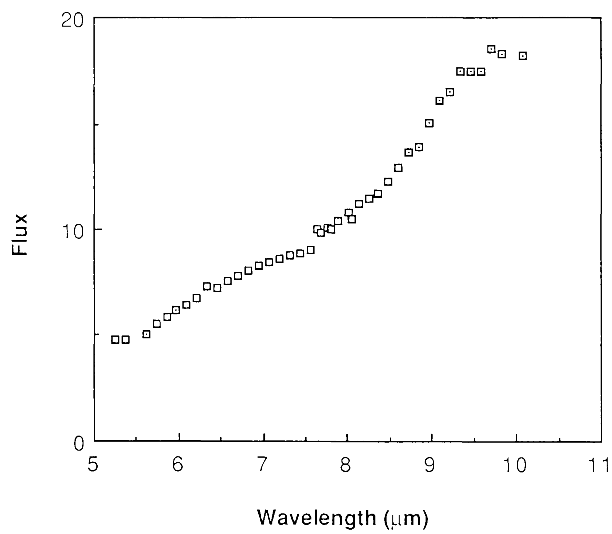

Fig. 2. The 5–9 μm spectrum of the central condensation of comet Halley taken on 1986 April 8.6, UT. Error bars representing the statistical errors are shown when the errors exceed the size of the data point. Units for the flux scale are 10^{-16} W cm^{-2} μm^{-1}

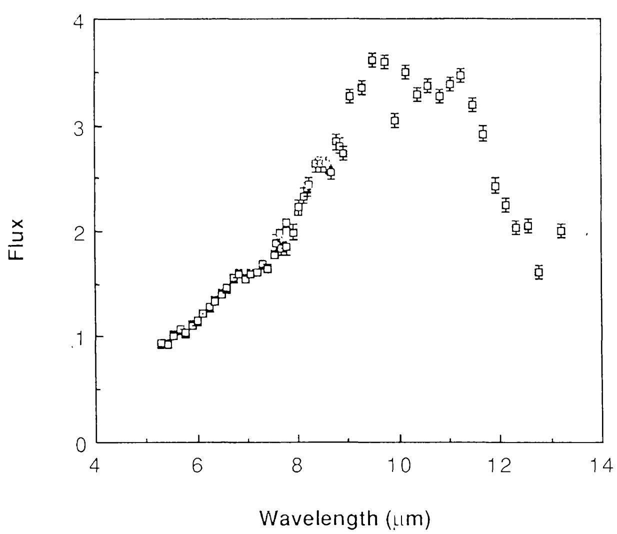

Fig. 1. The 5–13 μm spectrum of the central condensation of comet Halley taken on 1985 December 12.1 and 17.2, UT. Error bars representing the statistical errors are shown when the errors exceed the size of the data point. Units for the flux scale are 10^{-16} W cm^{-2} μm^{-1}. The low data point at 9.7 μm is due to a miscorrection for terrestrial ozone

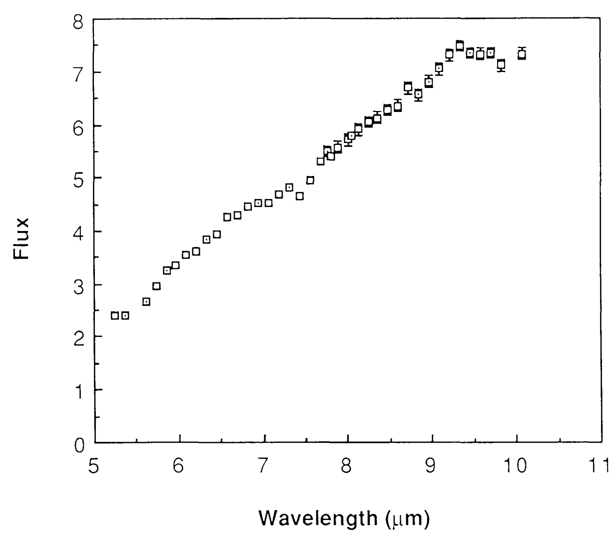

Fig. 3. The 5–9 μm spectrum of the central condensation of comet Halley taken on 1986 April 10.5, UT. Error bars representing the statistical errors are shown when the errors exceed the size of the data point. Units for the flux scale are 10^{-16} W cm^{-2} μm^{-1}

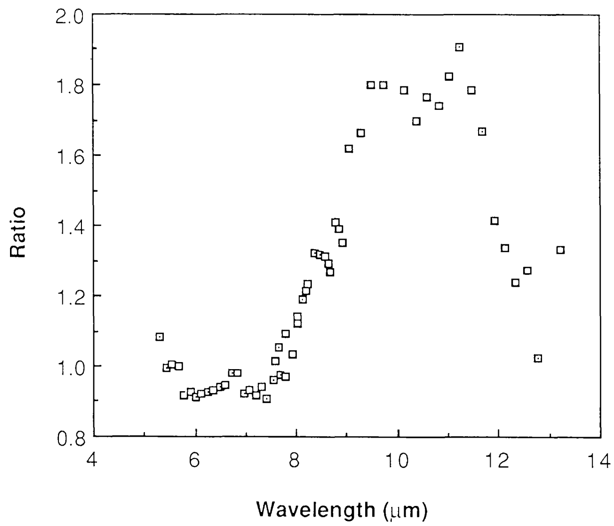

Fig. 4. The ratio of the 1985 December spectrum to a 320 K blackbody normalized to 1.0 at 6 μm. Note the deviations from a blackbody shortward at 5.6 μm and longward of 8 μm, and the return to the blackbody line at 13 μm

than farther out. However, the published IKS results were preliminary and had difficulties with calibration and instrument response variations (T. Encrenaz, private communication). Further analysis of the IKS data may resolve the discrepancy.

3.1. The continuum emission and the temperature of the dust

The shape of the continuum can yield information on the temperature and size distribution of the particles. If the thermal emission was produced by particles of only one size, fits to single blackbody curves would characterize the temperature of the particles. However, particles of a broad range of sizes are responsible for the thermal emission. At the shorter wavelengths, such as the 5 to 8 μm region, the emission will be dominated by small particles (small particles will be warmer than large ones) while at longer wavelengths, the larger grains will contribute most of the flux. For this reason, the color temperatures obtained from fits at shorter wavelengths are higher than those obtained from fits at the longer wavelengths. Hence, modeling of the thermal emission yields information on the sizes of the particles which contribute most of the light in this spectral region. We have not modeled the particle size distribution in this paper, but just taken a single blackbody that reasonably fits the 5.6–8 μm range. This wavelength range is short enough to be approximated with a single temperature. The excess above a blackbody shortward of 5.5 μm rises sharply, and may not be explained by emission from a population of small hot dust grains.

The presence of a 10 μm emission feature implies that particles small compared to the wavelength (radius less than about 1 μm) dominate the emission from 8–13 μm. Large particles become optically thick at wavelengths outside the emission features, so if large particles dominated, the spectrum would be a featureless blackbody. Thus, the presence of such a strong feature implies the dominance of small particles. The temperatures measured from the 5–8 μm continuum on the nucleus and in the vicinity of the nucleus are all higher than the equilibrium blackbody temperature expected for large particles ($r > 1$ μm), indicating that small dust particles ($r < 1$ μm) are also dominant at these wavelengths. Note that the color temperature is not a good measure of the dust temperature. The Table shows that on all three dates, the nuclear temperature was the same, while on 1986, April 8 the sunward and tailward temperatures were significantly higher. It is difficult to see how the nuclear temperatures on the two dates could be the same while the dust temperatures 20″ (6600 km) from the nucleus differ by 10–15 K unless there was an ejection of small particles from the nucleus a few hours before the observations of April 8. An increase of 10–15 K requires a decrease of the dominant particle size by about 20%. There was an outburst observed from the nucleus on April 8 that might have provided the increased abundance of small particles. The outburst was also observed in the IR brightness, as the flux from the comet was twice as bright on the 8th as on the 10th. Also, the silicate emission was 80% higher than the 5–8 μm continuum on the 8th as compared to 40% higher on the 10th. This variation of the

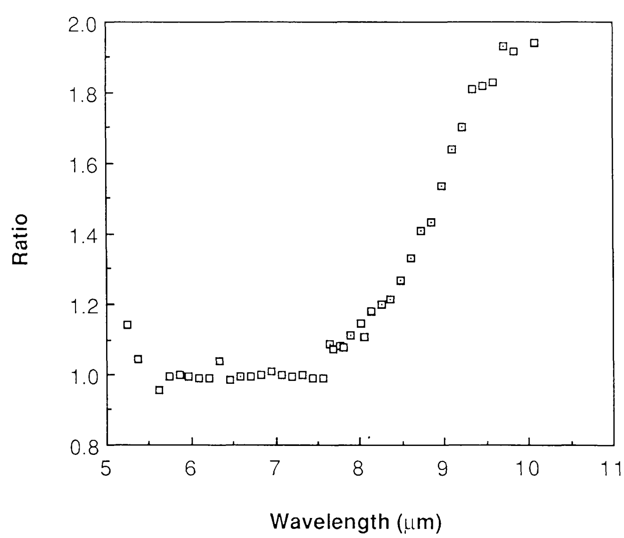

Fig. 5. The ratio of the 1986 April 8.6 data divided by a 325 K blackbody normalized to 1.0 at 6 μm

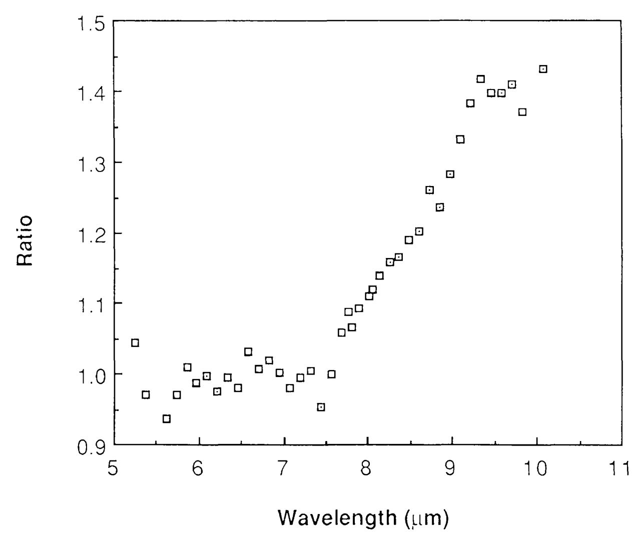

Fig. 6. The ratio of the 1986 April 10.5 data divided by a 325 K blackbody normalized to 1.0 at 6 μm

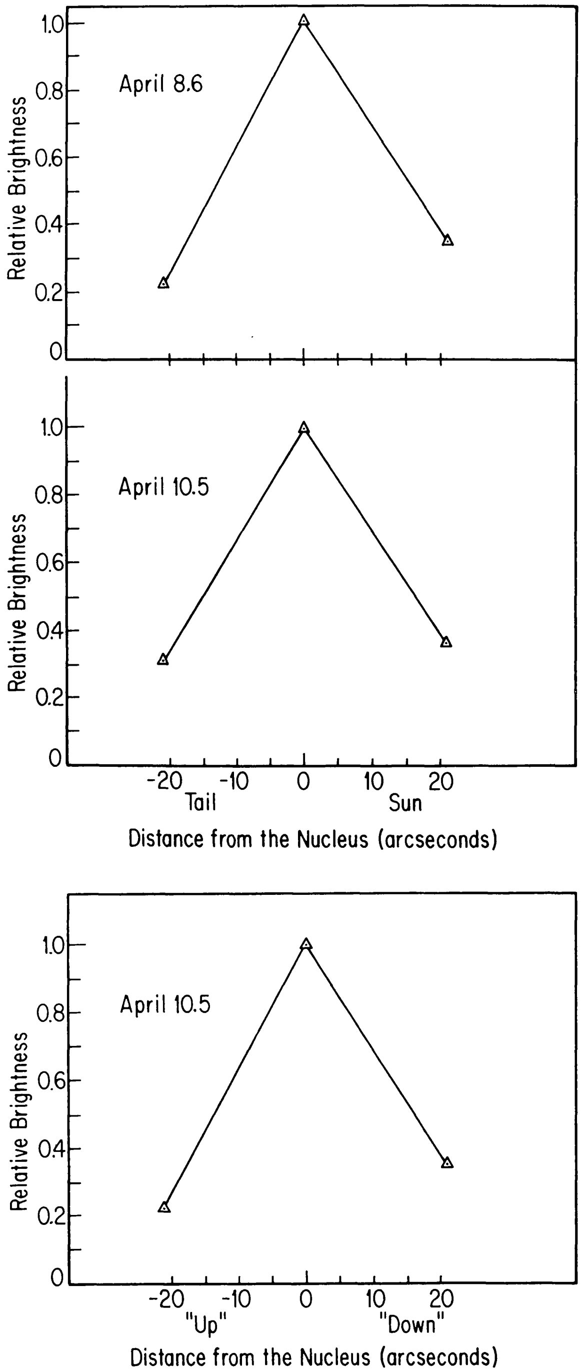

Fig. 7. Comparison of the brightness of the coma at various positions. Note the increased brightness in the sunward direction relative to the anti-sunward direction

strength of the silicate feature suggests that there are two components to the dust, the silicates producing the 10 μm emission and a featureless component (such as graphite or amorphous carbon) producing the continuum from 5–8 μm. Large silicate particles are ruled out as the source of the continuum since the continuum temperature is higher than the equilibrium blackbody temperature (and because the 10 μm silicate feature is so prominent). The timescale for observing variability in the dust emission is hours since it only takes about 9 hours for a dust particle to travel half a beam diameter (3300 km) at a velocity of 0.1 km s^{-1}. These observations also imply that the small particles move away from the nucleus faster than the large particles, which is expected if they are all ejected from the nucleus with either the same force or the same pressure.

Figure 7 shows the relative intensities measured in the 5.5–8 μm region of different positions in the coma measured on April 8 and 10. The sunward fluxes on both days are brighter than the tailward fluxes. The asymmetry is greater on the 8th than the 10th which is when the comet was brightest, in agreement with spacecraft and groundbased observations. Measurements made above ("up") and below ("down") the nucleus on April 10 also show an asymmetry. These observations indicate that most of the dust ejection occurs on the sunward side of the nucleus.

3.2. *Emission features*

In Fig. 8 we show a fit to the silicate emission by using a sample of interplanetary dust particle (IDP) spectra. The IDP spectra have been reproduced by using the data of Sandford and Walker (1985). The fit is quite good, and consists of a mixture of the three different mineral classes of IDP's observed, olivines, pyroxenes, and layer lattice silicates. A reasonable fit requires including either pyroxenes or layer lattice silicates (but not necessarily both) combined with olivines. Olivines are essential for fitting the peak at 11.2 μm. The presence of structure in the data means that the silicates are crystalline, unlike the generally featureless silicates observed in the interstellar medium and around stars.

The 5–8 μm spectral results are surprising for their paucity of emission features. There is a small emission feature centered at 6.8 μm, which is strongest in the December data, that can be attributed either to the C—H deformation mode in organic compounds (see below), or emission from carbonates. Carbonates comprise about 1% of IDP's, and the observed 6.8 μm feature is

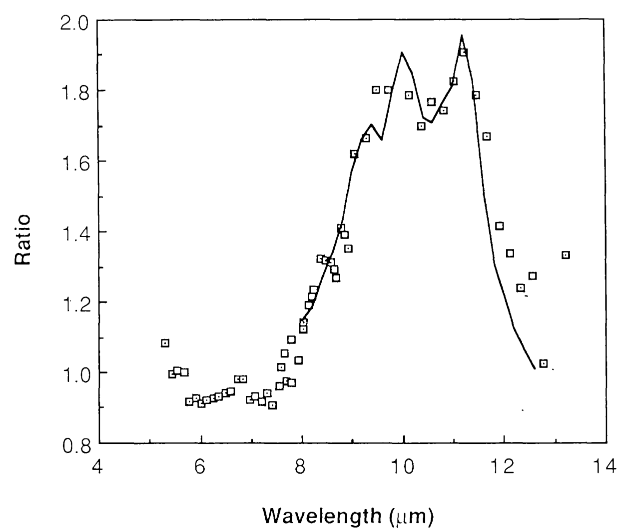

Fig. 8. The 1985 December data compared to a spectrum (the solid line) generated by combining spectra from a variety of interplanetary dust particles (Sandford and Walker, 1985). The dominant component is olivine, with some pyroxenes and a small amount of layer lattice silicate. The small feature at 6.8 μm could be due to carbonates associated with the layer lattice component in interplanetary dust particles or to simple saturated aliphatic hydrocarbons

about the same strength relative to the 10 μm silicate emission as it would be in a mixture of IDP's.

The strongest band observed in the 3–4 μm region is at 3.4 μm, which is due to simple saturated aliphatic hydrocarbons such as alkanes or alcohols. Either of these classes is allowed since their corresponding CH deformation modes near 6.8 μm are relatively weaker, and could in fact account for the weak emission observed at 6.8 μm. While the position of the 3.54 μm band is suggestive of aldehydes, it may well be a higher transition in the molecules responsible for the 3.4 μm peak, and is observed at 3.54 μm due to the anharmonic term in the energy levels. Since this implies a considerable amount of excitation energy per vibrational mode. it implies that molecular sized species are responsible (Barker, et al., 1987).

An intriguing result is the lack of other features in the 5.5–8 μm region, especially in light of the observed hydrocarbon emission features near 3.4 μm (Combes et al., 1986; Baas et al., 1986). Our results also place strong constraints on the types of hydrocarbons responsible for the 3.4 μm emission by eliminating classes of molecules. The spectrum of comet Halley obtained by Baas et al. (1986) shows a strong band at 3.34 μm. Two weaker bands at 3.28 and 3.54 μm may also be present. A 3.28 μm emission feature is observed in many interstellar nebulae and is generally attributed to IR fluorescence from PAH's (Leger and Puget, 1984; Allamandola et al., 1985). However, if aromatics were present, there should be corresponding bands at 6.2 and 7.7 μm; both of these are absent at levels well below what is expected, ruling out aromatics similar to the PAH's observed in interstellar nebulae as the origin of the 3.28 μm band. In a similar fashion we can rule out the presence of molecules such as aldehydes and ketones as these would have a strong carbonyl feature in the 5.5–5.9 μm range. Olefinic groups, which could account for the 3.28 μm band, cannot be ruled out since their corresponding CH deformation modes, which fall in the 10 μm region, would not be evident above the strong silicate emission. Gas phase formaldehyde is possible since its 5.8 μm band would be about the same strength as the ones at 3.54 μm and 3.60 μm. Bands at 3.54 and 3.60 μm may have been observed by the IKS spectrometer (Combes et al., 1986). Associated formaldehyde or formaldehyde mixed in an ice is not possible as these two bands shift to shorter wavelengths (van der Zwet et al., 1985). In general, large molecules of these types are ruled out since they would show the strong carbonyl (C=O) band in the 5–8 μm region.

4. Summary

Spectrophotometry of comet Halley was obtained from 5–13 μm in December, 1985 and twice from 5–10 μm in April, 1986. The results show that:

1. A strong silicate emission band extending from 8–13 μm which varies in strength relative to the 5–8 μm continuum, suggests that there are at least two physically separate dust components.
2. The infrared brightness towards the sun is higher than in the anti-sun direction, consistent with the dust ejection from the nucleus being predominantly in the sunward direction.
3. There is a weak emission feature at 6.8 μm which could be due either to carbonates or the C—H deformation mode in saturated aliphatic hydrocarbons. The only organic molecules that could simultaneously account for the 3.4 μm emission band observed by other authors and our data are alkanes and alcohols. The lack of other emission features in the 5–8 μm wavelength region also rules out significant amounts of free aromatic molecules.
4. The strong emission feature reported by Combes et al. (1986) at 7.5 μm is not present in any of our data. Either the species responsible for the feature is confined to the inner coma observed by the IKS instrument, or the preliminary calibration of the IKS data is not correct and subsequent recalibration will resolve the discrepancy.
5. The 8–13 μm silicate emission band shows two peaks, indicating that the silicates are crystalline. A good fit to the spectrum can be made by using a mixture of interplanetary dust particle spectra. Olivines are required to fit the 11.2 μm peak, while either layer lattice silicates or pyroxenes could account for the remaining emission.

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Note added in proof: Further reduction of the *IKS* Vega data had resulted in a new spectrum that agrees with our data, showing no 7 μm emission, but instead a doubly peaked silicate emission (Encrenaz, private communication).