The Thermal Infrared Spectra of Comets Hale-Bopp and 103P/Hartley 2 Observed with the Infrared Space Observatory

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Abstract. The Infrared Space Observatory (ISO) offered us the opportunity to observe celestial bodies from 2.4 to 196 μm, which is of particular interest for comets. We present here spectroscopic observations with ISO of comets C/1995 O1 (Hale-Bopp) and 103P/Hartley 2. The thermal infrared region of the spectra shows specifically the signatures of crystalline, Mg-rich olivine (forsterite), but also signs of the presence of crystalline pyroxenes and amorphous silicates, as well as continuum-like emission. A quantitative evaluation of the contributions of these various components is given for comet Hale-Bopp.
Keywords. Comets – Comet C/1995 O1 (Hale-Bopp) – Comet 103P/Hartley 2 – Infrared Space Observatory – Cometary dust – Silicates

1. Introduction

The Infrared Space Observatory (ISO) offered us the opportunity to observe celestial bodies over the full infrared range from 2.4 to 196 μm. This spectral domain is of particular interest for comets. Cometary parent molecules, likely to have sublimated from the nucleus ices, can be investigated through their fundamental bands of vibration in the 2.5–12 μm region. With typical temperatures of a few 100 K when within several AU from the Sun, cometary grains show ther-

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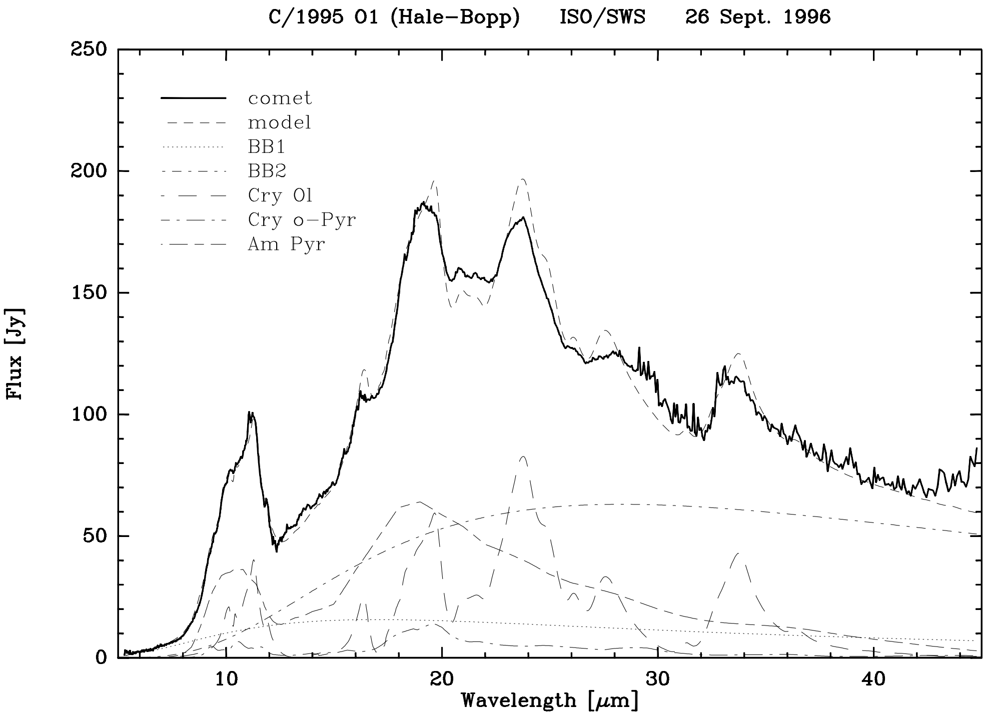

Figure 1. C/1995 O1 (Hale-Bopp) on 26 September 1996 at r_h = 2.9 AU. The 6 to 45 μm region of the SWS spectrum is represented here degraded to a resolution $\lambda/\delta\lambda = 500$ (full dark line). The instrument apertures range from 14" × 20" (short wavelengths) to 20" × 33" (long wavelengths). The intensity scale has been normalized to a 14" × 20" aperture assuming a $1/\rho$ brightness distribution law and slight scale adjustments have been applied to make the spectrum continuous. As explained in Section 3, the observed spectrum has been decomposed into several emission components: blackbody 1 and 2, forsterite, orthopyroxene and amorphous silicates, with the temperatures and relative abundances listed in Table 1.

mal emission in the mid-infrared (5–200 μm), where spectral features indicative of composition may be expected.

We present here ISO observations of two comets (C/1995 O1 (Hale-Bopp) and 103P/Hartley 2) and the analysis of their spectra, in order to constrain the nature of cometary dust.

2. Observations

We report here on spectroscopic observations of comets which were conducted with ISO by an international team of investigators. Other programmes by other teams were aimed at photometric and imaging observations, in order to study

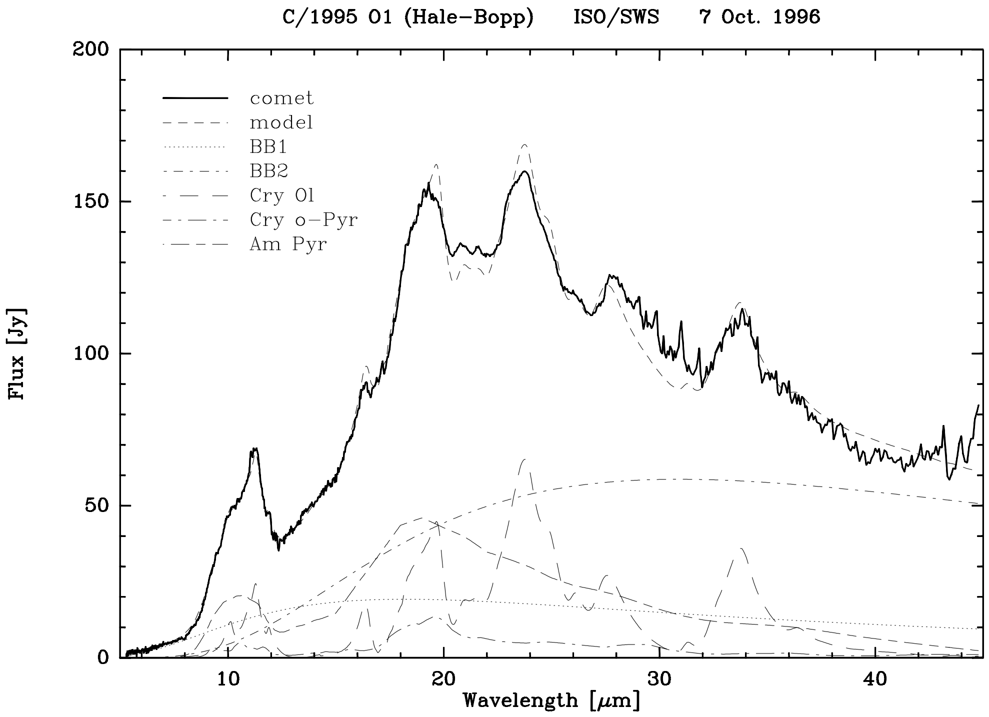

Figure 2. C/1995 O1 (Hale-Bopp) on 7 October 1996 at $r_h = 2.8$ AU. (Same description as for Fig. 1.)

cometary dust in the coma, the tails and the trails, and to try to disentangle the emission of the comet nuclei from that of the dust.

Our observations were undertaken under two programmes. The first one, a guaranteed time programme, had to be planned in advance. It was thus aimed at short-period, predictable comets. The nominal target, 22P/Kopff, was weaker than expected and could not be observed at the moment it was the brightest. Fortunately, it was possible to observe a second short-period comet, 103P/Hartley 2, during the extended lifetime of ISO, in January 1998 when the comet was at its brightest near perihelion (Crovisier et al. 1999b). The second programme, an open-time target-of-opportunity programme, was aimed at any bright comet which might appear during ISO's lifetime. We were lucky to benefit from the apparition of C/1995 O1 (Hale-Bopp), a comet of exceptional brightness. Unfortunately, because of the visibility constraints of ISO, the comet could only be observed when it was at $r_h > 2.8$ AU from the Sun. Observations were secured pre-perihelion in April 1996 ($r_h = 4.6$ AU) and September–October 1996 ($r_h = 2.8$ AU) and post-perihelion in December 1997 ($r_h = 3.9$ AU) and April 1998 ($r_h = 4.9$ AU) (Crovisier et al. 1996, 1997a, 1997b, 1999a, Lellouch et al. 1998).

The observations of gas-phase species will not be discussed in detail here: H_2O, CO_2 and CO were detected; their production rates were determined as a function of heliocentric distance; physical parameters for cometary water (rota-

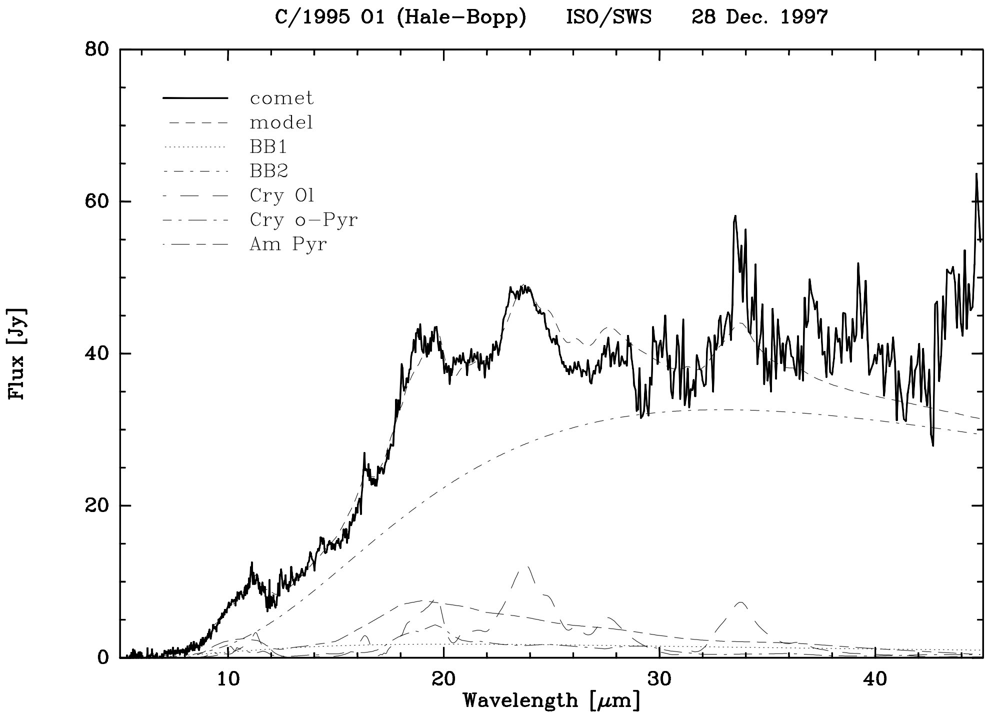

Figure 3. C/1995 O1 (Hale-Bopp) on 28 December 1997 at r_h = 3.9 AU. (Same description as for Fig. 1.)

tional and spin temperatures) were studied (Crovisier et al. 1996, 1997a, 1997b, 1999a, 1999b).

2.1. Results on comet Hale-Bopp

For the four observing periods of comet Hale-Bopp, low-resolution spectra from 2.5 to 12 μm were obtained with the grating spectrometer of the ISO photometer (PHT-S). All spectra show a strong silicate band at 10 μm with a peak at 11.3 μm indicating the presence of crystalline olivine. This constituent is observed to be present whatever the heliocentric distance (4.9 to 2.8 AU), both pre- and post-perihelion.

In September–October 1996 and December 1997, high signal-to-noise ratio spectra of the comet were obtained with the short- and long-wavelength spectrometers of ISO (SWS and LWS, respectively). The SWS spectra presented and analyzed here (Figs 1, 2 and 3) result from a new reduction from OLP (Off-Line Processing pipe-line) v7.0 using ISAP (ISO Spectroscopic Analysis Package). They are not to be considered as the final reduction, however. A detailed account of these observations and of their reduction will be presented elsewhere. Beyond 6 μm, the spectrum of comet Hale-Bopp is dominated by dust thermal continuum emission, upon which broad emission features are superimposed, the strongest appearing at 10, 19.5, 23.5 and 33.5 μm. The wavelengths of all these peaks correspond to those of Mg-rich crystalline olivine (namely forsterite,

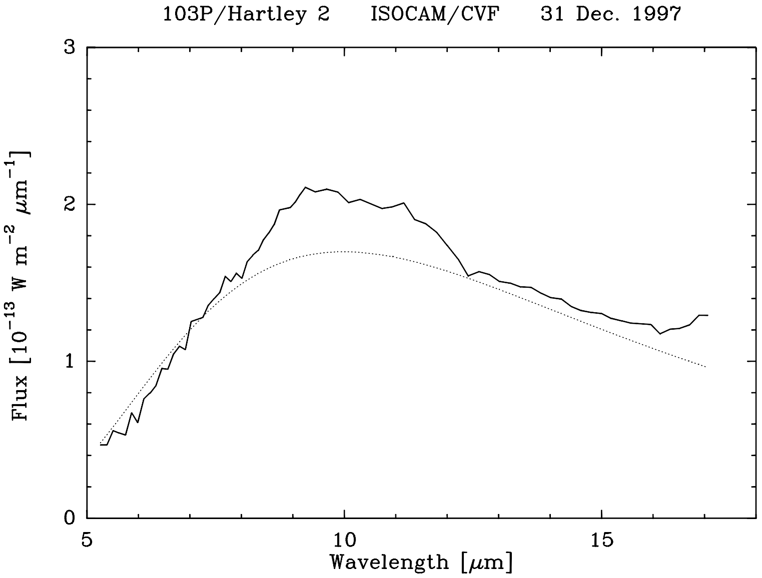

Figure 4. 103P/Hartley 2 on 31 December 1997 at r_h = 1.04 AU. This spectrum (full line), obtained with the CVF of ISOCAM, corresponds to a 24" × 24" field of view and has a spectral resolution $\lambda/\delta\lambda \approx 41$. The dotted line is a blackbody at 290 K.

Mg_2SiO_4) (Crovisier et al. 1997a, 1997b, 1999a; Malfait et al. 1998). It is remarkable that the spectrum of comet Hale-Bopp in this spectral domain closely resembles that of the dust discs around some young stars (such as that of HD 100546, an intermediate star between Vega-like objects and Herbig Ae-Be stars) which were also observed by ISO (Waelkens et al. 1996; Malfait et al. 1998). Thus, the dust contained in such discs appears to be similar to cometary dust. This contrasts with interstellar silicates, which are primarily amorphous.

In the September–October 1996 spectra, emission features at 44 and 65 μm and possible absorption at 2.9–3.2 μm were detected, characteristic of crystalline water ice (Lellouch et al. 1998). A temperature of 153 K was inferred for this water ice. This shows that grains of water ice were still present at a distance of 2.9 AU from the Sun, which could be a significant source of water release within the coma.

No sign of polycyclic aromatic hydrocarbons (PAHs), common in the interstellar medium, could be found in the ISO spectra of comet Hale-Bopp, especially in the 6-9 μm region, where they are expected to have strong bands not blended with silicate features (such features are conspicuous in, e.g., the ISO/SWS spectrum of HD 100546; Malfait et al. 1998). One cannot exclude that cometary PAHs could be present in the gas phase at smaller heliocentric distances than those of the present ISO observations, because of specific r_h-dependent release and excitation mechanisms. Indeed, emission at 3.28 μm, characteristic of aromatics, has been observed in several comets (Bockelée-Morvan et al. 1995). However, no such feature was reported from ground-based observations of comet Hale-Bopp at small r_h.

2.2. Results on comet P/Hartley 2

Whereas Hale-Bopp is a long-period comet presumably coming from the Oort cloud, 103P/Hartley 2 is a Jupiter-family comet believed to originate from the Edgeworth-Kuiper belt. It was observed in December 1997–January 1998 at $r_h \approx 1$ AU. A 6-17 μm low-resolution spectrum obtained with the CVF of ISOCAM shows a weak 10 μm silicate band with an intensity only 20% of the continuum (Crovisier et al. 1999b; a new reduction is presented in Fig. 4). The presence of a peak at 11.3 μm and the shape of the band (a broad flat top from 9.5 to 11.2 μm and then a steep decline beyond 11.3 μm) suggest the presence of crystalline silicates.

The 2.5–11.6 μm spectrum of P/Hartley 2 was also observed at the same period with PHT-S by Colangeli et al. (1999b); the silicate band could not be detected, presumably because of its small contrast over continuum emission, of the restricted spectral coverage, and of the limited signal-to-noise ratio.

3. Analysis

We have analysed the ISO spectra of comet Hale-Bopp in terms of sums of emission spectra of various components (Figs 1–3 and Table 1):

- Blackbody emission. A single blackbody was found to be insufficient to fit the data. We used two blackbodies ($BB1$ and $BB2$) to fit both the short- and long-wavelength parts of the spectrum. The blackbodies represent approximations to the emission from material that is spectrally featureless, or in large grains where spectral features are muted.

- Mg-rich crystalline olivine ("Cry Ol"). We used a transmission spectrum of forsterite from L. d'Hendecourt and X.-F. Thi (Institut d'Astrophysique Spatiale). Since this spectrum was not calibrated, we scaled it to the mass absorption coefficients of small ($a \approx 0.5$ μm) forsterite particles obtained by Koike et al. (1993).

- Crystalline ortho-pyroxene ("Cry o-Pyr"). Mass absorption coefficients of small particles were obtained from laboratory data of Koike et al. (1993). This species is found to fit a little better than clino-pyroxene.

- Amorphous silicates ("Am Pyr"). Mass absorption coefficients of sub-micrometre sized particles of amorphous pyroxene (bronzite) were obtained from laboratory data of Dorschner et al. (1995). It was difficult to distinguish between amorphous pyroxene and amorphous olivine; the former fits a little better near 20 μm, but this is probably not significant[1].

Mass absorption coefficients for the silicate particles were multiplied by a Planck function with $T = T_{sil.}$. This gives a reasonable approximation to silicate

[1] Analyses of ground-based spectra of comet Hale-Bopp by Hanner et al. (1999) and Wooden et al. (1999) include amorphous pyroxene, to fit a distinct shoulder at 9.3 μm, and amorphous olivine, which contributes to the 10 μm maximum.

emission features, provided they are due to small ($\approx$ sub-micrometre) particles. A single temperature for all of the silicates was assumed. This point is discussed further below. The derived parameters are the blackbody temperature(s), the silicate temperature, and the relative abundances of the small silicate grains by mass. Clearly this is an oversimplification of the emission by a size distribution of comet grains of mixed composition, but it is intended only to give a first order estimate of the silicate grain composition.

Table 1. Fitted parameters to the spectra of C/1995 O1 (Hale-Bopp).

Comet	r_h	T_{BB1}	T_{BB2}	$T_{sil.}$	relative abundances		
UT date	[AU]	[K]	[K]	[K]	Cry Ol	Cry o-Pyr	Am Pyr
26.6 Sep. 1996	2.9	300	180	230	0.22	0.06	0.72
7.1 Oct. 1996	2.8	280	165	210	0.22	0.08	0.70
28.1 Dec. 1997	3.9	250	155	190	0.22	0.14	0.64

See Section 3 for details.

The fitted temperatures and relative abundances of the species are listed in Table 1. Rough uncertainties on the temperatures are formally 5–10 K for the blackbodies, 20–30 K for the silicates (but the temperature differences between the September 26 and October 7 spectra, taken at about the same r_h, suggest that the true errors may be larger). The relative abundances have an error around 0.03–0.05. All of the silicates are assumed to have the same temperature; the uncertainties would be higher if their temperatures were allowed to vary. All the temperatures are higher than $270\,r_h^{-0.5}$ K, the temperature of a perfect blackbody at r_h from the Sun.

This analysis is based upon laboratory extinction data. It should be valid as long as the particles are small. The good agreement of the line shapes with the synthetic spectra (Figs 1–3) suggests that this is true. There is no significant difference between the spectra measured on 26 September and 7 October 1996 (except that the signal was stronger for the former spectrum). The 28 December 1997 spectrum shows similar relative abundances for silicates (within uncertainties), but the temperatures are cooler (as could be expected from the larger r_h) and the silicates/continuum ratio is smaller.

A large fraction of cometary dust only shows up as continuum emission and escapes characterisation. This material might be related to CHON particles such as those observed *in situ* in comet Halley. It must be noted, however, that the model of Li & Greenberg (1998), which does include organic refractories in addition to silicates, predicts a prominent emission feature at 7 μm that is not present in the ISO spectra.

A similar study on the spectrum of 7 October 1996 was performed by Brucato et al. (1999) (see also Colangeli et al. 1999a), using their own laboratory spectra of silicates. They also used an amorphous carbon component instead of a second blackbody component. In contrast to our analysis, they find more crystalline than amorphous silicates. This might be due to differences in the samples used to obtain the laboratory spectra.

Wooden et al. (1999) performed another analysis of this ISO spectrum, complemented by ground-based spectra of the 10 μm region obtained at smaller heliocentric distances. They derived a large abundance of crystalline pyroxene relative to olivine and a high crystalline/amorphous ratio for silicates. This comes from the cool temperature of pyroxene they derived (126 K, relative to 210 K for olivine at 2.9 AU). From the present analysis of the ISO spectra, we cannot tell whether the crystalline pyroxenes are that much cooler or not.

4. Conclusion

We presented ISO observations in the thermal infrared region of comets C/1995 O1 (Hale-Bopp) (6–45 μm) and 103P/Hartley 2 (5–17 μm). Crystalline silicates — and more specifically forsterite — were definitely identified in comet Hale-Bopp. The crystalline/amorphous ratio of silicates is around 40% by mass. Silicates (with a possible crystalline component) are also observed in P/Hartley 2, but their contribution is much smaller: only 20% of the continuum around 10 μm, to be compared to 200% in the spectrum of comet Hale-Bopp. It is interesting to note that the *dust-to-gas ratio*, as traced by the $Af\rho/Q$[CN] indicator, was an order of magnitude smaller in P/Hartley 2 (A'Hearn et al. 1995) than in comet Hale-Bopp (Schleicher et al. 1997) at the relevant r_h's. Comets with low dus-to-gast ratios present the general trend to have weak 10-μm features (Hanner et al. 1994; Bockelée-Morvan et al. 1995). According to Lisse et al. (1999), this reflects the fact that "dust-poor" comets are richer in large dust particles; hence their lower feature-to-continuum contrast.

The ISO observations — complemented by ground based spectroscopic observations in the infrared and radio domains — show that there is a great similarity in the composition of interstellar and cometary ices. This agrees with the hypothesis that comets could have formed from basically unprocessed interstellar matter. However, the presence of crystalline silicates in cometary dust shows that these bodies may have also incorporated processed material at some stage of their formation. We have found indications of the presence of crystalline silicates in comet P/Hartley 2, which would be the first time such material is found in a Jupiter-family comet, but this needs to be confirmed by further observations of similar comets. To assess the crystalline/amorphous ratio in long-period and Jupiter-family comets is an important goal, since these two kinds of comets are believed to have formed in different regions of the Solar Nebula and to have experienced different evolutions. This could have strong implications on the diffusion transport of material formed or processed in the inner regions of the Solar Nebula.

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