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The infrared spectrum of comet C/1995 O1 (Hale-Bopp) at 4.6 AU from the Sun*

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Abstract. Comet C/1995 O1 (Hale-Bopp) was observed on 27 April 1996 with the ISOPHOT instrument of ISO when it was at 4.6 AU from the Sun. The 2.5–12 μm spectrum was recorded at low resolution. We present here the preliminary results of this observation. The 2.5–5 μm spectrum shows emission in the CO_2 ν_3 band. The CO_2 production rate is about 1.3×10^{28} s^{-1}. The 6–12 μm spectrum shows thermal emission at a colour temperature of 162 K (6–8 μm range) and a strong silicate band around 10 μm, with a narrow feature at 11.2 μm indicative of crystalline silicates.

Key words: comets: general – comet: individual: C/1995 O1 (Hale-Bopp) – infrared: solar system

1. Introduction

C/1995 O1 (Hale-Bopp) is a long-period comet discovered in July 1995 when it was at 7 AU from the Sun. It was then already very active and about 200 times brighter than comet Halley at the same distance, making it an exceptional comet which is expected to become spectacular when reaching perihelion at 0.91 AU from the Sun in April 1997. We thus have the opportunity to follow the evolution of a *great comet* over a large range of heliocentric distances with modern instrumentation.

Comet Hale-Bopp was selected as a target-of-opportunity comet to be observed with the Infrared Space Observatory (ISO). The ISO mission is described by Kessler et al. (1996). Due to the constraints on solar elongation of ISO, this comet will not be observable when it is less than 2.8 AU from the Sun, but there were two pre-perihelion observing windows, in spring and autumn 1996. We present here the initial results of this program, which yielded the first ISO spectrum of a comet.

It may be noted that another outstanding comet, C/1996 B2 (Hyakutake), which passed close to the Earth at the end of March 1996, unfortunately could not be observed with ISO, due to solar elongation constraints and to its too large proper motion.

2. Observations

The low resolution 2.5–12 μm spectrum of the comet was obtained with ISOPHOT-S on 27.62 April 1996 UT, when it was at r = 4.59 AU from the Sun and 4.28 AU from the Earth. ISOPHOT-S (Lemke et al. 1996) can observe simultaneously the 2.5–5 and 6–12 μm spectral ranges with two 64-element detector arrays. The resolution is approximately 85 in the short-wavelength range and 95 in the long-wavelength range. The field of view is a 24" × 24" square. The integration time of the observation was 4096 s. The sky background was measured in the same conditions on the same sky position on 5 May, after the comet passage. Observations with ISOPHOT filters from 3.6 to 160 μm were also made as part of another program at the same period (Grün et al., in preparation); they will not be discussed here. At the present time, only a preliminary reduction of the data has been performed and the intensity calibration is still provisional. The spectra after background subtraction are shown in Fig. 1 and Fig. 2.

3. Analysis

3.1. The 2.5–5 μm region: molecular bands

The thermal continuum is too low in this spectral domain to be detected. The continuum due to reflected sunlight is barely detected. The only obvious features present in this spectral do-

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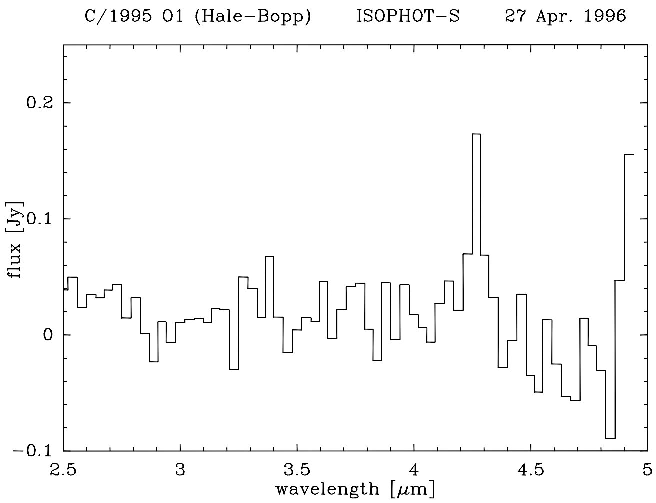

Fig. 1. The 2.5–5 μm spectrum of comet C/1995 O1 (HaleBopp) obtained by ISOPHOT-S on 27 April 1996

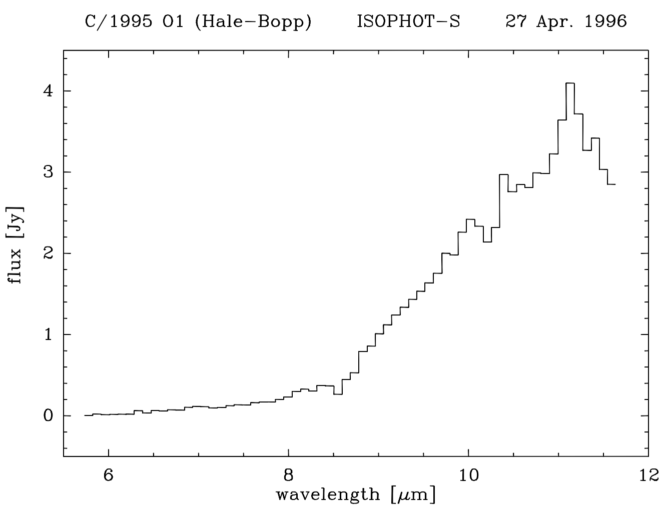

Fig. 2. The 6–12 μm spectrum of comet C/1995 O1 (HaleBopp) obtained by ISOPHOT-S on 27 April 1996

main are emissions at 4.26 μm, corresponding to the CO_2 ν_3 band, and at 4.92 μm, which is probably an artefact and will be discussed below.

The 2.5 to 5 μm spectral region covers most of the fundamental vibrational bands of putative cometary volatiles, resulting from resonant fluorescence excited by solar radiation (Crovisier 1992). Table 1 lists the intensities (or their upper limits) of some of these bands and the corresponding molecular production rates (see Crovisier 1992 for details on their derivations). An expansion velocity of 0.5 km s^{-1} was assumed, as derived from the radio line shapes (e.g. Biver et al. 1996a).

The strong ν_3 band of carbon dioxide is present at 4.26 μm. It is not resolved, which is in agreement with the low resolution of the instrument and the narrow band widths expected for linear molecules (see Crovisier 1987) at the cold temperatures of cometary atmospheres at this distance. Indeed, rotational temperatures of 10–25 K were inferred from the radio lines of CO and CH_3OH in this comet (Biver et al. 1996a, b; Womack et al. 1996). The observed intensity corresponds to a CO_2 production rate of $1.3 \pm 0.2 \times 10^{28}$ molecules s^{-1} (a calibration uncertainty of 50% not being included in the error).

The ν_3 band of CO_2 cannot be observed from the ground due to telluric absorption and this is its first direct detection in a comet from Earth or Earth orbit. The same CO_2 band was previously observed *in situ* in comet P/Halley by Vega/IKS (Combes et al. 1988). The presence of carbon dioxide in cometary atmospheres is also indirectly inferred from the bands of CO_2^+ in the visible, and by the Cameron bands of CO in the UV, which are believed to be partly due to prompt emission of CO following CO_2 photodissociation (Weaver et al. 1994).

The carbon monoxide $v(1-0)$ band at 4.67 μm is not present in our spectrum. CO was one of the first molecules to be detected in this comet, from its rotational lines at radio wavelengths (Jewitt et al. 1996a; Biver et al. 1996a) as far as 6.8 AU from the Sun. In the April–May 1996 period, the CO production rates estimated from these radio observations range from 0.8 to $\simeq 4 \times 10^{28}$ s^{-1} (Womack et al. 1996; Woodney et al. 1996b), in agreement with the upper limit derived from our spectrum (Table 1).

The ν_3 (2.66 μm) and ν_2 (6.27 μm) bands of water are not detected. In contrast to the bands of CO and CO_2, these bands of H_2O are expected to be spectrally resolved and to show up in several pixels, even at low temperature (Bockelée-Morvan 1987). Even though water sublimation was not expected to be important at this distance from the Sun, OH radicals were detected in the UV by the Hubble Space Telescope (Weaver et al. 1996) and at 18-cm wavelength with the Nançay radio telescope (Crovisier et al. 1996), showing that some water sublimation from the nucleus or from icy grains was already taking place. The water production rates depend on model assumptions and on the spatial resolution of the observations since we do not know if water is sublimating from the nucleus or from icy grains. The inferred rates assuming that water is coming from the nucleus range from 1.5×10^{28} s^{-1} (UV, 7 April) to 4.2×10^{28} s^{-1} (radio, 12 April–10 May). The upper limit derived from our spectrum (Table 1) is consistent with such production rates.

The 3.2–3.6 μm emission band, which is a prominent feature of comets closer to the Earth due to methanol and to as yet unidentified species (Bockelée-Morvan et al. 1995), is not detected either. In Table 1, we have listed the upper limit corresponding to the ν_3 band of CH_3OH only. The CH_3OH production rate effectively measured in the radio in April in the comet (Womack et al. 1996) is much smaller (10^{27} s^{-1})

The last bin of the spectrum (at 4.92 μm) is quite bright. An inspection of the individual subspectra of the observation reveals that this intensity was highly variable, suggesting that we are dealing with an instrumental effect. This rules out the possibility of an identification with the ν_3 band of OCS at 4.85 μm, a species already identified in comet C/1996 B2 (Hyakutake) in the radio (Woodney et al. 1996a) and infrared (Mumma et al. 1996) domains. Moreover, a search for OCS at millime-

Table 1. Molecular bands observed in C/1995 O1 (Hale-Bopp) with PHT-S

molecule	band	λ [μm]	flux [W m^{-2}]	g [s^{-1}]	Q [10^{28} s^{-1}]	
H_2O	ν_3	2.66	$< 2.6 \times 10^{-15}$	2.6×10^{-4}	$< 11.$	upper limit
CH_3OH	ν_3	3.52	$< 1.5 \times 10^{-15}$	1.5×10^{-4}	$< 15.$	upper limit
CO_2	ν_3	4.26	$2.1 \pm 0.4 \times 10^{-15}$	2.6×10^{-3}	1.3	
CO	$v(1-0)$	4.67	$< 1.2 \times 10^{-15}$	2.6×10^{-4}	$< 7.$	upper limit

The fluxes are estimated from a preliminary scale (50% accuracy); upper limits are $3-\sigma$;
quoted errors only include noise and not calibration uncertainties;
g = emission rate assuming resonant fluorescence excited by the Sun at 1 AU;
Q = production rate assuming parent molecule distribution with v_{exp} = 0.5 km s^{-1}

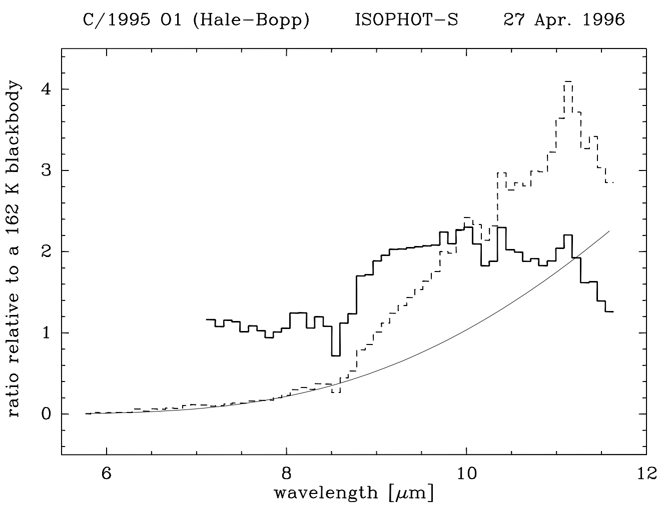

Fig. 3. The 6–12 μm spectrum of comet C/1995 O1 (HaleBopp) observed by ISOPHOT-S on 27 April 1996, divided by a 162 K blackbody (solid line). The dotted line shows the original spectrum and the thin line is the 162 K blackbody

tre wavelengths undertaken at IRAM on 14 June was negative (Biver et al. *private communication*).

The infrared fluorescence rates of cometary molecules vary proportionally to r^{-2}, which strongly penalizes their observations at large heliocentric distances when compared to radio observations of rotational lines which are collisionally excited. The fluorescence rate of the CO_2 ν_3 band is ten times larger than those of CO or H_2O, explaining why CO_2 only was detected.

The ISO observation shows that carbon dioxide is one of the major detected volatiles released by comet Hale-Bopp at more than 4 AU from the Sun, with a production rate which reaches one third of those of water and carbon monoxide. Other species, such as CH_3OH, H_2S, HCN and H_2CO detected at radio wavelengths, were found less abundant (Biver et al. 1996b, Jewitt et al. 1996b, Womack et al. 1996; Woodney et al. 1996b). The production rate ratios of about H_2O:CO:$CO_2 \simeq$ 1:1:0.3 are drastically different from the ratios of the same volatile species released at $r \simeq 1$ AU, where H_2O:CO:$CO_2 \simeq$ 1:0.05:0.03 (Combes et al. 1988; Crovisier 1994). The water production appears to be deficient in comet Hale-Bopp. This difference is not necessarily due to a difference of composition, but rather to an effect of the heliocentric distance on the sublimation processes. The sublimation equilibrium temperatures of CO, CO_2 and H_2O are 24, 72 and 152 K, respectively (Yamamoto 1985). Therefore, important fractionation effects are expected, and are effectively predicted by theoretical models (e.g. Espinasse et al. 1991).

3.2. The 6–12 μm region: thermal emission and dust features

The 6 to 12 μm spectral region shows the thermal emission from the dust coma, with a prominent feature at 11.2 μm (Fig. 2).

The 6 to 8 μm part of the spectrum can be fitted with a 162 K colour temperature. A better determination of the blackbody temperature of the cometary grains will be possible when the results of the ISOPHOT filter observations, which extend from 3.6 to 160 μm, will be available. Our colour temperature is in agreement with an extrapolation, using a $r^{-1/2}$ law, of the colour temperatures of comet P/Halley derived from the 5–8 μm spectra obtained by Tokunaga et al. (1988) over the $r = 0.9 - 1.65$ AU range of heliocentric distances. It is also consistent with the same $r^{-1/2}$ scaling of the 175 K temperature derived by Hanner & Hayward (1996) from a 8–13 μm spectrum obtained on 11 June 1996 on comet Hale-Bopp at $r = 4.13$ AU. A temperature above the equilibrium blackbody temperature ($\simeq$ 130 K at 4.6 AU) is expected from micrometre-sized absorbing grains, because these small grains do not radiate effectively near the peak of the Planck function.

Fig. 3 shows the 7–12 μm spectrum of the comet divided by the 162 K blackbody spectrum. A strong excess emission is visible from about 8 μm to the longward limit of the spectrum. This is the well-known 10 μm silicate band, which has a contrast of a factor two with respect to the assumed continuum of comet Hale-Bopp. The long-wavelength limit of the spectrum prevents us to have a full knowledge of the band shape. The sharp feature at 11.2 μm is conspicuous in both the original and the ratioed spectrum. This feature was first discovered in P/Halley (Bregman et al. 1987). It was thereafter observed in several other comets, all being long-period (Hanner et al. 1994a). However, it was also recently found in the dynamically new comet Mueller 1994 I (Hanner et al. 1994b).

This 11.2 μm feature has traditionally been interpreted as due to the presence of crystalline olivine grains (Bregman et al. 1987). The absence of any emission features at 6.2, 7.7 and 8.6 μm rules out PAH's as candidates for the 11.2 μm emission. Laboratory measurements by Colangeli et al. (1995) show that olivine bearing submicrometric grains exhibit main infrared bands between 11.2 and 11.3 μm, the exact location depending upon the composition. Olivine also shows structure near 10.5 μm similar to the comet spectrum (Koike et al. 1993). Bradley et al. (1992) have shown that two interplanetary dust particles dominated by glass and submicrometric silicate crystals offer a reasonable match to the cometary band.

4. Conclusion

The spectrum of comet Hale-Bopp observed by ISO at 4.6 AU from the Sun is the first mid-infrared spectrum of a comet at such a large heliocentric distance. A strong outgassing of carbon dioxide was observed, which reveals that this species is, together with carbon monoxide and water, a major volatile which sublimates from cometary ices and drives cometary activity at large heliocentric distances. This contrasts with cometary activity close to the Sun, which is dominated by water sublimation with much less release of CO and CO_2, as observed for instance in P/Halley (Combes et al. 1988).

The long-wavelength part of the spectrum indicates a colour temperature equal to that extrapolated from P/Halley's measurements. It shows a strong silicate band of a shape similar to that observed in that comet, with the 11.2 μm feature characteristic of crystalline olivine. Thus, there is no indication of differences of physical properties or composition for grains in comets Hale-Bopp and Halley.

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