Observations of Gas and Dust in Comets 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. Fluorescence emissions of H_2O, CO_2 and (for comet Hale-Bopp only) CO and CH_4 are observed, yielding the production rates of these species. High-resolution spectra of water permit the study of the rotational and spin temperatures of this molecule. In comet Hale-Bopp, the thermal infrared region of the spectra shows specifically, in addition to continuum-like emission, the signatures of crystalline, Mg-rich olivine (forsterite), and signs of crystalline pyroxenes, amorphous silicates and water ice. The presence of crystalline silicates is also suggested in the Jupiter-family comet P/Hartley 2.
Keywords. Comets – Comet C/1995 O1 (Hale-Bopp) – Comet 103P/Hartley 2 – Infrared Space Observatory

1. Introduction

Waiting for the direct investigation of cometary nuclei by space missions, we can only study the chemical composition of these bodies by observing the material they are rejecting during periods of cometary activity.

Recently, the Infrared Space Observatory (ISO) (Kessler et al. 1996) gave us access to the full infrared range from 2.4 to 196 μm. This spectral range, which covers the domain of thermal emission, the fundamental vibrational bands of gas-phase molecules, and specific bands of dust and ice constituents, is thus fully adequate for an investigation of the chemical and physical properties of cometary material (Fig. 1).

ISO could observe in some detail the spectra of the exceptionally bright, long-period comet C/1995 O1 (Hale-Bopp) and of the Jupiter-family comet 103P/Hartley 2 (Table 1). This provides an interesting comparison, these two comets having presumably different formation histories. A summary of the ISO results on these two comets is presented here[1].

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[1]This paper concentrates on spectroscopic results. Other cometary programmes with ISO, aimed at imaging (with ISOCAM) and broad-band photometry (with ISOPHOT) of comet Hale-Bopp and short-period comets, will not be reported here

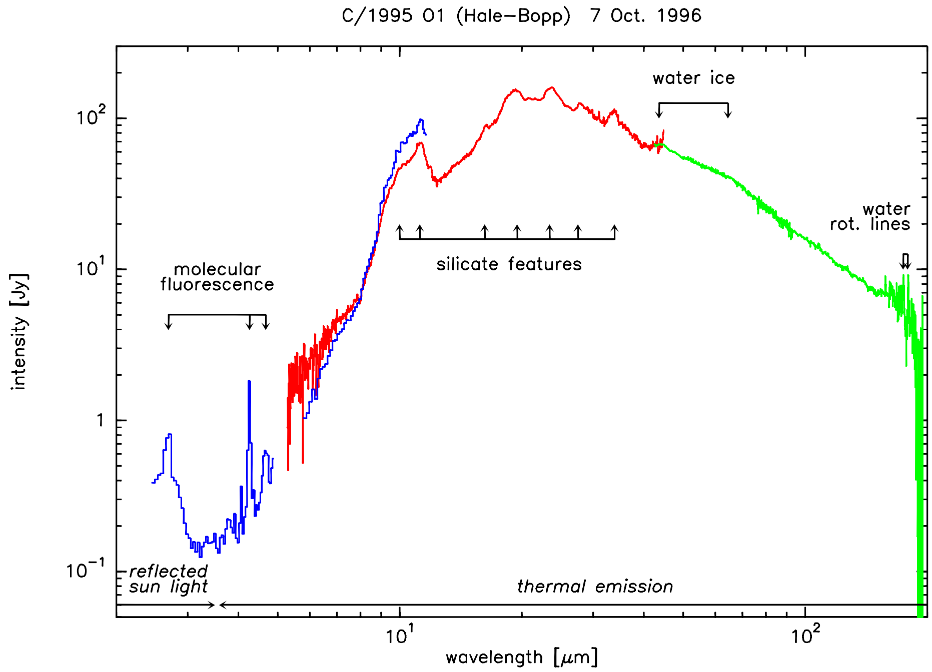

Figure 1. A composite spectrum of C/1995 O1 (Hale-Bopp) from 2.5 to 195 μm obtained with the PHT-S (2.5–5 and 6–12 μm), SWS (7–45 μm) and LWS (43–195 μm) instruments of ISO. The LSW spectrum has been arbitrarily rescaled in intensity to make the spectrum continuous.

2. Observations

Comet C/1995 O1 (Hale-Bopp) was observed by ISO as a target of opportunity (Crovisier et al. 1996, 1997a, 1997b, 1999a, 2000; Lellouch et al. 1998). It is an exceptionally bright comet, presumably coming from the Oort cloud. 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_h) between 2.8 and 4.9 AU. Unfortunately, this comet could not be observed around perihelion with ISO because of visibility constraints. At the largest heliocentric distances, only low-resolution spectra were obtained with the photometer (PHT-S; spectral range 2.5–5 and 6–12 μm, resolution $\lambda/\delta\lambda \approx 80$, field of view 24" $\times$ 24"). At the smallest r_h's, a high-resolution spectrum covering the full 2.4 to 196 μm spectral range was obtained for the first time in a comet, using the short-wavelength spectrometer (SWS; 2.4–45 μm, resolution $\approx$ 1500, field of view 14" $\times$ 20" to 20" $\times$ 33") and the long-wavelength spectrometer (LWS; 43–195 μm, resolution $\approx$ 200, field of view 100").

Other spectroscopic programmes were devoted to short-period comets of the Jupiter-family, presumably originating from the Edgeworth-Kuiper belt. 22P/Kopff was observed on October–December 1996 with SWS and LWS. Due to the weakness of the object, which was then at r_h = 1.9 AU, only the ν_3

Table 1. Properties of the two bright comets observed spectroscopically with ISO.

C/1995 O1 (Hale-Bopp)	103P/Hartley 2
long-period ($P \approx 4000$ years)	Jupiter-family ($P = 6.3$ years)
from Oort Cloud	from Kuiper Belt
formed at $r_h < 35$ AU	formed at $r_h > 35$ AU
$Q_{max}[H_2O] = 10^{31}$ s^{-1}	$Q_{max}[H_2O] = 10^{28}$ s^{-1}
observed at $2.8 < r_h < 4.9$ AU	observed at $r_h \approx 1$ AU

Table 2. Molecular production rates derived from the SWS and PHT-S spectra.

Date	r_h [AU]	H_2O	CO	CO_2	CH_4
		[10^{28} molec. s^{-1}]			
C/1995 O1 (Hale-Bopp)					
27/04/96	4.58		7.0	1.3	
26/09/96	2.93	33.0	23.0	7.4	0.55
29/12/97	3.89	2.8	15.0	3.5	
06/04/98	4.90		30.0	3.0	
103P/Hartley 2					
01/01/98	1.04	1.2		0.12	

ro-vibrational lines of water were detected, with SWS (Crovisier et al. 1999b). Comet 103P/Hartley 2 was observed close to its perihelion (at $r_h = 1.04$ AU from Sun and 0.82 AU from Earth) on January 1998 with SWS, LWS, PHT-S and the CVF (5–17 μm, spectral resolution ≈ 41) of the imaging instrument ISOCAM (Colangeli et al. 1999b; Crovisier et al. 1999b, 2000).

3. Results

3.1. Gas Composition

In comet Hale-Bopp, the vibrational bands of water, carbon dioxide, carbon monoxide and methane are detected in emission (Figs 2 and 5), as expected from molecular fluorescence models. Relative production rates H_2O:CO_2:CO:CH_4 were observed to be 100:20:70:1.5 at $r = 2.9$ AU. However, H_2O:CO_2:CO strongly vary as a function of heliocentric distance (Table 2), as could be expected from the different volatilities of these species. For instance, the onset of sublimation of water is expected to occur around $r_h = 4$–5 AU. Therefore, one must be cautious when extrapolating the relative abundances of cometary volatiles observed *in the coma* to the true composition of cometary ices *in the nucleus*.

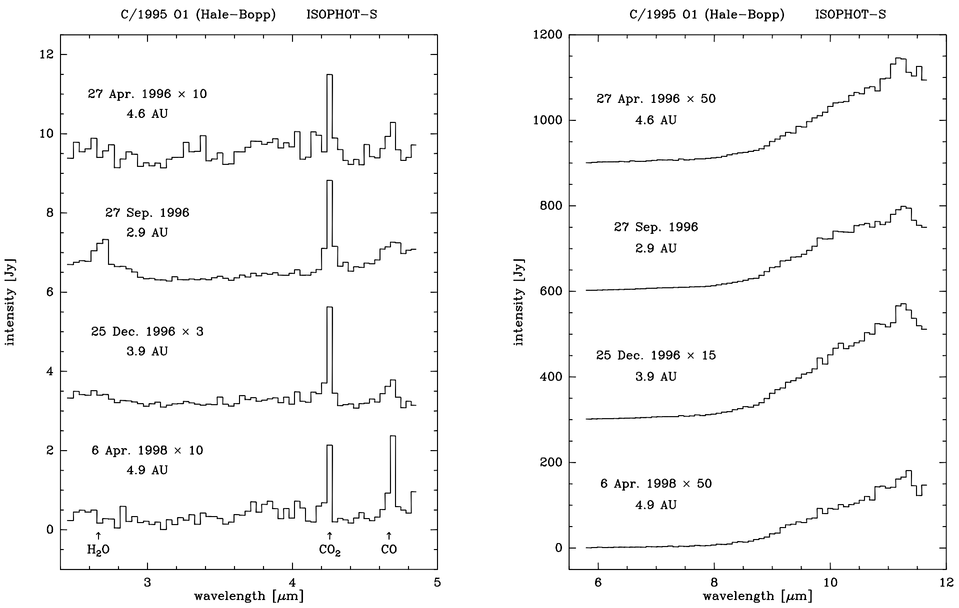

Figure 2. The 2.5–5 μm (left) and 6–12 μm (right) spectra of comet C/1995 O1 (Hale-Bopp) observed with ISOPHOT-S at four moments, showing evolution with heliocentric distance. Note the different intensity scales. From Crovisier et al. 1999a.

In comet P/Hartley 2, the bands of H_2O and CO_2 at 2.7 and 4.3 μm are detected with PHT-S (Colangeli et al. 1999b; Fig. 3), with CAM-CVF and with SWS (Crovisier et al. 1999b; Fig. 5). Relative production rates CO_2:H_2O = 10 % are observed (Table 2). Therefore, CO_2 is found to be a major cometary volatile in both comets, and appears to be the easiest gas species to detect at these wavelengths at large r_h. It must be noted that space-borne infrared spectroscopy is the only direct mean of observation of this molecule.

3.2. Gas Physical Properties

In comet Hale-Bopp, several rotational lines of H_2O were observed with LWS (Fig. 4). This is the first observation of rotational water lines in a comet[2]. These lines are heavily thick and need to be interpreted using sophisticated radiative transfer–excitation models.

The bands of H_2O around 2.7 μm (ν_1, ν_3 and hot bands) (Fig. 5) and 6 μm (ν_2 band) were observed with SWS at high spectral resolution. In September–October 1996, the ro-vibrational lines of the ν_3 band were observed with a

[2]Subsequently, the 1_{10}–1_{01} line of water was observed through heterodyne techniques by SWAS in comet C/1999 H1 (Lee) (Bergin et al. 1999).

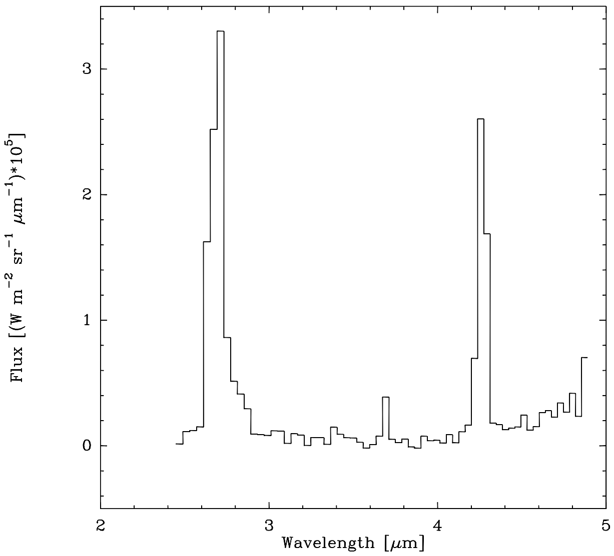

Figure 3. The 2.5–5 μm spectrum of comet 103P/Hartley 2 obtained with ISOPHOT-S on 1 January 1998, showing the strong bands of water at 2.7 μm and carbon dioxide at 4.65 μm. From Colangeli et al. 1999b.

Table 3. Water rotational temperature (T_{rot}), ortho-to-para ratio (OPR) and spin temperature (T_{spin}) derived from the high-resolution spectra.

Comet	date	T_{rot} [K]	OPR	T_{spin} [K]
C/Hale-Bopp	Sep.+Oct. 96	28.5	2.45 ± 0.10	28 ± 2
103P/Hartley 2	1 Jan. 98	20.3 ± 0.8	2.76 ± 0.08	36 ± 3
	19 Jan. 98	16.5 ± 1.6	2.63 ± 0.18	33 ± 5

high signal-to-noise ratio . 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 28 K) (Table 3).

In comet P/Hartley 2, the 2.7 μm band of H_2O is also observed with a high signal-to-noise ratio (Fig. 5), which permits to evaluate the rotational temperature of water averaged within the field of view to 20 K, and its ortho-to-para ratio to ≈ 2.7, corresponding to a spin temperature $T_{spin} \approx 35$ K (Table 3).

The cold rotational temperatures are in agreement with hydrodynamical models of cometary atmospheres which predict cooling of cometary atmospheres during their expansion. The higher temperature in comet Hale-Bopp, despite its larger r_h, may be attributed to a more efficient thermalization of the photolysis products, due to its higher coma density.

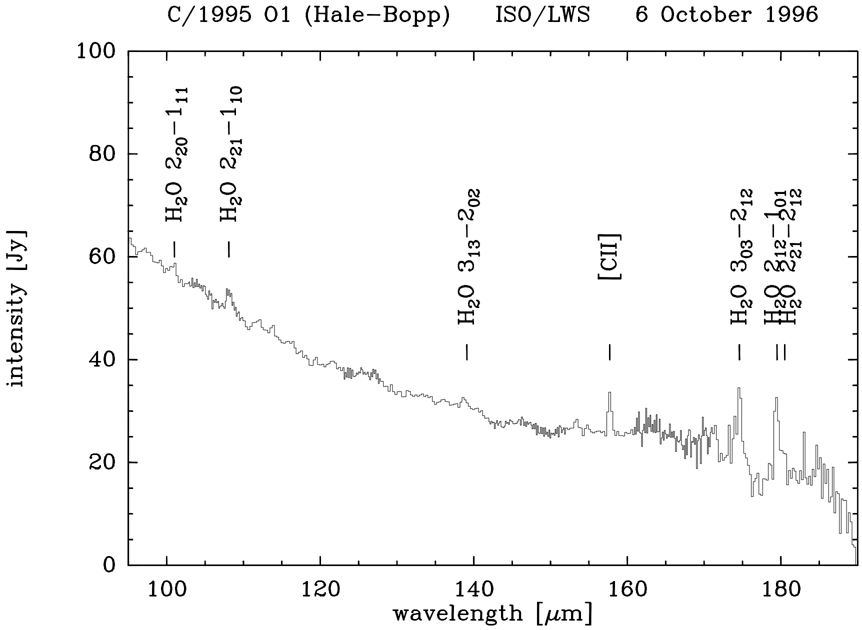

Figure 4. Several rotational lines of water observed with ISO/LWS in comet C/1995 O1 (Hale-Bopp). The CII line is not from the comet; it comes from the background. From Crovisier et al. 1999a.

The present spin temperature determinations, which rely on the analysis of lines of low optical depth for the whole ν_3 water band, are believed to be more reliable than previous ones (from KAO observations of comets 1P/Halley and C/1986 P1 Wilson). Their meaning is still a debated issue, however (see Mumma et al. 1993 for a summary of previous measurements and a discussion of the problem). T_{spin} could be the temperature of water at formation (on the surface of cold grains, since gas-phase reactions are exothermal and would yield "hot" water). Or the ortho-to-pare ratio could re-equilibrate within the nucleus, T_{spin} being then the equilibrium temperature of nucleus ices. Or it could betray fractionation effects when water condenses or sublimates. These two last mechanisms require a laboratory investigation of ortho-to-para conversion mechanisms for water under cometary conditions.

3.3. Icy Grains and Dust

Beyond 6 μm, the spectrum of comet Hale-Bopp is dominated by dust thermal continuum emission, upon which broad emission features are superimposed (Figs 1 and 6).

In the September–October 1996 spectra, emission features at 45 and 65 μm (Fig. 1) and a possible absorption at 2.9–3.2 μm are seen, characteristic of crystalline water ice (Lellouch et al. 1998). This suggest that water ice grains were still present at $r = 3$ AU in the coma, and that they could be a significant source of volatiles.

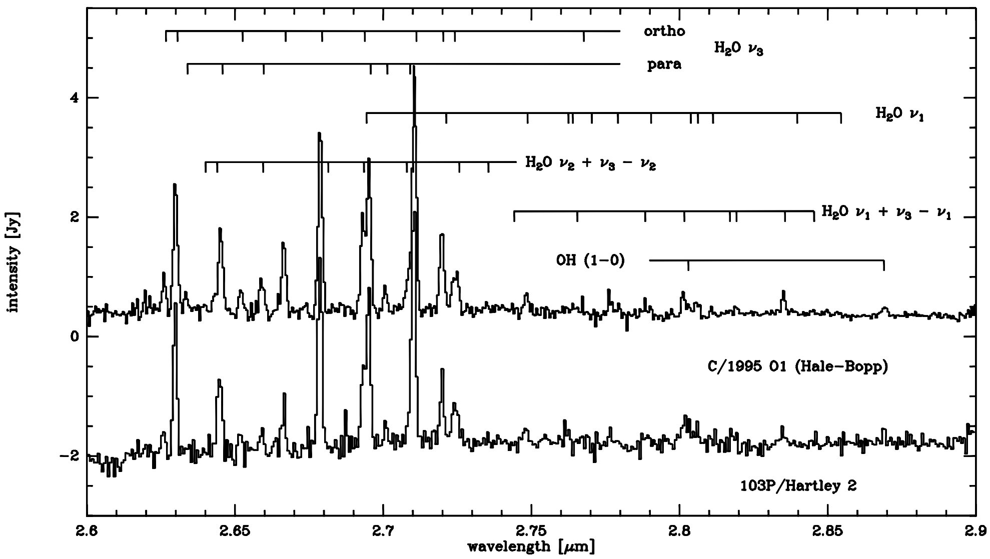

Figure 5. The region of the ν_3 band of water observed with ISO/SWS in comets C/1995 O1 (Hale-Bopp), average of 27 Sept. and 6 Oct. 1996 (top) and 103P/Hartley 2, 1st Jan. 1998 (bottom). Adapted from Crovisier et al. 1997a and 1999b.

The wavelengths of the other prominent features closely match those of Mg-rich crystalline olivine (forsterite Mg_2SiO_4) ((Crovisier et al. 1997a). A detailed analysis of the spectrum, using laboratory spectra of various kinds of silicates (Crovisier et al. 2000), also reveals the presence of pyroxene and amorphous silicates. The ratio of crystalline to amorphous silicates is found to be of the order of 40% by mass. The continuum emission cannot be interpreted in terms of a single-temperature blackbody emission.

Observations at different r_h's, before and after perihelion, do not show any significant evolution of the dust properties, except of course changes in the dust temperature (Fig. 2; Crovisier et al. 2000).

Independent analyses of the 7 October spectrum were performed by Brucato et al. (1999), Colangeli et al. (1999a) and Wooden et al. (1999). The results are qualitatively similar, but different proportions of the silicate components are found, however. As discussed by Crovisier et al. (2000), this may be ascribed to the use of different laboratory samples, and to different assumptions on the silicate temperatures.

The 5–17 μm spectrum of comet P/Hartley 2 observed with CAM-CVF shows the 9–12 μm band of silicates (at a level of about 20 % of the continuum, to be compared with $\approx$ 200% for comet Hale-Bopp) (Crovisier et al. 1999b, 2000). A possible emission at 11.3 μm suggests the presence of crystalline silicates, which would be the first time it is found in a Jupiter-family comet.

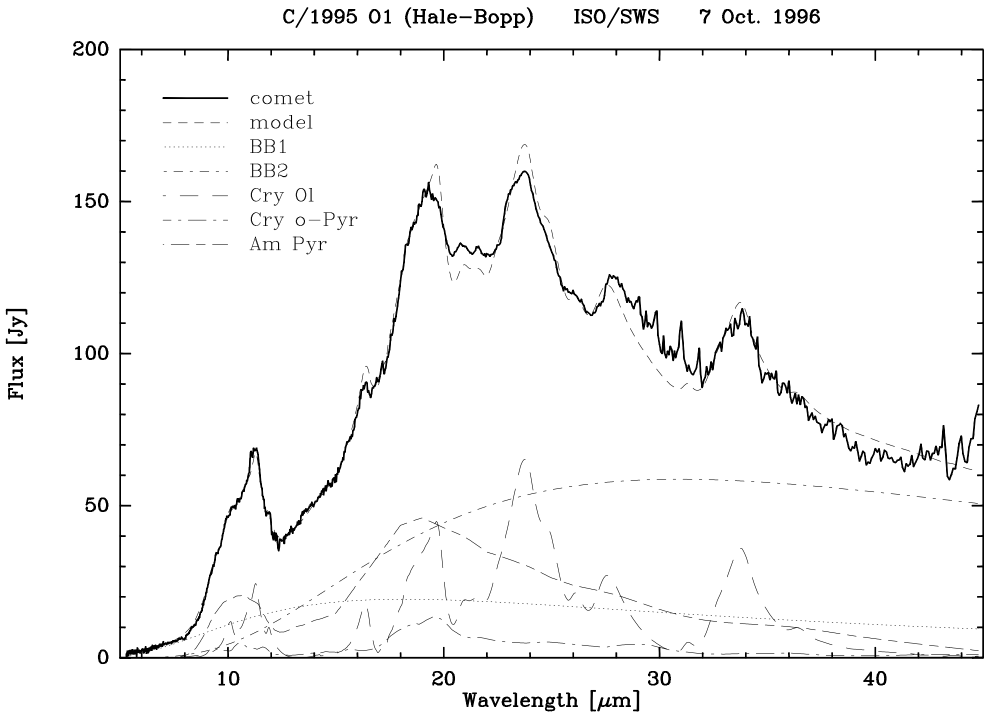

Figure 6. C/1995 O1 (Hale-Bopp) on 7 October 1996 at $r_h = 2.8$ AU. The 6 to 45 μm region of the SWS spectrum is represented here degraded to a resolution $\lambda/\delta\lambda = 500$ (full dark line). The intensity scale is normalized to a 14" $\times$ 20" aperture assuming a $1/\rho$ brightness distribution law. The observed spectrum has been decomposed into several emission components: two blackbody components, forsterite, orthopyroxene and amorphous silicates. From Crovisier et al. 2000.

No sign of PAHs could be found in these ISO spectra, especially in the 6–9 μm region where they have strong features unblended with silicates, which are conspicuous in many interstellar and circumstellar sources.

4. Conclusion

ISO observations of C/1995 O1 (Hale-Bopp) and 103P/Hartley 2 revealed to us the spectra of comets over the full infrared range.

These observations, complemented by ground-based infrared spectroscopy and by spectroscopy in the other spectral domains, now allow us to have a comprehensive view of the composition of cometary volatiles, of the evolution of their production as a function o heliocentric distance, and of their physical conditions. A remarkable similarity with the abundances of interstellar molecules molecules, in ices or in the gas phase, can be noted (cf. Bockelée-Morvan et al. 2000, Crovisier 1999 and Irvine et al. 2000).

The thermal infrared spectrum of comet Hale-Bopp permitted the identification of several kinds of silicates. This spectrum closely resembles the spectra observed by ISO on the protoplanetary dust discs around some young stars (cf. Waelkens 2000), emphasizing the similarity of the dust composition in both kinds of objects. This contrasts with interstellar silicates, which are primarily amorphous.

The history of cometary formation may be complex. Cometary nuclei may have retained unprocessed or little-processed matter from the primitive Solar Nebula, as well as processed matter such as crystalline silicates. Further investigations, especially by infrared spectroscopy, of comets from different families (i.e., of various origins) should help us in understanding their formation and the history of our Solar System.

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