CIRCUMSTELLAR, COMETARY AND INTERPLANETARY DUST

J. Crovisier

Observatoire de Paris-Meudon, F-92195 Meudon, France

ABSTRACT

The Infrared Space Observatory made us available for the first time the full infrared spectrum of cosmic dust in a variety of astrophysical environments. I review what we learned from ISO on the composition of dust in the Solar System (cometary and interplanetary) and in circumstellar discs around young or evolved stars, what are the commonalities and parallels between dust in these different environments, and what this tells us on the cosmic dust cycle.

Key words: circumstellar matter – comets – dust – interplanetary dust – silicates – zodiacal light

1. INTRODUCTION

Among the highlights from the Infrared Space Observatory observations were revelations on the nature of cosmic dust in various environments (d'Hendecourt et al. 1999).

The main sketch of the cycle of dust in the Universe (Fig. 1) is now known. Formed in the outflows of evolved stars (e.g., post-AGB stars), dust is released in the interstellar medium. During star-forming processes, a protoplanetary nebula with a dust disc is formed. Most of the dust will be incorporated into planetesimals, but a residual dust disc may remain.

In our Solar System, a permanent interplanetary dust cloud is regenerated by the release of dust from comets and (possibly) by collisions among small bodies. The smallest dust particles are blown away by solar radiation pressure, but the largest ones constitute cometary trails, asteroidal bands, and a cloud of interplanetary dust particles (IDPs) which are responsible for zodiacal light. The presence of similar dust clouds is suggested around other stars (e.g., around β Pictoris).

An important problem is to assess to which extent dust is preserved throughout this cycle, and to which extend it is processed or segregated. ISO observations, together with other (ground-based) recent observations, cast new light on this topic, by determining the chemical composition of dust particles and especially the nature of their silicates and their degree of crystallisation, in a variety of objects. The goal of the present review is to summarize these results and to point to the new questions they now raise.

Interplanetary dust particles and interstellar dust, which are reviewed in a companion paper by Waters (*these proceedings*), will not be described in details here.

2. DUST OBSERVABLE PARAMETERS

Several parameters of dust can be quantitatively derived from the observations (some of them are only available for comets, for which physical conditions and geometry are better known).

- The *colour temperature* T_c is defined in a spectral range by comparison to a Planck law. It generally depends upon this spectral range.
- For cometary and interplanetary, the *superheat factor* is T_c/T_{bb}, where T_{bb} is the equilibrium temperature of a black body at the same heliocentric distance r_h ($T_{bb} = 278/\sqrt{r_h}$ K). This factor cannot be determined for circumstellar dust, for which the heating conditions are not precisely known for the whole disc.
- The *silicate feature intensity* may be defined for the 10 μm silicate band, $F_{10.3}/F_{cont}$. It can be measured from the ground and is thus available for a number of objects and comets (Gehrz & Ney 1992).
- The *crystallinity indicator* may be defined for the 33 μm band of crystalline silicates, F_{33}/F_{cont}. It has been evaluated by ISO for a number of objects, but for one comet only (Fig. 4).
- For comets, the *Afρ parameter*, which measures the amount of solar light reflected on dust (see A'Hearn et al. 1984 for a definition), is a convenient indicator of the dust production rate. It has the dimension of a length (commonly expressed in cm) and is independent of the instrumental field of view. As a rule of thumb, a comet with $Af\rho = 1$ cm produces 1 kg s^{-1} of dust for a "standard" dust model (A'Hearn et al. 1995). However, large dust particles, which do not contribute significantly to reflected sun light, are ill-represented in the $Af\rho$ parameter.
  The interest of the $Af\rho$ parameter is that it can be conveniently measured from ground-based narrow-band spectrophotometry, as the production rates of several cometary radicals which can in turn serve as indicators of the gas production rate. This can lead to estimations of the gas-to-dust ratios in a number of comets,

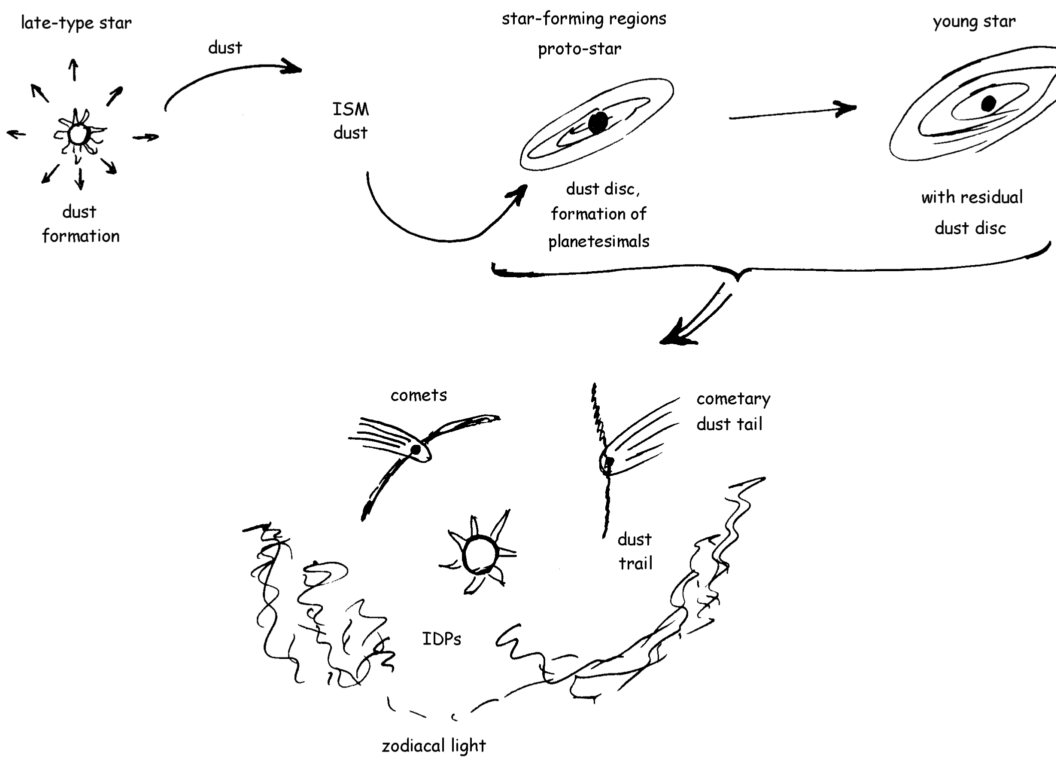

Figure 1. The story of dust in the Universe and in the Solar System.

permitting comparisons and statistical studies. CN is one of the most easily observed radicals in comets. Assuming $[\mathrm{CN}]/[\mathrm{H_2O}] = 0.003$, $Q[\mathrm{CN}]/Af\rho = 10^{27}$ molec. s^{-1} cm^{-1} corresponds to a gas-to-dust ratio of 1 in mass (this conversion factor has been used in the scales of Fig. 6).
- We just mention for completeness the *polarization properties* and the *albedo* of dust particles.

3. DISCUSSION OF OBSERVATIONS

Table 1 presents a summary of cosmic dust properties in various environments.

3.1. Dust in cometary comae

The ISO observations of cometary dust complete ground based spectroscopic observations, basically restricted to the investigation of the 10 μm band of silicates in a limited number of comets (e.g., Hanner et al. 1994). Only two comets were bright enough for a thorough spectroscopic investigation with ISO and provided detection of silicate features: C/1995 O1 (Hale-Bopp) (Crovisier et al. 1997, 1999, 2000) and 103P/Hartley 2 (Colangeli et al. 1999b; Crovisier et al. 2000). This does not mean that the other comets which were observed (Table 2) do not contain silicates, but rather that their silicate band emissions are below detection limit. For instance, the weak 10 μm silicate band of comet 103P/Hartley 2 (only $\approx 15\%$ of continuum) was detected with CAM-CVF (Crovisier et al. 2000), but not with PHT-S (Colangeli et al. 1999b).

Table 2. Comets observed with ISO (spectroscopy).

C/1995 O1 (Hale-Bopp)	PHT-S		SWS	LWS
2P/Encke	PHT-S			
22P/Kopff	PHT-S	CAM-CVF	SWS	LWS
43P/Wolf-Harrington	PHT-S			
103P/Hartley 2	PHT-S	CAM-CVF	SWS	LWS
126P/IRAS	PHT-S			

We concentrate here on spectroscopic observations of comets with ISO. However, one should mention the existence of complementary data: photometric observations with ISOPHOT (Grün et al. 2000 and *in preparation*) giving the overall shape of the continuum spectrum of cometary dust in the thermal infrared and its evolution with heliocentric distance; imaging observations with ISOCAM (Colangeli et al. 1998; Jorda et al. 2000; Reach et al. 2000) giving the dust spatial distribution and, in some cases, information of the dynamics of the dust tails and trails.

Table 1. Comparison of Solar System dust and circumstellar dust.

	comet dust C/Hale-Bopp (P/Hartley 2)	cometary trails	zodiacal dust	IDPs	ISM dust	young stars HD 100546 (β Pictoris)	evolved stars AC Herculis (IRAS 09425–6040)
			Dust Parameters				
Superheat factor	$\approx 80\%$ (low)	low	low	–	–	–	–
Silicate strength	2.8 (1.15)	?	≤ 1.15	–	–	2.00	≈ 2
Crystallinity factor	0.3 (?)	?	?	–	<?	0.25 (?)	0.35 (1.5)
			Dust Composition				
Silicates	yes	?	yes?	yes	yes	yes	yes
Water ice	yes	no	no	no	yes	yes (yes)	yes
PAHs	?	?	?	?	yes	yes (?)	yes

3.2. Cometary trails

Cometary trails and asteroidal bands were first discovered by IRAS. They consist of millimetre to centimetre size particles. They are presumed to be of the same nature as the meteoroids responsible for meteor swarms when the Earth crosses such a trail.

ISO observed the dust trails of comets 22P/Kopff (Davies et al. 1997b) and 2P/Encke (Reach et al. 2000). Attempts to observe the trails of comets 46P/Wirtanen and 65P/Gunn were unsuccessful (Colangeli et al. *personal communication*).

Cometary trails have low *superheat factors* (Sykes & Walker 1992; Gehrz & Ney 1992), as could be expected from large-size dust particles. They are unfortunately too faint to be investigated spectroscopically. It is thus not possible to evaluate their silicate composition or their *silicate feature intensity*.

3.3. The interplanetary dust cloud and zodiacal light

Interplanetary dust was the object of specific observations with ISOCAM and ISOPHOT. The CAM-CVF spectrum of zodiacal light suggests the presence of a silicate emission band around 9–11 μm (Reach et al. 1996), but the authors consider that this result is marginal (Reach, *personal communication*). No such band is apparent on the PHT-S spectra of zodiacal light (Ábrahám et al. 1999a, 1999b). An upper limit < 15% can thus be obtained for the *silicate strength* of interplanetary dust.

The zodiacal light colour temperature depends upon the line of sight direction ($T_{\rm bb} = 261.5 \pm 1.5$ K for the field observed by ISOCAM). When the space distribution is taken into account, the ISO, IRAS and COBE observations are compatible with *no* significant superheating of the interplanetary dust particle, as could be expected from large-size particles.

3.4. The composition of silicates

The ISO spectrum of comet Hale-Bopp has been the object of several independent analyses in terms of silicate composition (Brucato et al. 1999 and Colangeli et al. 1999a; Wooden et al. 1999, 2000; Crovisier et al. 2000; see Fig. 2). These studies qualitatively agree: namely, they conclude to the presence of amorphous silicates, Mg-rich crystalline olivine (close to forsterite), crystalline pyroxene, and a strong continuum contribution, corresponding to uncharacterized components, which cannot be accounted for by a single-temperature black-body curve. These studies differ quantitatively, however (i.e., they lead to significantly different amounts of amorphous silicates, olivine and pyroxene). One can thus question the reliability of the published compositions and especially of the crystalline/amorphous ratios. Obviously, the decomposition of the observed spectrum is not unique. This may be ascribed to the different assumptions made by the different groups of analysts, and to the different laboratory spectra used as cometary matter analogues. In particular, Wooden et al. (1999, 2000) assumed that cometary pyroxene could have a different (cooler) temperature from the other dust components, resulting in a much larger evaluation of the crystalline/amorphous ratio.

3.5. Dust and ice

The presence of icy grains in interstellar and circumstellar matter is testified by many observations. Both crystalline and amorphous water ice are apparently present. In comet Hale-Bopp, grains of water ice were observed at 7 AU from the Sun by Davies et al. (1997a), who tentatively identified amorphous ice in its near-infrared spectrum, and at 3 AU (crystalline ice) in mid- and far-infrared ISO spectra (Lellouch et al. 1998).

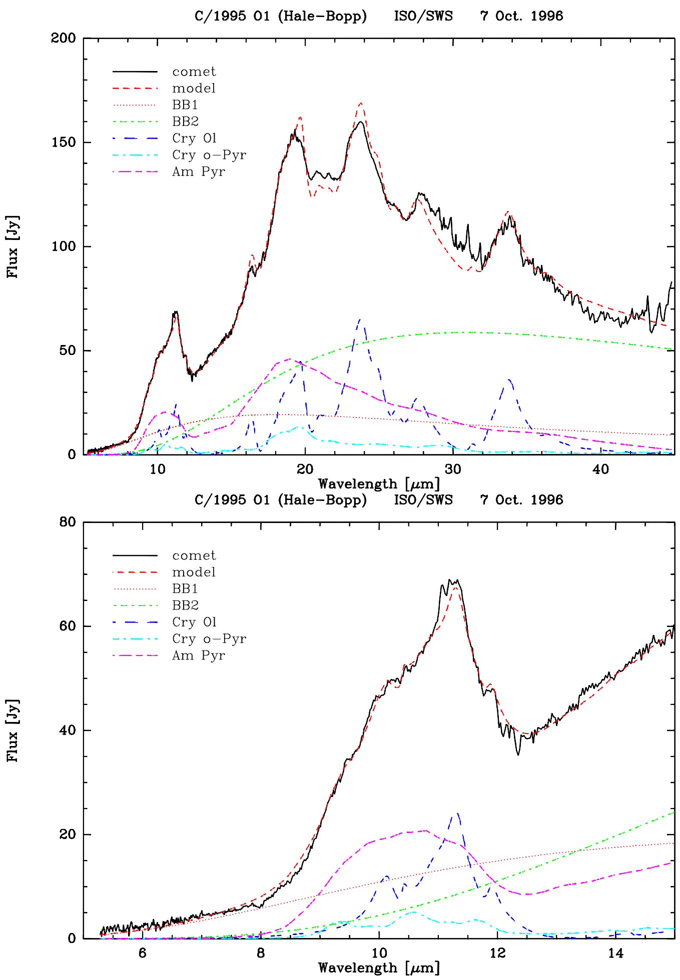

Figure 2. Top: The 6–45 μm SWS spectrum of C/1995 O1 (Hale-Bopp) observed at 2.8 AU from the Sun, decomposed into several emission components: forsterite, ortho-pyroxene, amorphous silicates and two black-body components (from Crovisier et al. 2000). Bottom: Enlargement of the 10 μm region.

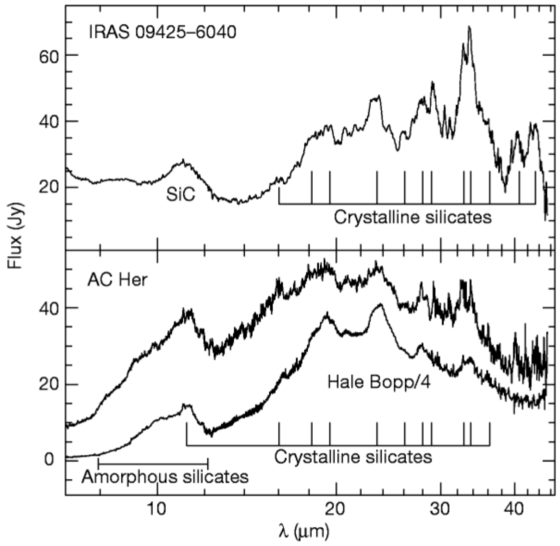

Figure 3. ISO spectra showing amorphous and crystalline silicate features in comet Hale-Bopp, the carbon-rich giant star IRAS 09425–6040, and the post-AGB star AC Herculis. (From Molster et al. 1999.)

3.6. The PAHs issue

Polycyclic aromatic hydrocarbons (PAHs) are ubiquitous in the interstellar and circumstellar media (e.g., d'Hendecourt et al. 1999).

The presence of PAHs in comets is an open issue. The 3.28 μm emission band observed in some comets suggests the existence of aromatics (Bockelée-Morvan et al. 1995). Moreels et al. (1993) have tentatively identified phenantrene in the near-UV spectrum of 1P/Halley, but this is still to be confirmed in high-resolution spectra of other comets. The ISO spectra of comet Hale-Bopp do not show any PAH signal, especially in the 6–8 μm region (Crovisier et al. 1999) where PAH bands well separated from silicate features are obvious in other objects (e.g., Malfait et al. 1998). However, comet Hale-Bopp could only be observed by ISO at heliocentric distances larger than 2.9 AU because of visibility constrains; at these distances, the nucleus and dust temperatures may not be high enough to permit the release of PAHs in the gas phase. No feature at 3.28 μm was reported from ground-based observations of this comet at small $r_{\rm h}$, but it might have been hidden by the very strong dust continuum of this comet.

3.7. Circumstellar dust

The similarity between the ISO spectra of evolved and young stars on the one side, of comet Hale-Bopp on the other side, has been noted many times (Waelkens et al. 1996, 1999; Malfait et al. 1998; Molster et al. 1999; Figs 3 and 4). The analogy of cometary dust with dust in Herbig Ae-Be stars such as HD 100546 is not so surprising in our current scheme of dust evolution, since it is widely accepted that the dust discs around such stars are associated to planetary system formation. Much more surprising is the strong analogy between cometary dust and newly formed dust around evolved stars, such as AC Herculis (Fig. 3). The link between this newly formed dust and planetary system dust passes through a long phase of storage in the interstellar medium, where silicates are observed to be essentially amorphous.

β Pictoris presents the archetype of the Vega-type systems where a second-generation dust disc succeeded the initial disc from the stellar formation stage. Ground-based observations of the 10-μm spectral region undoubtedly shows the presence of crystalline silicates similar to cometary silicates (Knacke et al. 1993). Unfortunately, β Pict is a weak object, and its observation with ISO SWS was deceiving because of the low S/N ratio (Pantin et al.

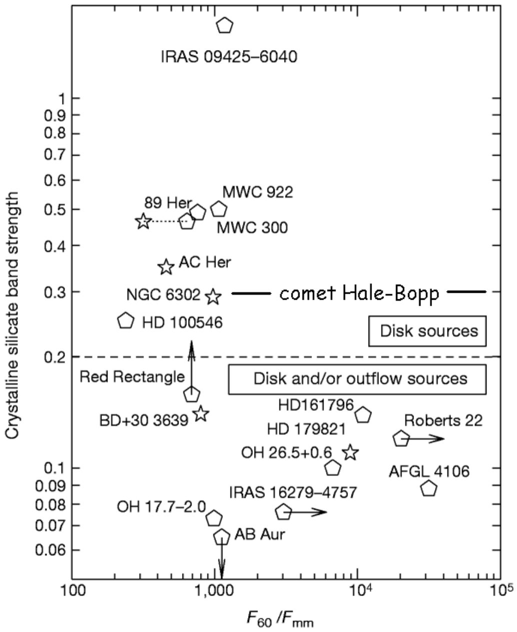

Figure 4. Correlation between the relative strength of the crystalline silicate band at 33.6 μm and the F_{60}/F_{mm} IRAS flux ratio as dust size indicator. (From Molster et al. 1999.) We have added the level of crystallinity of comet Hale-Bopp, for which F_{60}/F_{mm} has not been evaluated.

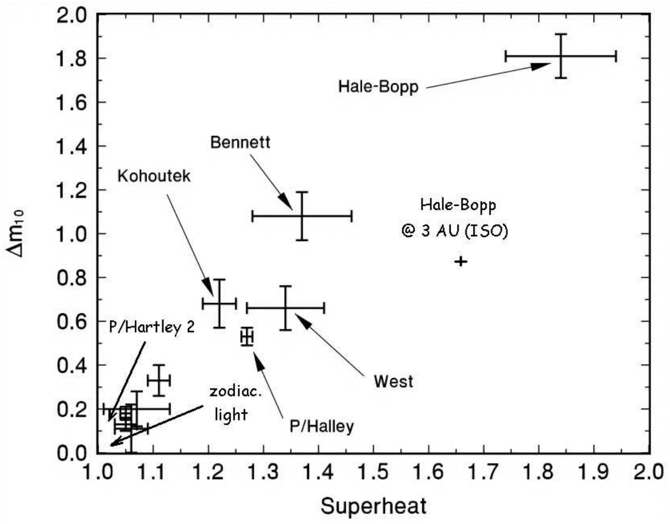

Figure 5. Silicate feature excess (on a magnitude scale) as a function of the superheat factor in comets. The figure is taken from Williams et al. 1997, who have evaluated the superheat factor in the 3–5 μm region. ISO data for comets Hale-Bopp and P/Hartley 2 and for zodiacal light have been added, with the superheat factor evaluated in the 10 μm region.

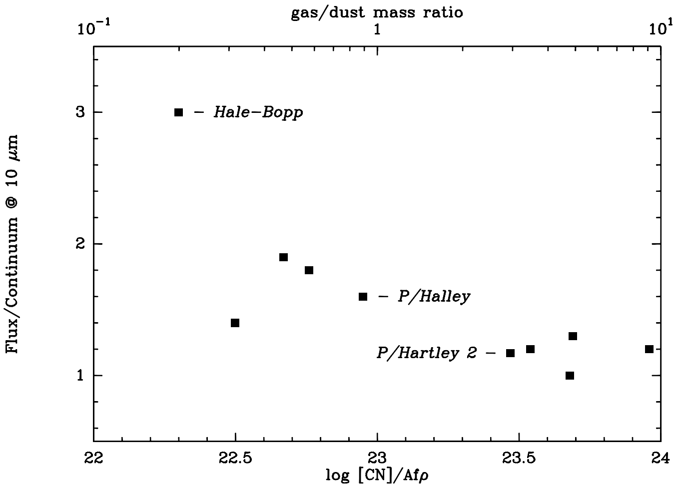

Figure 6. Silicate feature intensity as a function of gas-to-dust ratio for several comets (compiled from A'Hearn et al. 1995, Harker et al. 1999, ISO results, and various other sources).

1999). The LWS spectrum, however, may show signs of crystalline water ice (Pantin, *personal communication*).

3.8. Diversity among comets

Whereas C/1995 O1 (Hale-Bopp) is a comet coming from the Oort cloud, believed to have formed in the Jupiter–Uranus region, 103P/Hartley 2 is a short-period, Jupiter-family comet, believed to have formed in the Edgeworth-Kuiper belt and to have subsequently evolved into a short-period orbit. Comet Hale-Bopp is not only exceptional because of the giant size of its nucleus (≈ 50 km) and of its huge gas and dust production rates, but also because its dust presents the highest silicate strength and superheat factor ever observed (Williams et al. 1997).

Comets show a large diversity in their dust parameters: silicate strength factor, superheat factor, and gas-to-dust ratio. These parameters are linked, as shown in Figs 5 and 6. This diversity may be attributed to different size distributions of the dust particle (Williams et al. 1997; Lisse et al. 1999): small-size particles reflect more efficiently the solar visible light, hence a higher $Af\rho$ parameter; they are subject to important superheating and they are more efficiently emitting silicate bands.

Could this diversity be linked to cometary origins? A'Hearn et al. (1995) have proposed, from spectrophotometry of radicals, that Jupiter-family comets are C_2–depleted relative to CN and OH. This is a controversial result, however (Schulz et al. 1998), and we do not know how it translates into relative abundances of cometary ices (because direct observations of parent molecules in Jupiter-family comets are still sparse). As to the dust properties, there is also a paucity of data for Jupiter-family comets (they are obviously under-represented in Figs 5 and 6). However, they do show extremely weak, or even undetectable silicate bands (e.g., Harker et al. 1999). But the ISO observations suggest that the dust of 103P/Hartley 2, at least, contains crystalline silicates, and is weakly overheated. An extreme case is perhaps comet 2P/Encke which has almost no visible dust tail, but is the source of an important dust trail (Reach et al. 2000). It is certainly premature to conclude that all Jupiter-family comets are preferentially releasing large-size dust particles and to speculate whether this effect could be due to a difference in the initial composition, or to different aging of the two classes of comets (cf. Lisse et al. 1999).

4. CONCLUSIONS AND PENDING PROBLEMS

The ISO results have considerably increased our knowledge on cosmic dust. However, new questions have arisen, challenging further studies.

- Striking similarities were observed between the composition and properties of Solar System dust and of circumstellar dust observed in both evolved and new stars.
- Differences (silicate band strength, overheating) are observed between dust freshly released from comet nuclei and the *old dust* of the cometary trails and IDPs. They may be ascribed to the size-dependent emission of dust particles and size-dependent segregation of dust.
- Considerable differences in cometary dust properties are observed among comets, that can also mainly be explained by different dust particle sizes. Is this due to different origins, or to different evolutions of the comets?
- The different degrees of crystallinity of cosmic dust (partly crystalline in dust-forming regions, amorphous in the interstellar medium, and partly crystalline around young stars and in comet-related dust) are highly surprising and difficult to understand. Some *ad hoc* mechanisms have been proposed: annealing at low temperature in circumstellar environments and amorphization by cosmic ray bombardment in interstellar environments; they will have to be assessed in further studies.
- PAHs are much more difficultly observed in comets than in circumstellar and interstellar dust. Is this due to a real lack of PAHs in cometary material, or to the particularities of the cometary environment?

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