Thermal Infrared Spectra of Comet Hale-Bopp at Heliocentric Distances of 4 and 2.9 AU.

John K. Davies and Thomas R. Geballe
Joint Astronomy Centre
660 N A'Ohoku Pl, Hilo, HI, USA

Martha S. Hanner
Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena,California, USA

H. A. Weaver
Department of Physics and Astronomy
Johns Hopkins University, Baltimore, Maryland, USA

Jacques Crovisier and Dominique Bockelée-Morvan
Observatoire de Paris-Meudon
F-92195 Meudon, France

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Abstract.
We present 10 and 20μm spectra of Comet Hale-Bopp taken at UKIRT on 1996 June 20 and 1996 September 29. The 10μm spectra clearly show a strong silicate feature with peaks at 10.0 and 11.2μm. The 20μm spectrum on September 29 has strong excess flux relative to a blackbody and a peak near 19μm, in good agreement with the ISO SWS spectra obtained a week later. However, the 20μm spectrum on June 20 has significantly lower flux than would be expected based on a blackbody extrapolation from the flux at 12.5μm.

Key words: comet, infrared, dust, silicates

1. Introduction

Emission features in the 10μm region have been seen in a number of comets, including long period comets Bradfield 1987 XXIX (Hanner et al. 1990) and Levy 1990 XX (Lynch et al. 1992), new comet Mueller 1994 I (Hanner et al. 1994a), and P/Halley (Bregman et al. 1987, Campins & Ryan 1989). These four comets display a feature at 11.2μm which has been attributed to crystalline olivine. Yet some other new and long period comets do not show the 11.2μm peak (Hanner et al. 1994b). Short-period comets, such as P/Faye and P/Borrelly have broader, weaker 10μm emission excess (Hanner et al. 1996). The presence of crystalline olivine is surprising since it is formed at high temperatures and it is not common in the interstellar medium. It is also puzzling that not all comets show the olivine peak.

We observed comet Hale-Bopp at 10μm, and in the 20μm region where silicates have other spectral features, when it was at heliocentric distances of 4 and 2.9 AU. Observations closer to perihelion were precluded by the pointing constraints of UKIRT; extensive 10μm spectra closer to perihelion have been obtained elsewhere (Wooden et al. 1998; Hayward & Hanner 1997; Hanner et al. 1998; Williams et al. 1997).

2. Observations and Data Reduction

The observations were carried out with the UKIRT low resolution ($\lambda/\delta\lambda$ = 40-80) spectrometer CGS3 which has a linear array of 32 Si:As photoconductive detectors for spectrophotometry in the 10 and 20μm bands. An aperture of 5.5 arcsec (Full Width at 10% Max) was used for all the observations. Each spectrum in the 10μm region was triple sampled, and each in the 20μm region double sampled, by making small movements of the CGS3 grating to record individual sub-spectra with slightly different central wavelengths which were interleaved during the data processing. Wavelength calibration was by means of a Krypton lamp on the CGS3 platform. The observational circumstances are described in Table 1. Some details of CGS3 and its performance can be found in Cohen and Davies (1995).

TABLE I
UKIRT Observations

UT Date (mid-time)	λ Range (μm)	R (AU)	Δ (AU)	Comet Airmass	Standard Star
1996 Jun 20.43	8-13	4.0	3.1	1.21-1.19	BS7525
1996 Jun 20.58	16-24	4.0	3.1	1.38-1.55	BS337
1996 Sep 29.21	8-13	2.9	3.0	1.21-1.23	BS6406
1996 Sep 29.26	16-24	2.9	3.0	1.40-1.71	BS6406

Data reduction was performed using the Starlink package Figaro. The comet spectra were divided by the spectrum of a standard star observed at similar airmass and were then multiplied by a blackbody typical of the effective temperature of the standard star. Flux calibration was done assuming the following magnitudes for the standards, BS7525; N=-0.78, BS337;Q=-2.09, BS6406; N=-3.94, Q=-4.17. In the case of the 10μm spectra it is well known (eg. Cohen and Davies 1995) that late type stars have a broad SiO absorption entending longward of 7.55μm and that ratioing by such stars for the purposes of calibration and the removal of atmospheric lines leads to spurious spectral slopes in the short end of the 10μm window. To correct for the effect of the SiO absorption, the spectra of the standards used were ratioed with stars known to be featureless in the 10μm region that had been observed on the same nights at matching airmasses. The stars used were BS6556 (A5V) and BS7001 (A0V) for the two dates respectively.

3. Discussion

The 10μm spectra on both dates clearly show the presence of the silicate emission feature. In order to investigate the shape of the feature we fitted a blackbody at a suitable temperature (180K and 200K for 20 June and 29 September respectively) to the data in the 12-13μm region and then subtracted this blackbody from each spectrum. We note that while this approach of fitting a blackbody is commonly used for interpreting cometary spectra, it is relatively crude compared with developing a detailed dust model taking into account contributions from grains with a range of sizes and albedoes which may contribute excess flux in some regions of the spectrum.

The result of the blackbody subtraction from the data of 29 September is shown in Fig. 1. which clearly shows a strong 8-12μm silicate feature. The shape of this feature is similar to that observed in Hale-Bopp over a wide range of heliocentric distances (Crovisier et al. 1997; Hanner et al. 1998), including peaks at 10.0 and 11.2μm, a bump at 11.8-11.9μm and a change in slope near 9.2μm. The region from 9.5-9.8μm is affected by uncertainty in correction for the atmospheric ozone absorption. The observation on 1996 June 20 is of lower signal to noise, but has a shape indistinguishable from that of the 1996 September 29 data.

The combined 10 and 20μm UKIRT spectrum of 1996 September 29 is shown in Fig. 2 together with the flux from a 200K blackbody normalised to fit the comet spectrum in the 12-13μm region. An ISO SWS spectrum taken on 1996 October 6 (Crovisier et al. 1997) is shown for comparison. Although the UKIRT 20μm data are noisy, due to the presence of regions of the spectrum in which transmission is low and over which atmospheric lines are difficult to remove, it is clear that the flux lies considerably above the adopted blackbody continuum throughout the 20μm region. In addition there is a broad emission feature centred at about 19μm and a suggestion of a further feature beginning about 21.5μm and rising beyond the point at which the spectrum is cut off by the atmosphere around 23μm. Similar features are seen at much higher signal to noise in the ISO SWS spectrum.

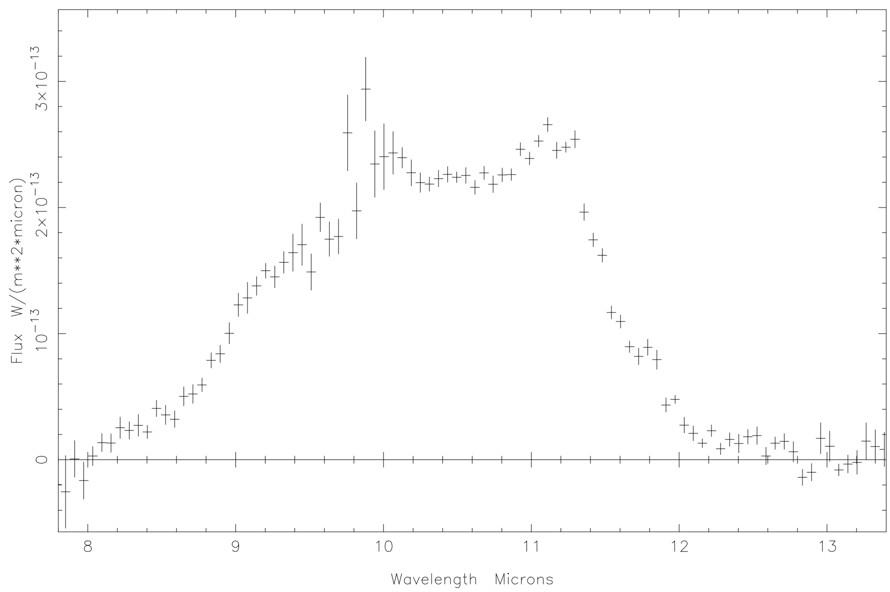

Figure 1. The 10μm emission feature on 29 September 1996.

The ISO spectrum presented here is a recalibrated version of that shown by Crovisier et al (1997) which was kindly supplied to us by K. Leech. The ISO instrumental aperture is 14 x 20 arcsec up to 12μm and 14 x 27 arcsec from 12-29μm. The ISO data longward of 12μm were first normalised to that at the shorter wavelengths by assuming the dust emission flux scales proportionally to the aperture, as expected for a 1/r dust density distribution where r is the cometocentric distance. This spectrum was then multiplied by 0.34 to facilitate the comparison of the UKIRT and ISO data. Note that, assuming a 1/r distribution, this factor is close to the correction that would be expected from adjusting the 5.5 arcsec diameter circular UKIRT aperture to the rectangular ISO SWS aperture and shows that the ISO and UKIRT data are in good agreement.

The combined spectrum from June 20th is shown as Fig. 3 along with its adopted black body fit at 180K. Although the signal to noise is worse than for the September data, particularly in the 20μm region, the 20μm flux lies considerably below the expected continuum fit at 12-13μm. We have checked the flux calibration of these data carefully

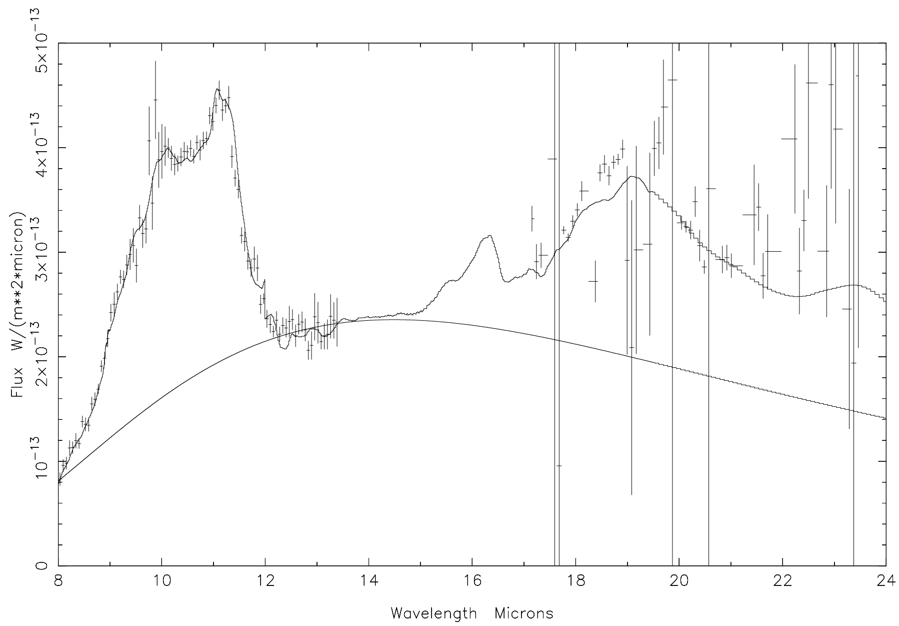

Figure 2. The UKIRT 10 and 20μm spectrum on 29 September 1996 (crosses) plotted over the ISO SWS spectrum taken on October 6th. The ISO spectrum, which has been multiplied by 0.34, shows the agreement in spectral shape between the UKIRT and ISO data. A 200K blackbody fitted to the 12-13μm continuum is also shown. Where data from regions of low transmission have been removed, the errorbars are extended to the left or right to show this.

with respect to 2 standard stars in each wavelength region and believe it to be reliable at better than the 50% level. Thus, errors in the flux calibration of the 20μm data cannot be responsible for the mismatch of the 10 and 20μm fluxes which appear to differ by a factor of at least 5 compared with that expected from the blackbody fit to the 10μm data.

The 20μm spectrum on 20 June does not show any evidence of spectral structure which is surprising in view of the strength of the 10μm feature on this date. The ratio of the flux in the 10μm emission feature to that in the fitted continuum is 2 on both 20 June and 29 September. In contrast to the 17 to 21μm spectrum on 29 September which shows strong evidence for at least one emission feature, the spectrum from 20 June is virtually flat across the entire bandpass. In this respect the 20 June spectra of Hale-Bopp are similar to those of P/Halley when on 1995 December 17 (heliocentric distance 1.2AU) a strong 10μm fea-

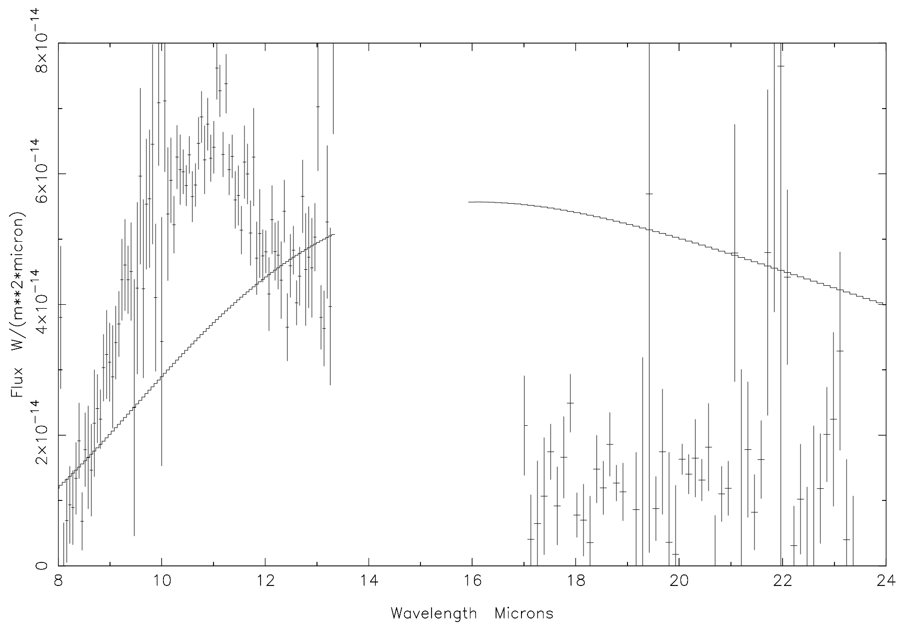

Figure 3. The 10 and 20μm spectrum on 20 June 1996 plus a 180K blackbody fitted to the 12-13μm continuum.

ture was present (Bregman et al 1987) but there was no evidence for spectral features with a value greater than 6% of the continuum in the 20μm region (Glaccum et al. 1987).

The UKIRT observations of Hale-Bopp were made 90 minutes apart and with a circular aperture, so temporal variability or the rotation of jet-like structures is unlikely to be responsible for the different flux levels at 10 and 20μm. We are still considering possible explanations for this behaviour.

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