THE INFRARED SPECTRUM OF COMET HALE-BOPP*

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ABSTRACT

Spectra of comet C/1995 O1 (Hale-Bopp) were observed at medium resolution with PHT-S on April and September-October 1996. High-resolution spectra were obtained with the long- and short-wavelength spectrometers of the Infrared Space Observatory on September-October 1996, when the comet was at about 3 AU from the Sun. For the first time, a high-resolution spectrum of a comet covering the entire 2.4 to 200 μm spectral range was obtained. Highlights of these results were briefly reported in Crovisier *et al.* (1997). We present here the latest developments of their analysis.

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

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 made with ISOPHOT broad filters (Peschke et al. 1997) and ISOCAM (Lamy et al., in preparation).

2. OBSERVATIONS

Due to the visibility constraints of the comet by ISO (and especially of 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 2.9 AU from the Sun, excluding the perihelion (at 0.91 AU from the Sun on April 1, 1997). A summary of the observations is given in Table 1.

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

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)

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

Further observations in another window at the end of December 1997 (when the comet is at 3.9 AU from the Sun) are under consideration.

During the spring 1996 observations, at 4.6 AU from the Sun, only PHT-S spectra were obtained. They resulted in the detection of the CO_2 band at 2.25 μm and of the band of silicates at $\simeq 10$ μm (Crovisier et al. 1996). More extensive observations were made in autumn 1996 with PHT-S, SWS, and LWS, including full spectral scans with SWS and observations of dedicated spectral domains with higher sensitivity. A first account of these observations was given by Crovisier et al. (1997). We present here the latest developments of their analysis.

Fig. 1 shows a composite spectrum of comet Hale-Bopp from the results of all spectrometers. The PHT-S and SWS spectra previously reported in Crovisier et al. (1997) have been improved using the latest calibration files. The subspectra obtained for observations in different bands (and for the "up" and "down" SWS scans) have been plotted separately. In

*Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with participation of ISAS and NASA.

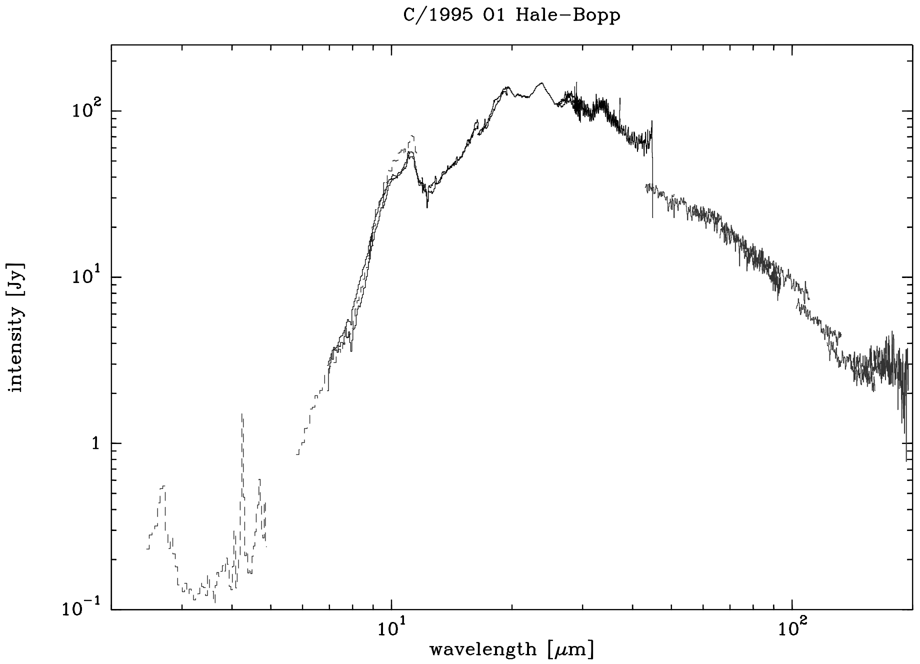

Figure 1. A composite spectrum of C/1995 O1 (Hale-Bopp) obtained on 6 October 1996 with PHT-S (dotted line), SWS and LWS (plain lines, different bands and "up" and "down" scans being plotted separately). Note that the scales are logarithmic. At short wavelengths, one can see the H_2O (2.7 μm), CO_2 (4.25 μm) and CO (4.65 μm) bands. A correction factor has been applied to take into account the different apertures of the instruments (see text).

contrast to our preliminary spectrum, no attempt has been made to joint the different bands together. Only a correction for different apertures has been made. The spectra were scaled to an equivalent aperture diameter of 19" (which is the equivalent aperture diameter for the shortest wavelengths of the SWS). For this, we assumed that the cometary signal is proportional to the aperture diameter (which is what is expected for a spherical coma in uniform expansion). Nominal apertures and perfectly flat-top beam profiles were assumed; future work will have to use the actual beam profiles.

We can see from the figure that there are no strong jumps between the various bands of the SWS and that the PHT-S observations are in good agreement with the SWS. There is, however, a large jump at 45 μm between the SWS and the LWS spectra, and the various LWS bands are not well adjusted one to the other. This LWS spectrum is still to be considered as preliminary and will be improved in the future using updated calibration files. Part of the jump may also be due to the inadequacy of the aperture correction for this comet, which is known to show strong asymmetric jets.

3. DISCUSSION

The fundamental vibrational bands of water, carbon dioxide and carbon monoxide are detected in emission with PHT-S, as expected from molecular fluorescence models. Relative production rates of 100:22:70 are derived for H_2O:CO_2:CO. These rates can be considered as characteristic of the sublimation of cometary ices at 2.9 AU from the Sun and should help in constraining models of active cometary nuclei. They show that water is the dominant cometary volatile, but that — at least at this distance from the Sun — CO and CO_2 are important contributors.

3.1. The water spectrum

H_2O is observed at high spectral resolution in the group of bands around 2.7 μm and the ν_2 band around 6 μm in dedicated observations with SWS, and in a couple of rotational lines ($2_{12} - 1_{01}$ and $3_{03} - 2_{12}$ near 180 μm) with LWS.

Fig. 2 shows the spectrum of comet Hale-Bopp in the region of the 2.7 μm band of water. Line assignations for the ν_1, ν_3, and several hot bands of water, as well as for $v(1-0)$ OH lines, are shown. There are apparently no other lines in the spectrum. In this spectral domain, which corresponds to the O–H stretching mode, one could expect lines from CHO species (such as CH_3OH) or from the H_3O^+ ion: they are below detection limit.

The most intense rovibrational lines are those of the ν_3 band which are observed with a high signal-to-noise ratio. These emission lines are only moderately thick and contain full information on the rotational distribution of water. The comparison with a model of fluorescence excitation and radiative transfer for all the water bands around 2.7 μm allows us to make accurate determinations of the water rotational temperature (T_{rot}) and of its ortho-to-para ratio. As explained in Crovisier et al. (1997), $T_{rot} = 28$ K was retrieved and the ortho-to-para ratio is estimated to

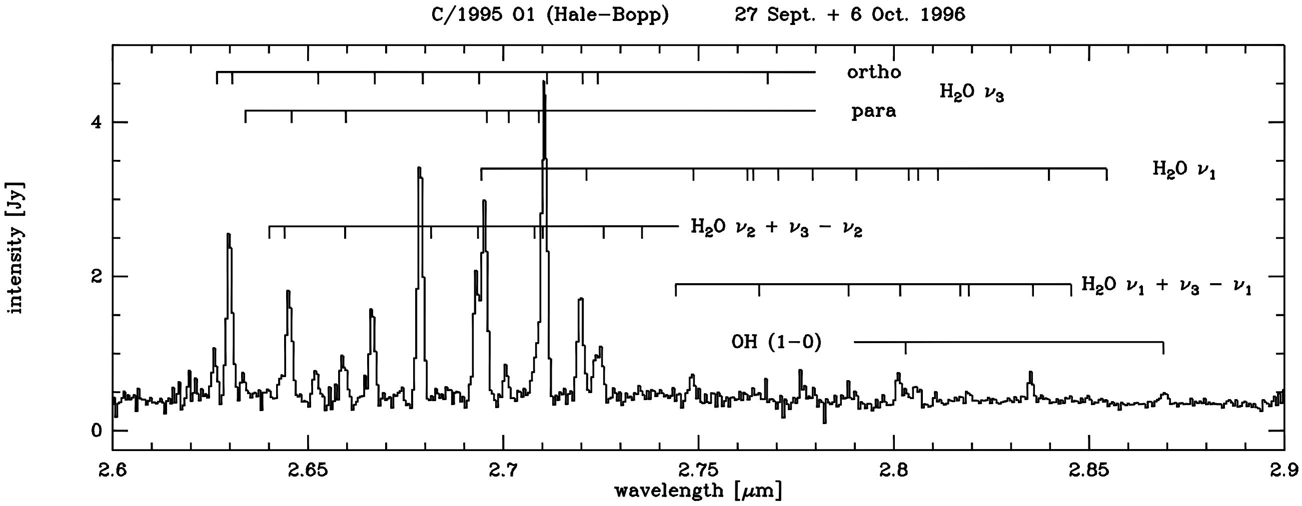

Figure 2. The region of the ν_3 band of water observed in C/1995 O1 (Hale-Bopp) on 26 September and 6 October 1996 with SWS, with line assignations.

2.45 ± 0.10, corresponding to a spin temperature of $\simeq 25$ K. The cold T_{rot} is in agreement with hydrodynamical models which predict an efficient cooling of cometary atmospheres during their expansion. Since no ortho-to-para exchange is possible during sublimation, radiative processes or collisions, the spin temperature corresponding to the observed ortho-to-para ratio is believed to be of a primordial nature and to characterize the early steps of the formation of cometary water.

Fig. 3 shows the spectrum in the region of the ν_2 band of water. All the strongest lines expected from water at $T_{rot} = 28$ K (from the model of Bockelée-Morvan 1987) are detected, but the low signal-to-noise ratio does not allow us to derive an accurateortho-to-para ratio, as was done for the ν_3 band.

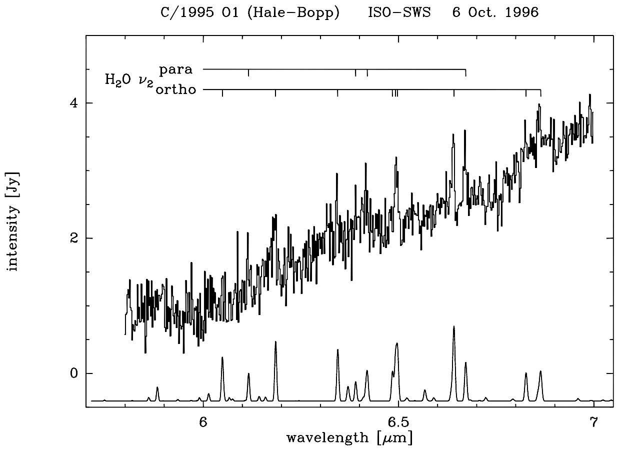

Figure 3. The ν_2 band of water (top) observed in C/1995 O1 (Hale-Bopp) on 6 October 1996 with SWS, with line assignations and a synthetic spectrum of water computed for $T_{rot} = 28$ K (bottom).

3.2. Minerals

Longward of 6 μm, the spectrum is dominated by dust thermal continuum emission, upon which broad emission features are superimposed. Inspection of laboratory infrared spectra of silicates in data bases (e.g. in Salisbury et al. 1991) shows that the wavelengths of the emission peaks correspond best to those of Mg-rich crystalline olivine (pure forsterite, Mg_2SiO_4).

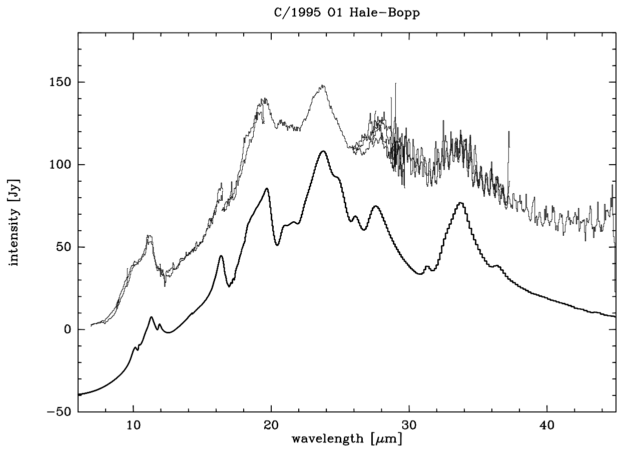

Figure 4. The SWS spectrum of C/1995 O1 (Hale-Bopp) and a modelled spectrum of forsterite (from a laboratory spectrum provided by W.-F. Thi and L. d'Hendecourt).

Fig. 4 shows the SWS spectrum of comet Hale-Bopp with, for comparison, a modelled spectrum of forsterite. The forsterite emission spectrum is modelled as:

$$F(\lambda) = B(\lambda, T)[1 + \alpha K(\lambda)],$$

where $B(\lambda, T)$ is the Planck function and $K(\lambda)$ is the mass absorption spectrum of forsterite, from laboratory data of Thi and d'Hendecourt (private communication). No special attempt has been made to adjust the temperature T (set to 200 K in the figure) nor the scaling factor α for obtaining the best fit. The plot of the two spectra in the figure is just intended to show the match in wavelengths of the peaks.

4. CONCLUSION

Cometary volatiles, as observed by ISO and by other instruments, have a composition similar to interstellar ices, in agreement with the hypothesis of a formation of comets from preserved interstellar grains. The dust in Hale-Bopp — as that observed in several other comets — contains crystalline silicates. This contrasts with interstellar silicates which are amorphous. The dust of comet Hale-Bopp is rather similar to that observed in the circumstellar discs of Vega-type stars, which was found to be crystalline, and even to contain forsterite (Waelkens et al. 1996). Future scenarios of the formation of comets in the Protosolar Nebula will have to take these results into account.

ACKNOWLEDGMENTS

We are very grateful to Wing-Fai Thi and Louis d'Hendecourt for providing their laboratory spectrum of forsterite.

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