THE SPECTRUM OF COMET HALE-BOPP AS SEEN BY ISO*

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ABSTRACT

Comet C/1995 O1 (Hale-Bopp) was observed with the Infrared Space Observatory within the target-of-opportunity comet programme. Spectra were obtained pre-perihelion on April 1996 and September–October 1996, and post-perihelion on December 1997 and April 1998, spanning heliocentric distances (r) between 2.8 and 4.9 AU. At the largest r's, only PHT-S spectra were obtained. At the smallest r's, a high-resolution spectrum covering the full 2.4 to 195 μm spectral range was obtained for the first time in a comet, using SWS and LWS. Spectra of dedicated regions (H_2O, CO and CO_2 bands) were also observed with SWS. The vibrational bands of water, carbon dioxide and carbon monoxide are detected in emission, as expected from molecular fluorescence models. Relative production rates for H_2O:CO_2:CO vary, as a function of r, as could be expected from the different volatilities of these species. H_2O was observed at high spectral resolution in the ν_3 group of bands around 2.7 μm, the ν_2 group around 6 μm with SWS, and in several rotational lines with LWS. The ro-vibrational lines of the ν_3 band were observed with a high S/N in September–October 1996. This allows an accurate determination of the water rotational temperature (28 K) and of its ortho-to-para ratio (2.45 ± 0.10), which significantly differs from the high temperature limit and corresponds to a spin temperature of 25 K). Longward of 6 μm, the spectrum is dominated by dust thermal continuum emission, upon which broad emission features are superimposed whose peak wavelengths correspond to those of Mg-rich crystalline olivine (forsterite). In the September–October spectra, emission features at 44 and 65 μm and possible absorption at 2.9–3.2 μm suggest that grains of water ice were present at 2.9 AU from the Sun.

Key words: comets; C/1995 O1 (Hale-Bopp); dust; ISO; molecules; spectroscopy.

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1. INTRODUCTION

Most programmes of cometary observations with ISO had to be aimed at known, periodic comets, which are generally weak objects, whereas the *target-of-opportunity* comet programmes could be aimed at unpredicted comets. During ISO's life, we had the chance to witness the apparition of C/1995 O1 (Hale-Bopp), an exceptionally bright comet and an ideal goal for these programmes.

We report here on spectroscopic observations of comet Hale-Bopp with ISO. Companion observations were also made with ISOPHOT broad filters (Grün et al. 1998) and ISOCAM (Lamy et al. 1998).

Table 1. Summary of the spectroscopic observations of C/1995 O1 (Hale-Bopp) with ISO.

Date dd/mm/yy	r [AU]	Δ [AU]	instrument
27/04/96	4.58	4.26	PHT-S
05/05/96			PHT-S (background)
01/09/96[a)]	3.22	2.83	PHT-S, SWS
06/09/96			PHT-S (background)
26/09/96	2.93	2.96	PHT-S, SWS
06/10/96	2.82	3.01	PHT-S, SWS, LWS
10/10/96			PHT-S, LWS (background)
25/12/97	3.85	3.68	PHT-S
29/12/97	3.89	3.73	SWS
06/04/98	4.90	5.00	PHT-S

[a)] erroneously made at a position offset by 38"

2. OBSERVATIONS

Due to the visibility constraints of the comet by ISO (and especially the solar elongation constraint) the comet was only observable pre-perihelion during two windows in spring and autumn 1996. It unfortunately could not be observed closer than r =

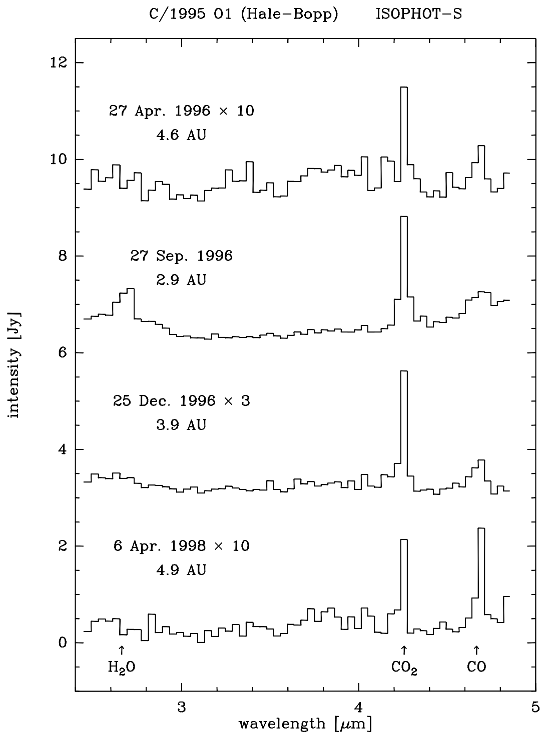

Figure 1. The 2.5–5 μm spectra of C/1995 O1 (Hale-Bopp) observed with ISOPHOT-S at four moments. Note the different scaling factors.

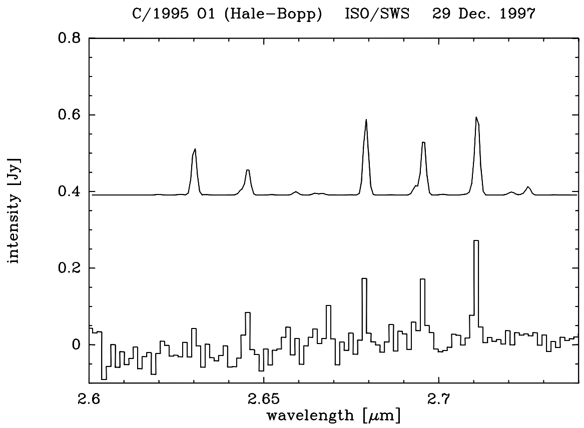

Figure 2. The spectrum of water (ν_3 region) observed in December 1997 in C/1995 O1 (Hale-Bopp) with SWS (bottom). At the top is shown a synthetic spectrum computed for $T_{\rm rot}$ = 5 K and an ortho-to-para ratio of 2.5.

Table 2. Molecular production rates observed in C/1995 O1 (Hale-Bopp) with ISO.

Date dd/mm/yy	r [AU]	H_2O	CO [10^{28} molec. s^{-1}]	CO_2
27/04/96	4.58	–	≈ 7.0	1.3
26/09/96	2.93	33.0	23.0	7.4
29/12/97	3.89	2.8	15.0	3.5
06/04/98	4.90	–	30.0	3.0

2.8 AU from the Sun, excluding the perihelion (at $r = 0.91$ AU on April 1, 1997).

During the extended life of ISO, another observing window appeared, and the comet could be observed at the end of December 1997[1] ($r = 3.9$ AU) and in April 1998[2] ($r = 4.9$ AU), two days before ISO died. A summary of the observations is given in Table 1.

3. RESULTS

Pre-perihelion observations were already reported elsewhere (Crovisier et al. 1996, 1997a, 1997b; Leech et al. 1998; Lellouch et al. 1998); they will only be briefly summarized here, and we will rather emphasize the results of the post-perihelion observations. A re-analysis of the data using improved calibration and reduction software is still to be done.

[1]thanks to additional discretionary time

[2]as part of remaining time on the COMETS guaranteed time programme

3.1. Gas

Figure 1 shows the evolution of the 2.5–5 μm spectrum of the comet observed at low resolution with PHT-S. The CO_2 band is strong and ubiquitous. This is the only direct observations of this molecule. The H_2O band could only be detected at the shortest distance to the Sun with this instrument. The CO band is always present — note that although not seen in the first analysis of the April 1996 observation (Crovisier et al. 1996), it is now marginally detected thanks to improved calibration. Water could be detected with SWS on December 1997, thanks to a long integration of ≈ 7000 s (Fig. 2); this is the only observation of water in a comet at such a large heliocentric distance.

The molecular production rates inferred from our ISO observations are given in Table 2. The H_2O and CO production rates are in close agreement with those obtained by other methods (e.g., Biver et al. 1998a, 1998b). The high CO production observed on 6 April 1998, however, is quite surprising. It is much larger (by a factor of 4) than the production rates observed from radio observations before and after this date (Biver et al. 1998a, 1998b; no really simultaneous radio observation is available). An outburst could have occurred (but no increase of the visual brightness of the comet was reported to our knowl-

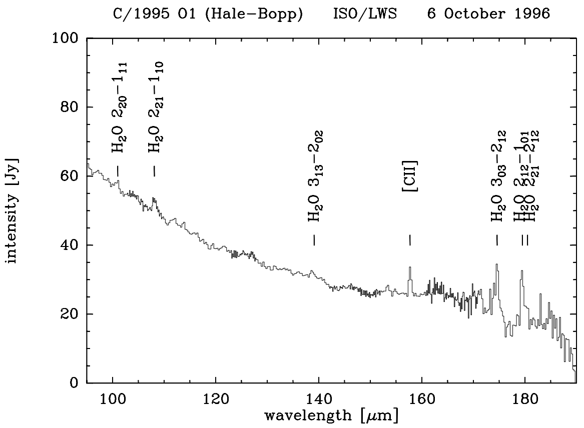

Figure 3. The spectrum of C/1995 O1 (Hale-Bopp) observed with LWS on October 1996, showing several rotational lines of water. The ionized carbon line is due to background.

edge).

Table 2 shows that [CO]/[H_2O], [CO_2]/[H_2O] and [CO]/[CO_2] are increasing with heliocentric distance. This obviously reflects the difference of volatility of the three molecular species. At large heliocentric distances (i.e., $r \geq 4$ AU), cometary activity is governed by CO sublimation rather than water sublimation. The relative production rates of H_2O, CO_2 and CO thus do not directly reflect the abundance ratios of these species in cometary ices. (For a discussion of these phenomena, see Bockelée-Morvan & Rickman 1998.)

H_2O was observed at high spectral resolution in September–October 1996 in the ν_3 group of bands around 2.7 μm, the ν_2 group around 6 μm with SWS, and in several rotational lines with LWS (Figure 3). The ro-vibrational lines of the ν_3 band were observed with a high S/N: this allows an accurate determination of the water rotational temperature (28 K) and of its ortho-to-para ratio (2.45 ± 0.10, which significantly differs from the high temperature limit and corresponds to a spin temperature of 25 K) (Crovisier et al. 1997a). From the SWS observation of water in December 1997 at 3.9 AU (Fig. 2), the relative ro-vibrational line intensities are different from those observed at 2.9 AU (Crovisier et al. 1997) and correspond to a colder rotational temperature ($T_{\rm rot} \leq 10$ K).

3.2. Dust and Ice

The first ISO spectrum of comet Hale-Bopp, taken at $r = 4.6$ AU, already showed the presence of crystalline silicates from the presence of a feature at 11.3 μm (Crovisier et al. 1996).

Figure 4 shows the evolution of the 6–12 μm spectrum of the comet observed at low resolution with PHT-S. Besides an evolution of the general shape due to the variation of dust temperature with heliocentric distance, the shape of the 10 μm silicate feature is remarkably constant and always present the 11.3 μm peak attributed to crystalline silicates.

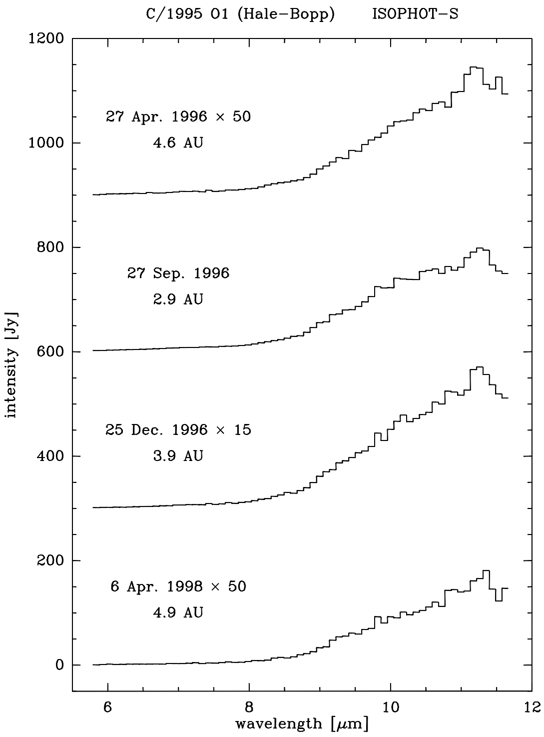

Figure 4. The 6–12 μm spectra of C/1995 O1 (Hale-Bopp) observed with ISOPHOT-S at four moments. Note the different scaling factors.

The full SWS spectra observed in September–October 1996 show a series of broad emission features that may be unambiguously attributed to crystalline, Mg-rich olivine (forsterite) (Crovisier et al. 1997a, 1997b). It has been remarked that these spectra are very similar to those observed in the circumstellar environment of some young stars (e.g., Waelkens 1998). Quantitative fits of the ISO spectrum of comet Hale-Bopp with laboratory analogues (Brucato et al. 1998; Wooden et al. 1999) show that amorphous silicates are also significantly present in the cometary dust. Pyroxene has also been identified in ground-based spectra around 10 μm; its non-detection in the ISO spectra has been attributed to a temperature effect (Wooden et al. 1999).

Figure 5 shows the new 6–45 μm SWS spectrum observed at 3.9 AU post-perihelion and for comparison the spectrum taken at 2.9 AU pre-perihelion. The two spectra are remarkably similar; they both have the features attributed to Mg-rich olivine, suggesting that the dust composition is similar before and after perihelion.

In the September–October 1996 spectra, emission features at 44 and 65 μm and possible absorption at 2.9–3.2 μm have been observed with ISO/LWS and

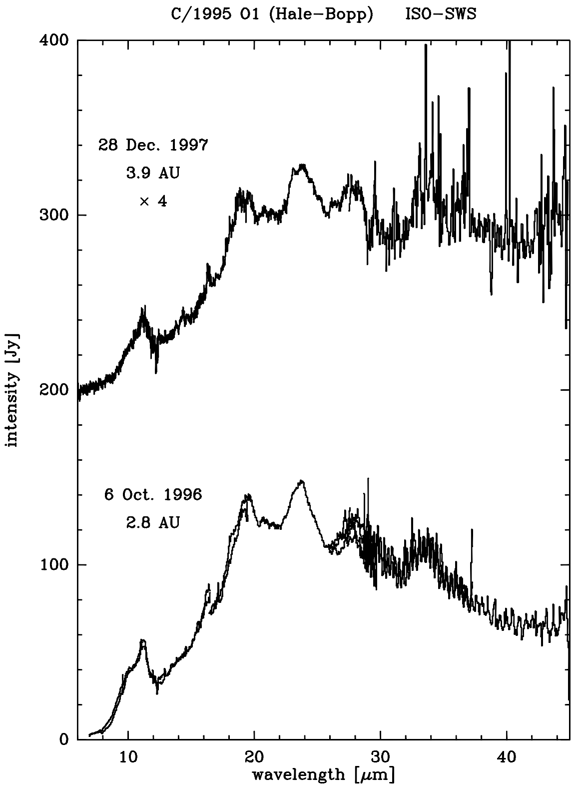

Figure 5. The 6–45 μm spectrum of C/1995 O1 (Hale-Bopp) observed with SWS at 2.8 AU pre-perihelion (bottom) and at 3.9 AU post-perihelion (top). The dust features are remarkably similar.

PHT. They are characteristic of water ice. This suggests that grains of water ice were present at 2.9 AU from the Sun (Lellouch et al. 1998). The icy grains have mean radii of 15 μm within a factor of 2, lifetimes of ~ 2 days, a temperature of ~ 150 K, and a total mass of $\sim 2\times10^9$ kg. Such grains could be an important source of water sublimation in addition to the nucleus, at such heliocentric distances. From investigation of the continuum spectrum at 43–195 μm, a production rate of large particles ($\sim 100\,\mu$m) dust of about 4×10^4 kg s^{-1} is also inferred.

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