SOLIDS AND VOLATILES IN COMETS

From Cometary Nuclei to Cometary Atmospheres

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Abstract.

Comets occupy a key position in the cycles of ices and dust in the Universe. Their nuclei have mostly kept intact the composition and morphology they had at their formation. The return of a comet close to the Earth and Sun is thus an appreciated opportunity to investigate the original state of the material which built up our Solar System. The physical processes occurring in cometary nuclei and cometary atmospheres, as well as the interface between the two media, are reviewed. The status of our present knowledge of the chemical composition and physical state of comets is presented. The recent observations of comets C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp), which provided a bonanza of new cometary molecules, are outlined. There are strong analogies between interstellar and cometary ices. In contrast, the silicates of cometary dust (for comet Hale-Bopp) are akin to circumstellar, rather than interstellar dust. Different families of comets may have different composition and history, however. These clues will have to be taken into consideration to achieve a consistent scenario of cometary formation.

1. Introduction: comets, a historical perspective

Comet nuclei are conglomerates of ices and dust particles. They spend most of their time at large heliocentric distances as bare solid bodies. When one of them enters the inner Solar System, heating by the Sun causes sublimation of the ice, release of dust, and formation of an expanding atmosphere and of a tail: this is the popular *comet* phenomenon, which may be very spectacular (Fig. 1). Thus, if we unfortunately cannot witness the formation of cometary nuclei — at least in our own Solar System — we have the priv-

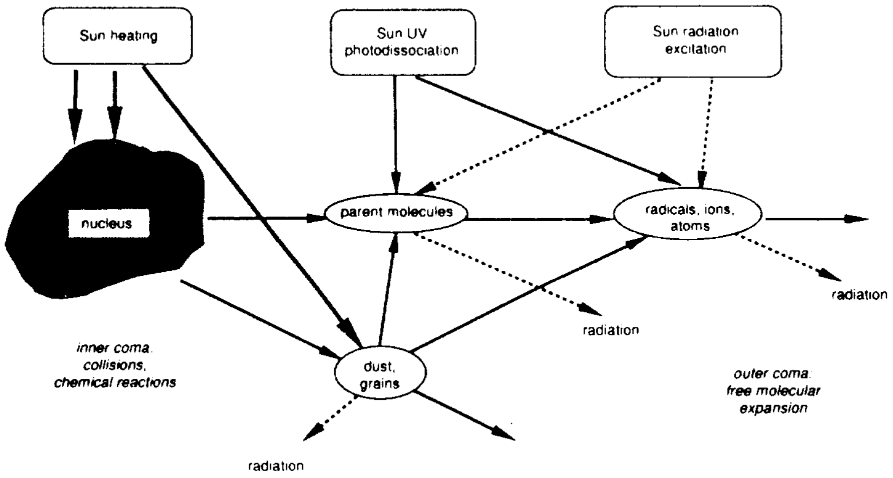

Figure 1. Physical and molecular processes initiated by solar radiation in comets.

ilege to see in many occasions the progressive (or catastrophic) evolution and destruction of these bodies.

Besides the show, the interest for studying comets is at least twofold. First, they are pieces of cosmic matter testifying for the formation of our Solar System. Second, the variety of physical conditions and processes that can be encountered in these objects makes them an appreciated natural laboratory.

Table 1 lists some of the most famous comets as well as several comets which were recently well studied. Since the rule for naming comets changed recently, the correspondence between the old designations (*provisional* and *definitive*) and the new ones is also given, so that the reader could find his way in the literature.

Spectroscopy and the long-term study of the evolution of comets enabled us to understand their nature and composition. It was already known in the 50's that their activity was governed by water sublimation and at that time emerged the *dirty snowball* concept. However, the detailed composition of cometary volatiles was then very uncertain. One had to rely on the presence of secondary species — radicals, ions and atoms — in the visible cometary spectra and to *guess* the nature of their parents. One had to wait for the emergence of astronomical spectroscopy in other spectral domains to see the first direct detections of cometary parent molecules: carbon monoxide in the ultraviolet in 1976 in comet West [49], hydrogen cyanide at radio wavelengths [44] and water in the infrared [86] in 1985 in comet 1P/Halley.

TABLE 1. A selection of famous comets. Comets are listed by order of perihelion date for non-periodic or long-period comets, and by order of periodic comet number for short-period comets. For comets that appeared before 1995, the old-style provisional and definitive numberings are also given.

Comet			perihelion date	q [AU]
C/1882 R1 Great Comet	1882 II	1882b	17 Sep. 1882	0.00775
C/1965 S1 Ikeya-Seki	1965 VIII	1965f	21 Oct. 1965	0.00779
C/1969 Y1 Bennett	1970 II	1969i	20 Mar. 1970	0.538
C/1973 E1 Kohoutek	1973 XII	1973f	28 Dec. 1973	0.142
C/1975 V1 West	1976 VI	1975n	25 Feb. 1976	0.197
C/1980 E1 Bowell	1982 I	1980b	12 Mar. 1982	3.364
C/1983 H1 IRAS-Araki-Alcock	1983 VII	1983d	21 May 1983	0.991
C/1986 P1 Wilson	1987 VII	1986l	20 Apr. 1987	1.200
C/1989 X1 Austin	1990 V	1989c_1	10 Apr. 1990	0.350
C/1990 K1 Levy	1990 XX	1990c	24 Oct. 1990	0.939
C/1996 B2 Hyakutake			1 May 1996	0.230
C/1995 O1 Hale-Bopp			1 Apr. 1997	0.914
D/1993 F2 Shoemaker-Levy 9		1993e		
1P/Halley	1986 III	1982i	9 Feb. 1986	0.587
2P/Encke			23 May. 1997	0.331
21P/Giacobini-Zinner	1985 XIII	1984e	5 Sep. 1985	1.028
22P/Kopff			2 Jul. 1996	1.585
23P/Brorsen-Metcalf	1989 X	1989o	11 Sep. 1989	0.479
29P/Schwassmann-Wachmann 1				5.772
46P/Wirtanen			14 Mar. 1997	1.083
73P/Schwassmann-Wachmann 3			22 Sep. 1995	0.936
95P/Chiron			14 Feb. 1996	8.454
109P/Swift-Tuttle	1992 XXVIII	1992t	12 Dec. 1992	0.958

The space exploration of P/Halley by several space probes [88] permitted for the first time the imaging of a comet nucleus and the *in situ* observation of coma material by mass spectroscopy. Then a rapid sequence of new discoveries took place as new technologies were available or improved. These two last years (1996 and 1997) we were granted with the apparition of two exceptional comets: C/1996 B2 (Hyakutake), which passed at only 0.10 AU from the Earth, and C/1995 O1 (Hale-Bopp), the *Great Comet* of this century, which passed at perihelion on 1 April 1997.

TABLE 2. Characteristics of cometary nuclei and other Solar System small bodies (compiled from various sources).

Object	revolution period [y]	radius [km]	rotation period [h]	albedo
Comets:				
IRAS-Araki-Alcock 1983 VII	long	8×3	?	0.03
Sugano-Saigusa-Fujikawa 1983 V	long	0.4		0.03?
C/1995 O1 (Hale-Bopp)	long	22	11.5	?
109P/Swift-Tuttle	135	12	72.	12
1P/Halley	76.0	8×4	complex	0.04
28P/Neujmin 1	18.2	11×9	12.7	0.02
29P/Schwassmann-Wachmann 1	14.9	20	complex?	0.10
49P/Arend-Rigaux	6.8	7×4	13.6	0.03
31P/Schwassmann-Wachmann 2	6.4	3	5.6	0.04?
10P/Tempel 2	5.5	8×4	8.9	0.02
2P/Encke	3.3	~ 2	15.1	~ 0.03
C/1996 B2 (Hyakutake)	long	~ 1	~ 6	
46P/Wirtanen	5.5	~ 0.6	6?	
Asteroids:				
(4179) Toutatis	4.0	2.3	complex	
(1) Ceres	4.6	456	9.1	0.10
(243) Ida	4.8	28	4.5	
Centaurs:				
(2060) Chiron = 95P/Chiron	50.9	90	5.9	0.13
(5145) Pholus	92.3	~ 100	?	?
Trans-Neptunian objects:				
Pluto	247.7	1150	153	0.61
1992 QB_1	~ 285	~ 100	?	?

2. Physical processes in comets.

2.1. PHYSICAL PROCESSES IN COMETARY NUCLEI

2.1.1. *The physical nature of cometary nuclei*

Little is know on the actual physical properties of comet nuclei. Only 1P/Halley's nucleus has been explored and imaged by a space probe. A bare cometary nucleus can in principle be observed in the same way as an asteroid, providing estimation of its size and albedo from visible and infrared photometry, and of its rotation period from the light curve. However, this is only possible when the comet is inactive, i.e. far from the Sun when the object is very faint. Such informations are summarized in Table 2.

The density of cometary nuclei is still very poorly known. Their masses have never been measured directly (this could be done in the future by orbiting a spacecraft like *ROSETTA* around a comet nucleus). They have been inferred, quite indirectly, by comparing the forces of the rocket effect, due to anisotropic outgassing, to the non-gravitational forces estimated from the perturbations of their orbits [93]. The inferred densities are poorly constrained: from 0.1 to 0.9.

The tensile strength of cometary nuclei is very low. This is testified by the high fragility of these bodies which are very easily disrupted by tidal forces when passing close to Jupiter (e.g. D/1993 F2 (Shoemaker-Levy 9); [89, 114]) or to the Sun (Sun-grazing comets such as C/1965 S1 (Ikeya-Seki)). But there are also many examples of comets which split *spontaneously*, merely under the stresses caused by their activity [25]. Tensile strengths as low as 10^{-3} bar are estimated [59]. This further suggests that cometary nuclei have a low density and are probably a very porous medium.

2.1.2. *Physical processes in cometary nuclei and the activity of distant comets*

The activity of comets is governed by the sublimation of the nucleus ices caused by solar insolation. Close to the Sun, water is believed to be the major sublimating species. At heliocentric distances r larger than ~ 4 AU, however, the equilibrium temperature of the nucleus surface is too low to permit efficient water sublimation. Many examples of cometary activity at larger distances have however been observed: 95P/Chiron at $r \sim 11$ AU, 29P/Schwassmann-Wachmann 1 at $r \sim 6$ AU, the outburst of 1P/Halley observed at $r \sim 14$ AU, C/1995 O1 (Hale-Bopp) already quite active when discovered at $r = 7$ AU. Thus, species more volatile than water should be responsible for these distant activities.

Table 3 lists the sublimation temperatures for a selection of molecular species identified, or likely to be present, in cometary ices. These temperatures, which correspond to pure ice species in equilibrium with their own vapours, must be taken with a pinch of salt, because real cometary ices are mixtures which behave in a much more complicated way. For instance, a significant fraction of CO or CO_2 can remain trapped in water ice at temperatures higher than 100 K [96].

A significant step was made in the understanding of distant activity of comets when important quantities of CO were found to be outgassed from comets 29P/Schwassmann-Wachmann 1 at $r = 6$ AU ([34, 98]; Fig. 3) and C/1995 O1 (Hale-Bopp) at $r = 6.7$ AU [10, 69]. For this latter comet, it was possible to watch for the apparition of every molecular species when it approached from 7 to 1 AU to the Sun (Table 4).

Radio observations of comet C/1995 O1 (Hale-Bopp) also allowed us to monitor the production rates of various molecules from $r = 7$ to 1 AU

TABLE 3. Sublimation temperatures of selected cometary volatiles. Sublimation temperatures are given for a pure species in equilibrium with its own vapour, the total gas density being 10^{13} cm^{-3} with the listed relative abundance [X]/[H] of the given species. These temperatures are either taken from [110] (Y) or extrapolated from the Clausius-Clapeyon equation, using the data of the *Handbook of Chemistry and Physics* for species in the solid (S) or liquid (L) phase.

Species		log [X]/[H]	T_{subl}	Reference
anthracene	$C_{14}H_{10}$	−8	200	HCP(S)
phenanthrene	$C_{14}H_{10}$	−8	160	HCP(S)
naphtalene	$C_{10}H_8$	−8	160	HCP(S)
water	H_2O	−4	152	Y
hydrogen peroxide	H_2O_2	−7	128	HCP(S)
formic acid	HCOOH	−7	112	Y
acetic acid	CH_3COOH	−8	106	HCP(S)
ethanol	C_2H_5OH	−8	105	HCP(L)
benzene	C_6H_6	−8	104	HCP(S)
methanol	CH_3OH	−8	99	Y
hydrogen cyanide	HCN	−7	95	Y
methyl formate	CH_3OHCO	−8	95	HCP(L)
methyl cyanide	CH_3CN	−8	93	HCP
sulphur dioxide	SO_2	−8	83	Y
ammonia	NH_3	−7	78	Y
carbon disulphide	CS_2	−8	78	HCP(L)
cyanoacetylene	HC_3N	−8	74	Y
carbon suboxide	C_3O_2	−8	73	HCP(L)
acetaldehyde	CH_3CHO	−8	73	HCP(L)
carbon dioxide	CO_2	−5	72	Y
propyne	CH_3CCH	−8	65	Y
formaldehyde	H_2CO	−8	64	Y
dimethyl ether	CH_3OCH_3	−8	60	HCP(L)
nitrous oxide	N_2O	−7	59	HCP(S)
hydrogen sulphide	H_2S	−7	57	Y
carbonyl sulphide	OCS	−8	57	HCP(L)
acetylene	C_2H_2	−8	54	HCP(S)
ethane	C_2H_6	−8	44	HCP
ethylene	C_2H_4	−8	38	HCP(L)
methane	CH_4	−4.5	31	Y
carbon monoxide	CO	−5	24	Y
dinitrogen	N_2	−4	22	Y
dihydrogen	H_2	0	5	Y

([9]; Fig. 2). The evolution of the production rates differs from one species to another. For CO and for OH (which traces H_2O), slope variations are observed, which may be related to different regimes of sublimation. For instance, water was detected as far as $r = 4.7$ AU and showed a steep increase up to $r \sim 3$ AU: this may be due to water sublimated from icy grains at these large distances (such icy grains were indeed observed at $r \sim 7$ AU: [41]; Fig. 7).

2.1.3. *Models of cometary nuclei*

A series of thermal models of cometary nuclei have been achieved by several groups (e.g. [24, 72, 96, 112, 115]). They have to take into account:

- the sublimation/recondensation of volatiles in a porous matrix;
- the amorphous-crystalline water ice phase transition, which is exothermal and may induce sublimation of volatiles;
- gas transport in a porous medium;
- heat transport;
- dust transport and mantle formation/destruction, controlling solar heating and ice sublimation;
- the role of nucleus rotation and of the spin axis direction in day-night and seasonal effects;
- the secular variation over several orbits and the possibility of orbit variations.

These models are solving through numerical integration (now in several dimensions) for the gas production evolution of several species as a function of a set of initial parameters (nucleus composition and physical parameters, comet orbital parameters). The main result is that the abundances of volatiles in the coma are a complex function of the abundances of the ices in the nucleus, of the heliocentric distance and of the comet history. In other terms, sublimation fractionation is an important effect, and it would be an error to consider the volatile abundances measured in the coma as directly representative of the cometary ice composition.

2.2. PHYSICAL PROCESSES IN COMETARY ATMOSPHERES

Although the physical processes in cometary atmospheres are not directly relevant to the knowledge of cometary nuclei, they must be fully understood in order to relate the secondary products — which are those observed by remote sensing in cometary atmospheres — to the original material of cometary nuclei.

TABLE 4. Molecules observed in distant comets. Each entry gives the observation at the farthest distance r from the Sun at which the given molecule has been observed.

Comet	r [AU]	molecule	Q 10^{28} s^{-1}	reference
C/1980 E1 (Bowell)	5.2	OH	7.	[4]
	4.6	CN	0.00002	[4]
1P/Halley	4.8	CN	0.0003	[107]
	2.8	OH (radio)		[55]
	2.6	OH (UV)		[50]
95P/Chiron	11.3	CN$^{a)}$	0.14	[23]
		CO (radio)$^{a)}$		*IAUC* 6193
29P/Schwassmann-Wach. 1	5.8	CN	0.0008	[26]
	6.1	CO (radio)	4.	[34, 98]
	6.	CO^+		*several*
C/1995 O1 (Hale-Bopp)	6.7	CO (radio)	2.	[10, 69]
	6.8	CN	0.006	[54, 100]
	4.9	CH_3OH (radio)	0.09	*IAUC* 6382, [9]
	4.8	OH (UV)	1.5	[101]
	4.8	CS (UV)	0.012	[101]
	4.8	HCN (radio)	0.02	*IAUC* 6377
	4.7	OH (radio)	5.	[9]
	4.7	CO_2 (IR)	1.3	[36]
	4.6	C_2	0.05	[91]
	4.6	C_3		[91]
	4.3	H_2S (radio)	0.03	*IAUC* 6408, [9]
	4.3	NH_2		[91]
	4.1	CS (radio)	0.014	[9]
	4.1	H_2CO (radio)	0.01	[9]
	3.4	CH_3CN (radio)	0.012	[9]
	3.4	CO^+		*IAUC* 6468
	2.8	H_2O^+		[91]
	2.4	HNC		[9]

a) unconfirmed observation; see [92].

2.2.1. *Chemistry in cometary atmospheres*

The chemistry of cometary atmospheres and tails is dominated by photolysis due to solar irradiation and interaction with the solar wind. Photolysis is mainly destructive, causing the disruption of the *parent molecules* directly sublimated from the nucleus ices into radicals, molecular ions, atoms and atomic ions — all these species being usually designated as *daughter molecules* (which is a misnomer). Some of the photolysis rates β of cometary

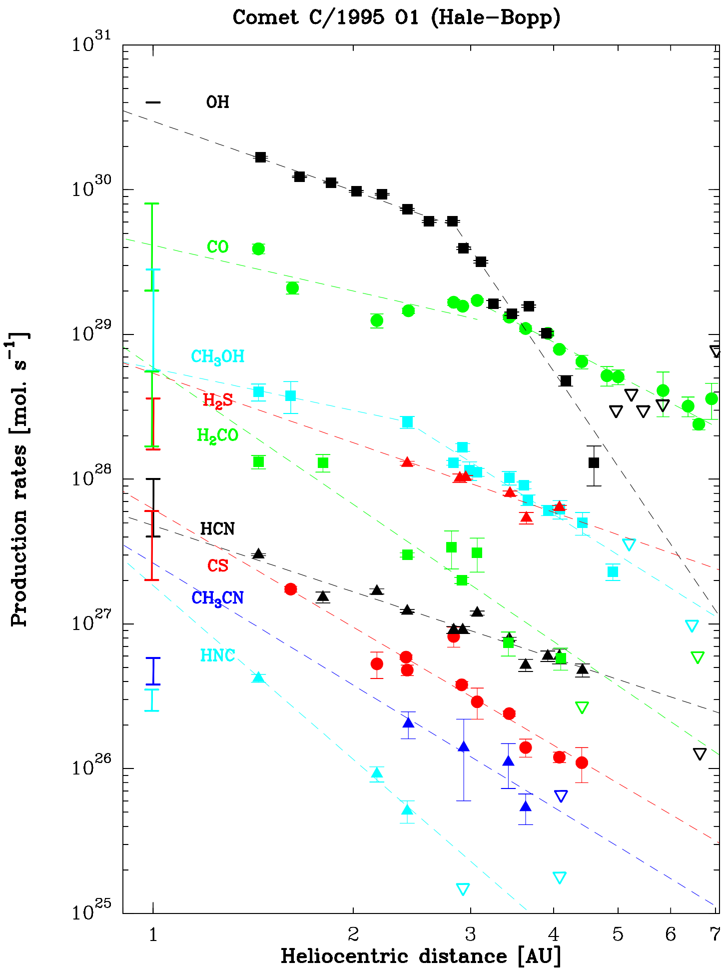

Figure 2. The evolution of molecular production rates in comet C/1995 O1 (Hale-Bopp) as a function of heliocentric distance, derived from pre-perihelion radio observations (from [9]).

parent molecules, from which the lifetimes $1/\beta$ and scalelengths v_{exp}/β may be inferred, are listed in Table 5. At $r = 1$ AU, molecular lifetimes range from hours to days .

Solar photolysis leads to partial ionisation of the cometary atmosphere. Interaction with the energetic ions of the solar wind leads ultimately to the formation of the ionic tail (its main constituents being H_2O^+, CO^+,

TABLE 5. Photo-destruction rates of cometary parent molecules for quiet Sun at 1 AU. Compiled from [32, 65], and references therein.

	Molecule		rate [s^{-1}]
water group:	water	H_2O	1.3×10^{-5}
	hydrogen peroxide	H_2O_2	1.3×10^{-4}
hydrocarbons:	methane	CH_4	8.0×10^{-6}
	acetylene	C_2H_2	1.4×10^{-5}
	ethylene	C_2H_4	4.8×10^{-5}
	ethane	C_2H_6	1.1×10^{-5}
	benzene	C_6H_6	1.1×10^{-3}
CO group:	carbon monoxide	CO	7.5×10^{-7}
	carbon dioxide	CO_2	2.0×10^{-6}
	carbon suboxide	C_3O_2	1.1×10^{-4}
CHO species:	formaldehyde	H_2CO	2.0×10^{-4}
	methanol	CH_3OH	1.3×10^{-5}
	formic acid	$HCOOH$	3.2×10^{-5}
	ethanol	C_2H_5OH	1.8×10^{-5}
	dimethyl ether	$(CH_3)_2O$	3.1×10^{-5}
	acetic acid	CH_3COOH	5.1×10^{-5}
nitrogen compounds:	ammonia	NH_3	1.5×10^{-4}
	hydrogen cyanide	HCN	1.5×10^{-5}
	cyanoacetylene	HC_3N	6.6×10^{-5}
	methyl cyanide	CH_3CN	6.7×10^{-6}
	isocyanic acid	$HNCO$	2.9×10^{-5}
sulphur compounds:	hydrogen sulphide	H_2S	2.5×10^{-4}
	carbon disulphide	CS_2	1.7×10^{-3}
	sulphur monoxide	SO	1.5×10^{-4}
	sulphur dioxide	SO_2	2.1×10^{-4}
	carbonyl sulphide	OCS	9.4×10^{-5}

CO_2^+). In the collisional region of the coma, ion-neutral reactions are much more efficient that neutral-neutral reactions, and lead to the formation of protonated molecules. Of these, HCO^+ and H_3O^+ have been recently identified by radio spectroscopy in C/1995 O1 (Hale-Bopp). But several others such as NH_4^+ and H_3S^+ have been inferred from the mass spectra observed *in situ* in 1P/Halley.

An important ingredient to cometary chemistry is the role of grains, which are now recognized to be a significant source of release of molecules in the coma. This will be detailed in Section 3.3.

2.2.2. *Physics of cometary atmospheres*

Due to the very low gravity of comets, cometary atmospheres are not captive: they expand. This expansion, which is almost adiabatic, is similar to those of supersonic jets. The kinetic temperature is dropping rapidly with distance to nucleus. After several thousands kilometres from the nucleus, collisions are rare and the expanding atmosphere is similar to a free molecular jet.

The photodissociation of parent molecules by solar UV radiation produces high-velocity atoms and radicals which, if they can get thermalized by collisions, will heat the coma and increase its expansion velocity. The cometary atmosphere can also be radiatively cooled; the most efficient process is the emission of water rotational lines, but the large optical depth of these lines limits the efficiency of this process.

The temperatures and expansion velocities of the coma were measured *in situ* in comet Halley by the *Giotto* probe. They can also be measured by remote sensing. The analysis of radio line shapes (Fig. 3) provides the expansion velocity. The rotational population distribution of molecules, which can be determined from their rotational radio lines (Fig. 4) or their rovibrational IR lines (Fig. 12), provides the coma temperature.

Observed expansion velocities v_{exp} range from less than 0.5 to more than 1 km s^{-1}, and temperatures T_{kin}, from about 10 K to about 100 K, when comets are approaching from $r \sim 6$ to ~ 1 AU [9]. v_{exp} and T_{kin} are controlled not only by r, but also by the total gas production rate Q of the comet, which governs the collision rates and thus the efficiency of the photolytic heating. Except for comet Halley for which they were measured *in situ*, the velocity and temperature profiles (i.e. their variation with distance to nucleus) are still poorly known.

Many detailed models of the hydrodynamical processes within cometary atmospheres have been achieved [29, 30]. They are qualitatively in good agreement with the observed v_{exp} and T_{kin}, and their variations with r, Q and distance to nucleus.

The formation and evolution of cometary tails, their relation with interstellar dust, will not be reviewed here (see [42]).

3. The composition of comets from remote-sensing observations

Our knowledge of the composition of cometary ices built up progressively. First, by guessing which molecules could be the parents of the radicals identified in the visible spectra. Then, with the help of the newly developed techniques: ultraviolet, radio and infrared spectroscopy, which enabled us to look for the signatures of parent molecules, not present in the visible domain. The space exploration of Halley's comet in 1986 and the ground-

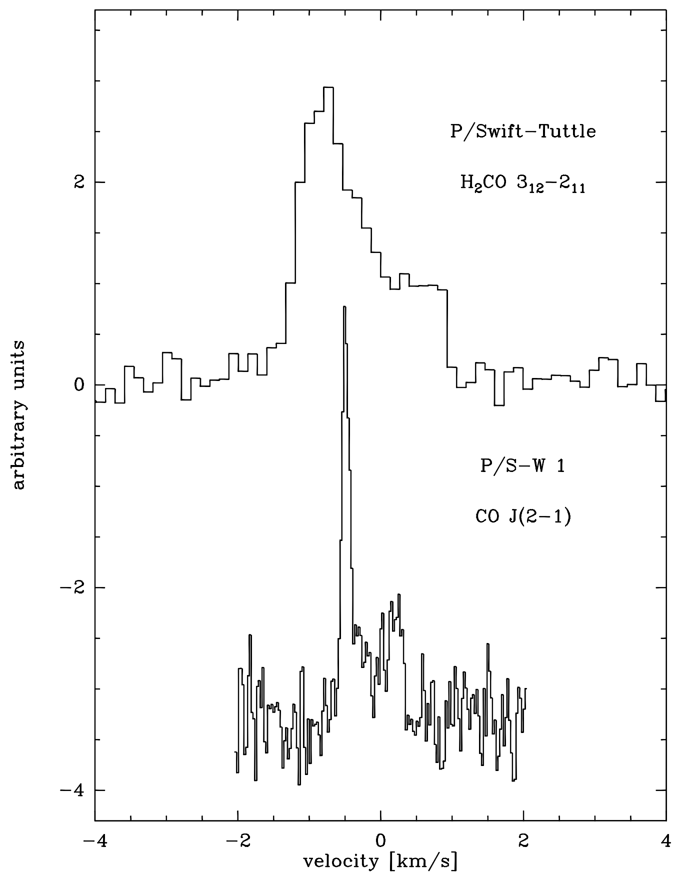

Figure 3. Two extreme examples of radio line profiles probing the kinematics of the coma. Top: the $3_{12} - 2_{11}$ formaldehyde line in 109P/Swift-Tuttle at 1 AU from the Sun; at this distance, strong sunward jets were present and the coma had a high expansion velocity (from [43]). Bottom: the $J(2-1)$ carbon monoxide line in 29P/Schwassmann-Wachmann 1 at 6 AU from the Sun; the coma was very cold (probably less than 10 K to explain the very narrow feature at negative velocities) and the expansion velocity was small (from [34]).

based International Halley Watch were an important milestone. Then several bright comets contributed to improve our knowledge: C/1986 P1 (Wilson), C/1989 X1 (Austin), C/1990 K1 (Levy), 109P/Swift-Tuttle...But

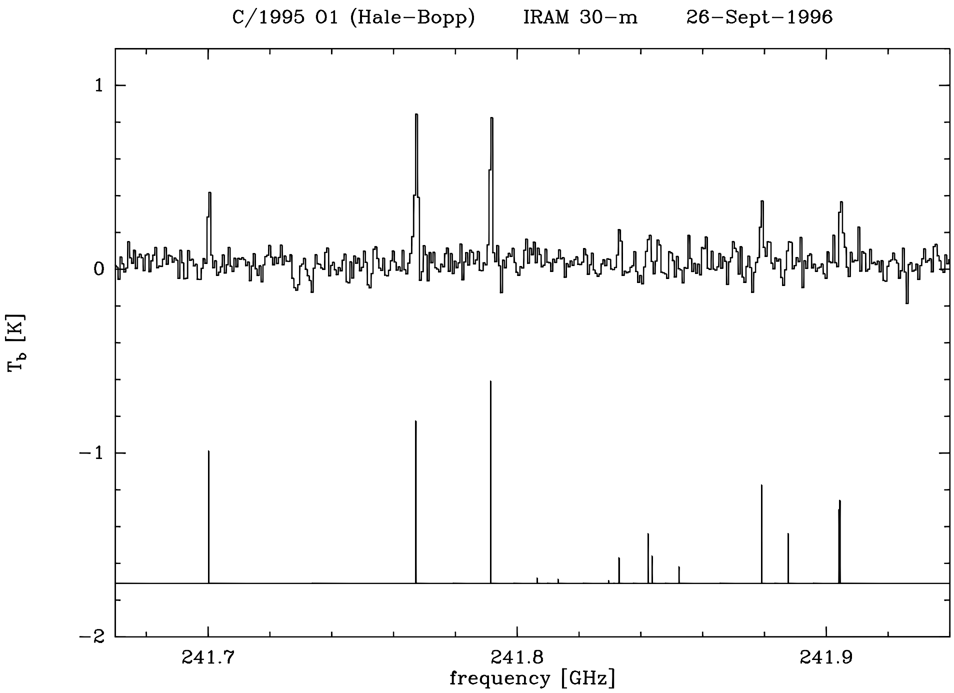

Figure 4. The lines of methanol around 242 GHz observed at IRAM in comet C/1995 O1 (Hale-Bopp), from which an accurate rotational temperature can be determined (from [11].)

a dramatic new step was made recently with the two exceptional comets C/1996 B2 (Hyakutake) and C/1996 B2 (Hyakutake).

3.1. THE COMPOSITION OF COMETARY ICES

Spectroscopy is a very powerful tool for investigating the composition of cometary gases. Cometary molecules are emitting through their electronic systems and vibrational bands following fluorescence excited by the Sun's radiation. Emission rates (the so-called g-factors, i.e. the numbers of photons emitted per second by one molecule) are typically 10^{-4} s^{-1} for fundamental bands of vibrations, 10^{-3} to 10^{-2} s^{-1} for electronic systems at 1 AU from the Sun. Unfortunately, for *parent* molecules, the electronic systems are not in the visible domain, but rather in the UV where their excitation by the Sun leads to destruction of the molecule rather than to fluorescence. Important exceptions are for CO, SO, SO_2 and S_2 which have strong non-dissociative electronic bands in the UV or near-UV. Vibrational fundamental bands are all in the IR, longward of 2.5 μm. Rotational lines are in the radio domain. They are excited both radiatively, at the final step of

TABLE 6. Parent molecules in comets: the chronology of first detections.

Year	comet/technique	molecules
1973	C/1973 E1 (Kohoutek)	
	radio	HCN?
1976	C/1975 V1 (West)	
	UV	CO
1983	C/1983 H1 (IRAS-Araki-Alcock)	
	radio	NH_3?
	UV	S_2
1985–86	1P/Halley	
	radio	HCN, H_2CO?
	IR	H_2O, CO_2
1990	C/1989 X1 (Austin), C/1990 K1 (Levy)	
	radio	H_2CO, H_2S, CH_3OH
1996	C/1996 B2 (Hyakutake)	
	radio	NH_3, HDO, HNC, CH_3CN, OCS? HNCO?
	IR	CH_4, C_2H_2, C_2H_6
1997	C/1995 O1 (Hale-Bopp)	
	radio	OCS, HNCO, HC_3N, SO_2, HCOOH, H_2CS, NH_2CHO, $HCOOCH_3$

the fluorescence cascades, and thermally by collisions. Radio spectroscopy proved to be a very sensitive way to probe even minor constituents. However, a whole class of molecules escape radio observations: the non-polar symmetric molecules, among which CO_2 and most of the simplest hydrocarbons. On the other hand, water and light hydrides have their stronger rotational lines in a submillimetric domain inaccessible from the ground.

It is usual to evaluate the abundances of cometary volatiles with respect to water, which appears to be the main constituent of cometary ices. Water, however, is very difficult to observe directly and its production rate has to be evaluated from the observations of its secondary products, such as the OH radical or the O and H atoms. Water has been directly observed from space in a very few number of comets, using the Kuiper Airborne Observatory [76, 86, 103], the *Vega* probes [28] or *ISO* [36, 38]. However, it has been recently demonstrated that the lines of a hot vibrational band of water can be observed from the ground using high-resolution infrared spectroscopy [84].

Table 6 lists the successive discoveries of cometary parent molecules from remote sensing and Table 7 summarizes our current knowledge of the abundances of cometary ices. It must be emphasized that these abundances may be still ill-known due to shortcomings in our knowledge of the molec-

TABLE 7. Abundances of cometary volatiles. This table has been established from [12,31] and from the preliminary reports given in the *IAU Circ.* for the results on comets C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp).

molecule	abundance (a)	method (b)	Nb (c)	comments
H_2O	=100.	IR	6	also indirect (from OH, O, H)
HDO	0.05	radio	2	
CO	2–20.	UV, radio, IR	> 5	extended source?
CO_2	2–6.	IR	2	
H_2CO	0.05–4.	radio	> 5	extended source
CH_3OH	1–7.	radio, IR	> 5	
HCOOH	~ 0.1	radio	1	
HNCO	0.07	radio	2	
NH_2CHO	~ 0.1	radio	1	
$HCOOCH_3$	0.05	radio	1	
CH_4	0.7	IR	2	
C_2H_2	0.3–0.9	IR	2	
C_2H_6	0.4	IR	2	
NH_3	0.5	radio	3	also indirect (from NH, NH_2)
HCN	0.1–0.2	radio, IR	> 5	
HNC	0.01	radio	2	
CH_3CN	0.01	radio	2	
HC_3N	0.01	radio	1	
H_2S	0.3	radio	> 5	
H_2CS	0.01	radio	1	
CS	0.1	UV, radio	> 5	from CS_2?
OCS	0.3	radio	2	
SO	~ 0.5	radio	1	from SO_2?
SO_2	~ 0.1	radio	1	
S_2	0.005–0.2	UV	2	

(a) abundance relative to water (100); listed abundances may be uncertain by a factor of 2 or more for some species.
(b) method of observation.
(c) number of comets in which this species was reliably and directly observed.

ular excitation conditions or space distributions. It must also be noted that many molecules with significant abundances may still have escaped detection, just because they do not have spectral signals appropriate for observation with present techniques (this may well be the case for the H_2, N_2 and O_2 molecules).

Detailed reviews on the composition of cometary volatiles may be found elsewhere [12, 16, 31, 52, 87]. They will not be repeated here, but a few

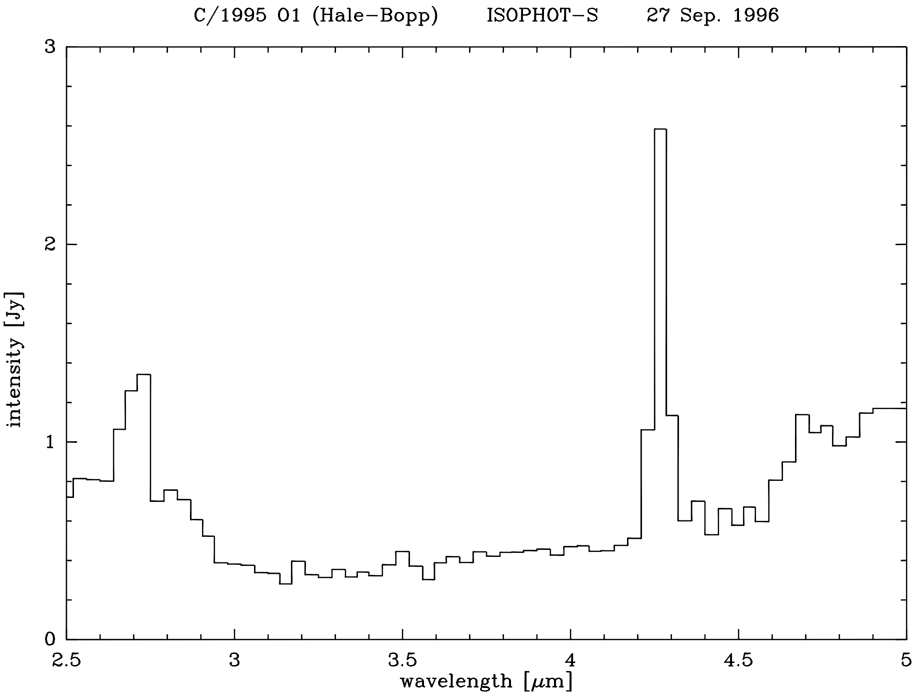

Figure 5. The 2.5–5 μm spectrum of comet C/1995 O1 (Hale-Bopp) observed at 2.9 AU from the Sun with the PHT-S instrument of *ISO*. The aperture is 24" × 24" and the spectral resolution is $\lambda/\delta\lambda \sim 90$. One can see the ν_3 band of H_2O at 2.9 μm, the ν_2 band of CO_2 at 4.25 μm, and the $v(1-0)$ band of CO at 4.65 μm (from [38]).

points raised by recent observations will be stressed below.

- Carbon dioxide is an important constituent of cometary ices, but it is very difficult to observe. It could only be observed directly from space in comets 1P/Halley from the *Vega* probes [28] and in C/1995 O1 (Hale-Bopp) with *ISO* (Fig. 5; [36, 38]). However, the *Cameron* bands of CO in the UV observed in comets are believed to come from prompt emission following photodissociation of CO_2 and could trace carbon dioxide [102].
- The C_2 and C_3 radicals have been for a long time *orphan molecules* for which no parent could be identified. This is no longer the case with the identification of several species with a C_2 skeleton (C_2H_2, C_2H_6, CH_3CN) and one with a C_3 skeleton (HC_3N).
- Many nitrogen-bearing molecules are now known; several nitriles (HCN, HNC, HC_3N, CH_3CN), HNCO [77], NH_2CHO and ammonia which is now firmly identified from radio observations [106]. The nitrogen depletion formerly found in comets is no longer a problem [51,

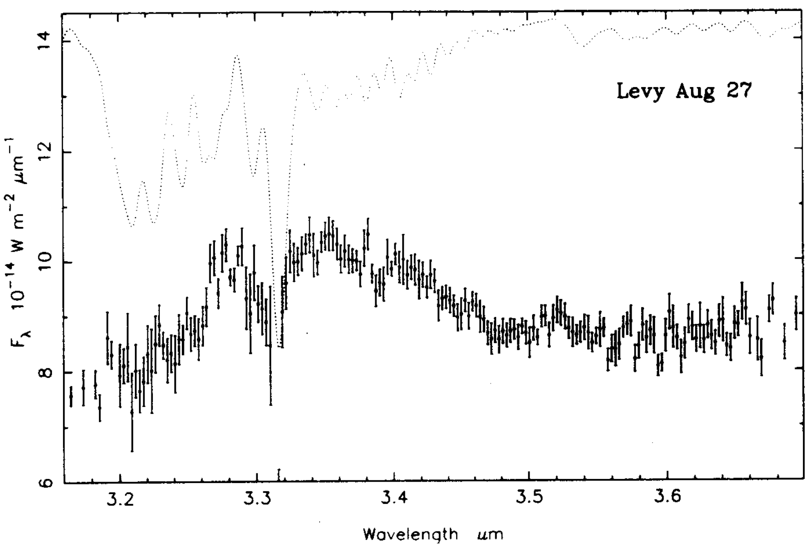

Figure 6. The spectrum of comet C/1990 K1 (Levy) observed on August 27 at the UKIRT telescope (from [39]). The top curve shows the transmission of the atmosphere. The feature at 3.52 μm is attributed to methanol (ν_3 band), the feature at 3.28 μm is possibly due to aromatics, and the broader feature at 3.4 μm is due to methanol and other species.

108, 109]. N_2, however, is still an elusive molecule (only inferred from difficult observations of the N_2^+ ion; [109]).

– Sulphur is now well represented with H_2S, OCS, CS (which could trace CS_2), SO, SO_2 and H_2CS [37, 81]. The S_2 molecule has now been observed in two comets which passed close to the Earth — C/1983 H1 (IRAS-Araki-Alcock) [1] and C/1996 B2 (Hyakutake) — but its origin is still mysterious. However, it has been suggested that it could have been produced by protoprocessing of interstellar dust mantles [111].
– The 3.2–3.5 μm emission band in comets has had for a long time a mysterious origin. Methanol is known to be an important contributor [14, 18, 19, 40, 63, 64]. Other contributors among species recently identified are ethane (C_2H_6) and formic acid (HCOOH). But other contributors, possibly in the dust phase, may still be present. A discrete band at 3.28 μm seen in several comets (Fig. 6; [14, 39]) is indicative of the presence of aromatics.
– There are still many unidentified lines in visible and IR cometary spectra, presumably due to ions, radicals or even parent molecules [6, 21, 22, 83]. Their identification is pending to laboratory work.

TABLE 8. The elemental composition of comets. Average elemental abundances measured in comet C/1965 S1 (Ikeya-Seki) (from [7]), in Halley's dust grains and in the whole comet dust and volatiles (from [67]), and in other solar system objects (from [5]). The abundances are normalized to Mg (to the solar system abundance of Fe for Ikeya-Seki, in which Mg was not observed).

element	Ikeya-Seki[a)]	P/Halley		Solar system	CI-chondrite
		dust	dust + ice		
H		2 025.	4 062.	2.6×10^6	492.
Li	†			0.0053	0.0053
C		814.	1 010.	0.	70.5
N		42.	95.	291.	5.6
O		890.	2 040.	2 216.	712.
Na	†	10.	10.	5.3	5.3
Mg	(=100.0)	=100.0	=100.0	=100.0	=100.0
Al		6.8	6.8	7.9	7.9
Si		185.	185.	93.	93.
P				1.0	1.0
S		72.	72.	48.	48.
K	†	0.2	0.2	0.35	0.35
Ca		6.3	6.3	5.7	5.7
Ti	<0.02	0.4	0.4	0.22	0.22
V	0.01			0.027	0.027
Cr	0.08	0.9	0.9	1.3	1.3
Mn	0.5	0.5	0.5	0.89	0.89
Fe	84.	52.	52.	84.	84.
Co	0.4	0.3	0.3	0.21	0.21
Ni	7.2	4.1	4.1	4.6	4.6
Cu	0.2			0.049	0.049

a) In addition, abundances relative to Na were determined to be 1.6×10^{-3} for K and $< 2.5\times10^{-5}$ for Li [90].

3.2. THE COMPOSITION OF COMETARY DUST

The *elemental* composition of cometary material could be determined (or constrained) in specific occasions.

- Comets passing very close to the Sun — the so-called *sun-grazers* — are disrupted and their refractories are volatilised. Their spectra show many atomic (mainly metallic) lines. A well documented case was that of comet C/1965 S1 (Ikeya-Seki) ([6, 90]; Table 8).
- The *Giotto* and *VEGA* mass spectrometers determined the elemental composition of 1P/Halley's dust particles ([67, 70]; Table 8).
- Recently, comet D/1993 F2 (Shoemaker-Levy 9) crashed on Jupiter. Its material was totally volatilised. The spectra lines of many atomic

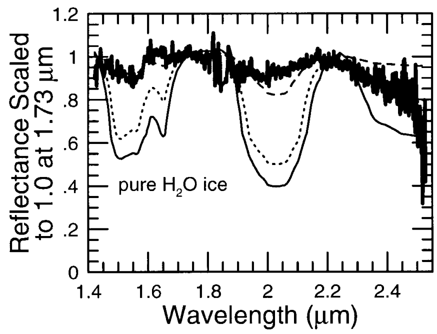

Figure 7. The 1.4–2.5 μm spectrum of comet C/1995 O1 (Hale-Bopp) observed at 7 AU from the Sun at UKIRT. The broad absorptions at 1.5 and 2.05 μm are attributed to water ice. The plain and dotted lines show a model spectrum of water ice (from [41]).

and molecular species (H_2O, CO, NH_3, HCN, S_2, CS, OCS, silicates), normally not present in the Jupiter spectrum, appeared during or just after the impact. It is, however, not easy to distinguish between original cometary material and processed Jupiter atmosphere. Atomic lines (Li, Na, Ca, Si, Fe, Mg, Mn, Cr) however, seen in the plumes following the impacts, could be attributed unambiguously to cometary matter (see review in [33] and references therein).

The study of cometary dust by mass spectroscopy, which is the subject of another lecture [70], will not be reviewed here. The composition of cometary dust can be also investigated by infrared spectroscopy. Infrared spectroscopy at low resolution revealed excess emissions at 10 and 20 μm, which correspond to the stretching and bending modes of the Si–O bond, respectively. Hence the hypothesis that silicates are an important constituent of cometary dust.

Two main kinds of silicates are olivines and pyroxenes. Olivines are solid solutions of fayalite (Fe_2SiO_4) and forsterite (Mg_2SiO_4). Pyroxenes are solid solutions of enstatite ($MgSiO_3$), ferrosilite ($FeSiO_3$) and wollastonite ($CaSiO_3$). The IR spectrum of all these species, when amorphous, presents only broad, featureless bands at 10 and 20 μm. In the crystalline form, these species have a structured 10 μm band and present a series of additional features at wavelengths depending upon their composition.

Detailed ground-based observations of the 10 μm band in several comets showed revealed that cometary dust could contain amorphous or crys-

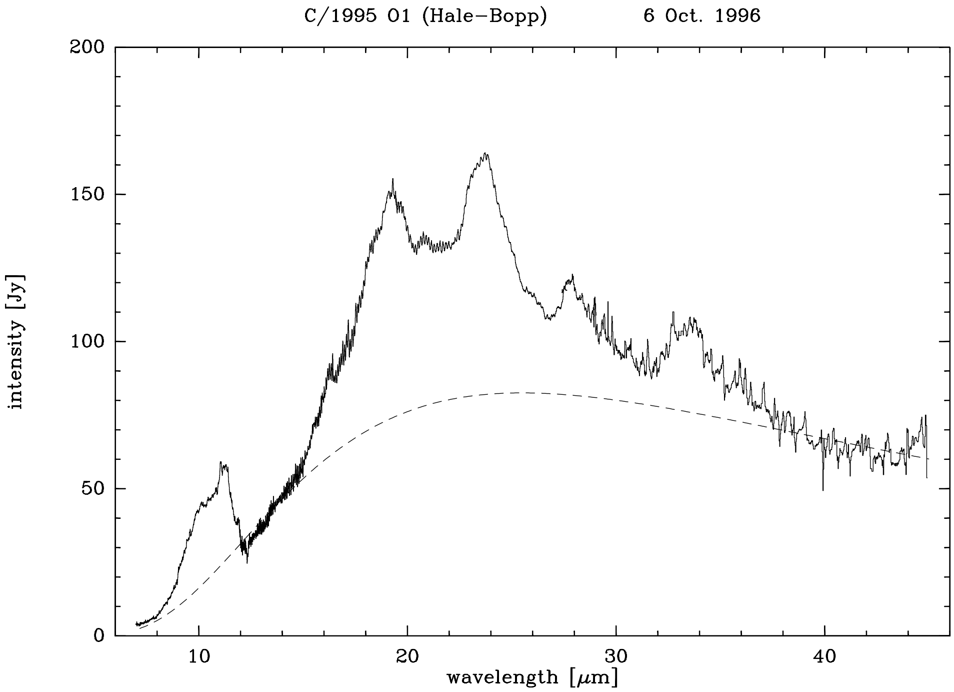

Figure 8. The 7–45 μm spectrum of comet C/1995 O1 (Hale-Bopp) at 2.9 AU from the Sun observed by the short-wavelength spectrometer of *ISO*. The spectral resolution has been degraded to $\lambda/\delta\lambda \sim 500$. The dotted line shows a 200 K black body emission. All spectral features in this region are attributed to Mg-rich crystalline olivine (from [38]).

talline silicates, depending upon the object (e.g. [60, 61]). Only for comet 1P/Halley could the dust spectrum be investigated at longer wavelengths, revealing features indicative of crystalline silicates [56, 62].

ISO observations of the complete 7 to 45 μm spectrum of comet Hale-Bopp at high-resolution (Fig. 8; [38]) showed a spectrum which is best matched by crystalline Mg-rich olivine (i.e. forsterite Mg_2SiO_4).

3.3. GRAINS AS SOURCES OF VOLATILES

It has been inferred in several occasions that grains could be important sources of volatiles in the coma. This is supported by several pieces of evidence:

- The necessity to include *extended* sources to explain the space distribution of CO [47] and H_2CO [16, 27].
- The space distribution of the CN radical [2], showing jets which could be related to dust jets.

- The production of water at large heliocentric distances, which can only be explained by superheated icy grains [9].
- The water ice absorption feature observed in comet Hale-Bopp at $r \sim$ 7 AU (Fig. 7; [41]), pointing to the presence of icy grains
- The high CHON content of some grains observed by mass spectroscopy [67, 70], attributed to an organic mantle.

Icy grains are undoubtedly subject to a high sublimation rate and important contributors to the gas production (see Section 2.1.2). Their lifetime, however, is very short at small r's. They thus can difficultly account for the distributed sources of CO and H_2CO at these heliocentric distances. The sublimation of *semi-refractory* species can also occur (e.g. PAH's).

The release of molecules or radicals from the refractory organic mantle of grains requires high energy processes. Sputtering by solar UV photons or high-velocity ions have been invoked. These processes, however, are highly inefficient, because of the small cross-section of molecules condensed on grains, and cannot account for significant molecular production rates.

3.4. THE DIVERSITY OF COMETS

Are comets all alike, or do they present diversity of composition? If existing, is this diversity related to a diversity of origin or history?

There are extreme cases of diversity: comet C/1988 Y1 (Yanaka) was dramatically depleted in C_2 and CN, but showed prominent bands of NH_2 [53]; comet 43P/Wolf-Harrington was depleted in C_2 and C_3 relative to CN and OH [95]. A systematic study of cometary composition, using narrow-band photometric observations of the OH, CN, C_2, C_3 and NH, has been undertaken on 85 comets [3]. A class of *carbon-depleted comets* which exhibits a lower $Q[C_2]/Q[CN]$ was identified. This class is significantly correlated with Jupiter-family comets

It would be interesting to investigate the meaning of such a correlation, by studying the variations of relative abundances of parent molecules rather than the daughter products. Unfortunately, such data, which require observations at radio or IR wavelengths, are available for less than ten comets, among which Jupiter-family comets (which are faint objects) are poorly represented. If important variations on molecular abundances, such as those of CH_3OH or H_2CO, do exist, it is not yet possible to relate them to cometary families.

Concerning cometary dust, the 10-μm feature shape points to either crystalline or amorphous silicates. Both classes are represented for all families of comets [60, 61].

TABLE 9. Comparison of the abundances of ices in the interstellar medium (towards IRS9) and of cometary volatiles (at $\sim$ 1 AU). Cometary abundances are from Table 7. ISM ice abundances are taken from a compilation of [97] from various sources as well as from recent *ISO* results [45, 105].

species	interstellar ices		cometary volatiles	
H_2O	$=100$		$=100$	
CO	10–40		2–20	
CH_3OH	5		1–7	
CO_2	10		2–6	
H_2CO	2–6	tentative	0.05–4	
HCOOH	3	tentative	~ 0.1	
CH_4	1–2		0.7	
other hydrocarbons	??		~ 1	C_2H_2, C_2H_6
NH_3	< 10		0.5	
O_3	≤ 2		??	
XCN	$\leq 0.5 - 2$		0.2	nitriles + HNCO
OCS, XCS	0.2		0.4	OCS + CS
SO_2	??		~ 0.1	
H_2	$>\sim 1$		??	
N_2	??		??	
O_2	??		??	

4. The origin of comets

The composition and physical state of cometary material are important clues to the origin and formation of comets.

4.1. COMETARY MATTER AND INTERSTELLAR MATTER

4.1.1. *The gross composition of cometary ices.*

Table 9 compares the composition of interstellar ices with that of the cometary volatiles. One must have in mind the importance of sublimation fractionation already stressed out in Sections 2.1.2 and 2.1.3. However, it is striking that cometary and interstellar ices have quite comparable relative abundances.

It has been noted [21, 83] that the important abundance of C_2 hydrocarbons (C_2H_2 and C_2H_6) relative to methane excludes a formation chemical reactions at thermal equilibrium.

The HNCO molecule recently identified might be the sublimation product of the OCN^- ion supposed to be present in ISM ices by [97].

4.1.2. *Cometary dust.*
C/1995 O1 (Hale-Bopp) is the first comet for which, thanks to *ISO* observations, a constituent of dust could be clearly identified: Mg-rich crystalline silicates, from the 6–45 μm high-resolution spectrum (Fig. 8; [38]).

There is no evidence of crystalline silicates in ISM dust. This is attested by the featureless 10 and 20 μm absorption bands and the absence of other dust features (see e.g. the IR absorption spectrum observed by *ISO* towards the Galactic Centre; [79]).

The dust in discs or envelopes of some stars do contain crystalline silicates. The β Pic disc presents a 10 μm feature with the characteristic structure of crystalline silicates [73]. Another case is HD 100546 is an object intermediate between Herbig Ae/Be stars and Vega-type objects for which *ISO* observations are available [99]. Its 6–45 μm spectrum shows the same features as that of comet Hale-Bopp, suggesting that dust in its disc also contains crystalline forsterite.

It may be surprising that cometary dust — at least that analyzed in comet Hale-Bopp — only shows the features of crystalline forsterite. The silicates of interplanetary dust particles (*IDPs*) contain a large fraction of pyroxenes and are mostly amorphous [20].

It has been argued that crystalline silicates could form in the coma itself through annealing of amorphous silicates in dust grains heated by the Sun. However, this hypothesis is ruined by the observation that olivine could be crystalline also far from the Sun (at $r = 4.6$ AU in comet Hale-Bopp; [36]) where the temperature is obviously too small for this process to occur.

4.1.3. *Isotopic ratios.*
Besides deuterium, isotopic species abundances are available for ^{13}C, ^{15}N, ^{18}O, and ^{34}S (Table 10). Measurements come either from *in situ* mass spectroscopy of dust particle in 1P/Halley, or high-resolution spectroscopy of recent comets (radio and visible). If one considers only the results of the highest accuracy, the isotopic ratios are *normal* (solar). One should note that the isotopic ratios for these species in the interstellar medium are also *normal*. However, *Giotto* measurements of individual grains revealed a high dispersion of the [^{13}C]/[^{12}C] ratio [67, 70].

The situation is quite different for deuterium; The [D]/[H] ratio has been measured in 1P/Halley from H_3O^+ observed by mass spectroscopy, and converted by modelling ion-neutral reactions to [D]/[H] in cometary water ice ([8, 48]; Table 10). A radio line of HDO was also observed in comet C/1996 B2 (Hyakutake) (Fig. 9). For both comets [D]/[H] $\sim 3\times10^{-4}$. This shows an important deuterium enrichment over the [D]/[H] values for the local interstellar medium ($\sim 1.5 \times 10^{-5}$) and the protosolar nebula ($\sim 2 \times 10^{-5}$). It is even larger than the Earth oceans value (1.5×10^{-4}),

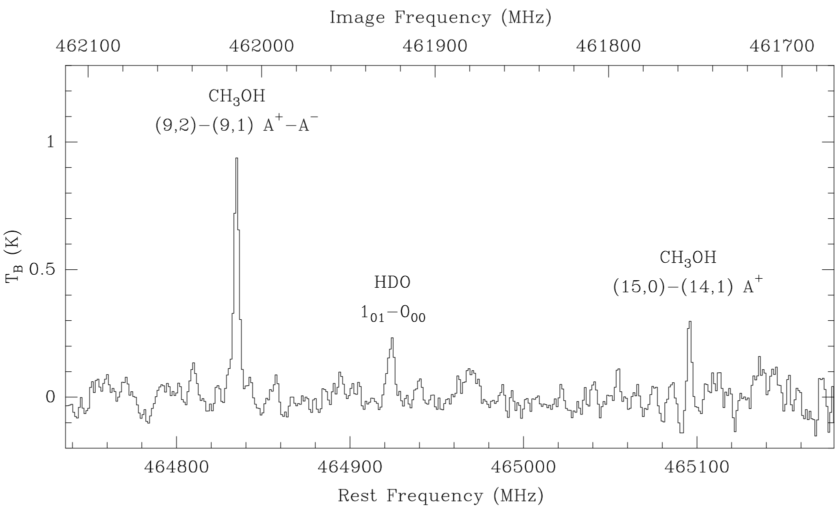

Figure 9. The $1_{10}-0_{00}$ HDO line at 465 GHz observed in comet C/1996 B2 (Hyakutake) at the Caltech Submillimeter Observatory. Two lines of methanol were observed in the same spectrum (from [13]).

suggesting that the Earth oceans were not due to infalling comets. On the other hand, important deuterium enrichments are also found for several interstellar molecules, including interstellar water.

4.1.4. *The [HNC]/[HCN] ratio.*

The HNC molecule has been detected in comets C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp) (Fig. 10; [66]). HNC is an unstable isomer of hydrogen cyanide HCN: at room temperature, [HNC]/[HCN] $< 10^{-15}$. In the interstellar medium, HNC is an abundant molecule with [HNC]/[HCN] as large as 1 in some clouds. In comets, [HNC]/[HCN] can be readily derived, because the same rotational transitions of the two molecules are observed in the same conditions and may be supposed to be excited in a similar way (a correction for possible saturation of the HCN lines is however necessary). A ratio [HNC]/[HCN] ~ 0.06 was observed for comet Hyakutake at $r \sim 1.1$ AU [66], which is typical of interstellar abundance ratios. This shows that cometary volatiles were not (all) formed by thermal equilibrium processes. In the interstellar medium, HNC and HCN are believed to be formed as the result of ion-neutral reactions, one of the final processes being

TABLE 10. Isotopic ratios in comets.

Isotopes		comet	method	cosmic	comet value	ref.
D/H	H_3O^+	1P/Halley	mass	1.5×10^{-5}	$3.08 \pm 0.53 \times 10^{-4}$	[8]
					$3.02 \pm 0.22 \times 10^{-4}$	[48]
	OH	1P/Halley	UV		$< 5 \times 10^{-4}$	[94]
	HDO	C/1990 K1	radio		$< 7 \times 10^{-3}$	[35]
		C/1996 B2	radio		$2.9 \pm 1.0 \times 10^{-4}$	[12]
		C/1995 O1	radio		$3.3 \pm 0.8 \times 10^{-4}$	[113]
$^{18}O/^{16}O$	H_3O^+	1P/Halley	mass	2.0×10^{-3}	$1.93 \pm 0.12 \times 10^{-3}$	[8]
					$2.13 \pm 0.18 \times 10^{-3}$	[48]
$^{13}C/^{12}C$	CN	1P/Halley	visible	1.1×10^{-2}	$1.05 \pm 0.13 \times 10^{-2}$	[71]
	HCN	C/1996 B2	radio		$2.9 \pm 1.0 \times 10^{-2}$	[77]
		C/1995 O1	radio		$1.11 \pm 0.18 \times 10^{-2}$	[78]
		C/1995 O1	radio		$0.90 \pm 0.09 \times 10^{-2}$	[80]
$^{15}N/^{14}N$	CN	1P/Halley	visible	3.6×10^{-3}	$< 3.6 \times 10^{-3}$	[71]
	HCN	C/1995 O1	radio		$3.1 \pm 0.4 \times 10^{-3}$	[80]
$^{34}S/^{32}S$		1P/Halley	mass	4.2×10^{-2}	$4.5 \pm 1.0 \times 10^{-2}$	[74]
	CS	C/1995 O1	radio		$3.7 \pm 0.4 \times 10^{-2}$	[80]

the dissociative recombination of $HCNH^+$ which leads to the two molecules with equal branching ratios.

In comet Hale-Bopp, [HNC]/[HCN] was found to increase from less than 0.03 to ~ 0.50 when the comet approached from 2.4 to 1 AU. The reason for such a variation is still ill-understood; the formation of HNC in the coma by chemical reactions which at first look seemed to be unlikely, has to be considered.

4.1.5. *The ortho-to-para ratio (OPR) of water.*

Molecules with hydrogen atoms at symmetrical positions may exist in different nuclear-spin species according to the relative orientations of the spins of their H-atoms. These species are called *ortho* and *para* for molecules with two H-atoms like H_2, H_2O or H_2CO, A and E for molecules with three H-atoms like NH_3 or CH_3OH, A, E and F for CH_4, and so forth. Conversions between different species, either by radiative transition or by collisions, are strictly forbidden, at least in the gas phase, and presumably very slow (by proton-exchange mechanisms) in the solid phase [85]. Therefore, the *ortho*-to-*para* ratio (OPR) (or E/A ratio) of the molecular rotational distribution is characteristic of the formation conditions of the molecules. Fig. 11 shows the OPR (or E/A) as a function of the equilibrium temperature for various

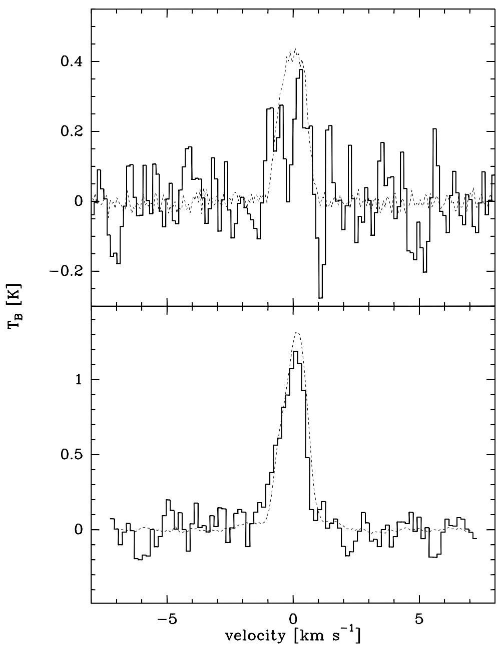

Figure 10. The $J(4-3)$ lines of the HCN (solid lines) and HNC (dotted lines) molecules observed in comet C/1996 B2 (Hyakutake) at the James Clerk Maxwell Telescope (top) and at the Caltech Submillimeter Observatory (bottom). The HCN lines have been scaled down by a factor of 10 (from [66]).

molecules. For increasing temperatures, the *OPR* rapidly tends to the statistical weight ratio and is only useful for probing very cold temperatures, except for the H_2 molecule (which is of little interest for comets because it is not expected to be incorporated in the nucleus in significant abundances and because its transitions are excessively weak and not observed). Temperatures of the order of 30 K may be probed by H_2O, NH_3 or CH_4. The molecules H_2S, H_2CO or CH_3OH would only be sensitive to cooler temperatures.

First attempts have been made to evaluate the *OPR* of water from the *KAO* observations of comets 1P/Halley and C/1986 P1 (Wilson) [82]. For comet Halley, an *OPR* of 2.3 was claimed, smaller than the limit value of 3 and corresponding to an equilibrium temperature of 23 K; a value close

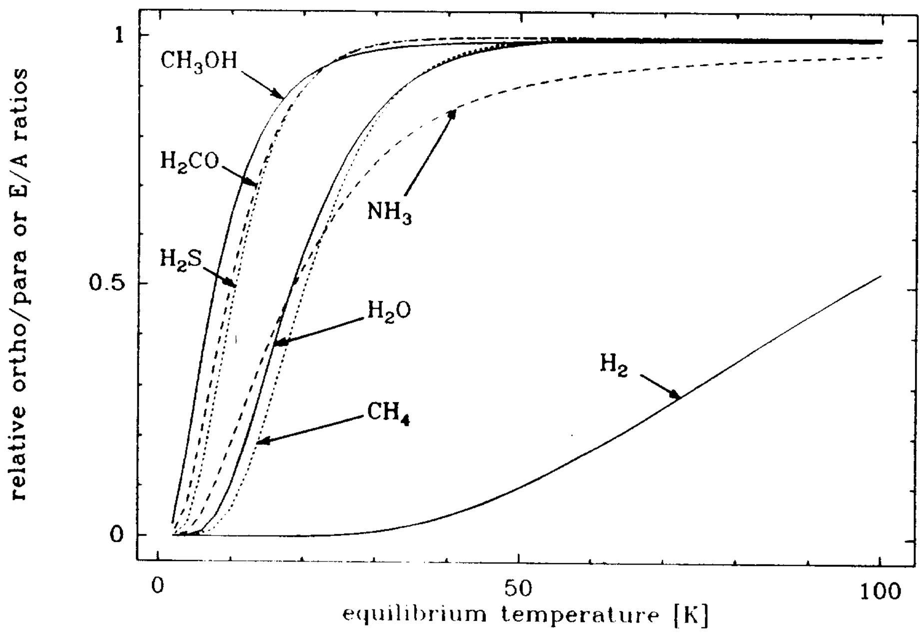

Figure 11. The *ortho*-to-*para* and E/A population ratios as a function of equilibrium temperature for several molecules with identical H atoms. The ratios have been normalized to their limit values for high temperatures.

to 3 was found for comet Wilson. These results are controversial, however, because retrieving the rotational population distributions from the *KAO* is model-dependent [15].

A high-resolution spectrum of the whole ν_3 band of water was observed in comet C/1995 O1 (Hale-Bopp) with *ISO* (Fig. 12). The retrieved *OPR*, taking into account opacity effects, is 2.45 ± 0.1 and corresponds to a temperature of 25 K [38]. This could be the formation temperature of water, thus excluding formation in a warm Solar Nebula. The possibility of equilibration in the nucleus during the long storage time in the Oort's cloud, however, should also be investigated.

4.2. SCENARIOS FOR COMETARY FORMATION AND EVOLUTION

Our present understanding is that there are at least two different classes of comets with different origins (Fig. 13; [75]).

New comets have orbits of any possible inclination. They were shown by Oort to come from a very distant isotropic reservoir, now known as the *Oort cloud.* Following gravitational perturbations, they could either be ejected from the Solar System or migrate as short-period comets ($P < 200$ years)

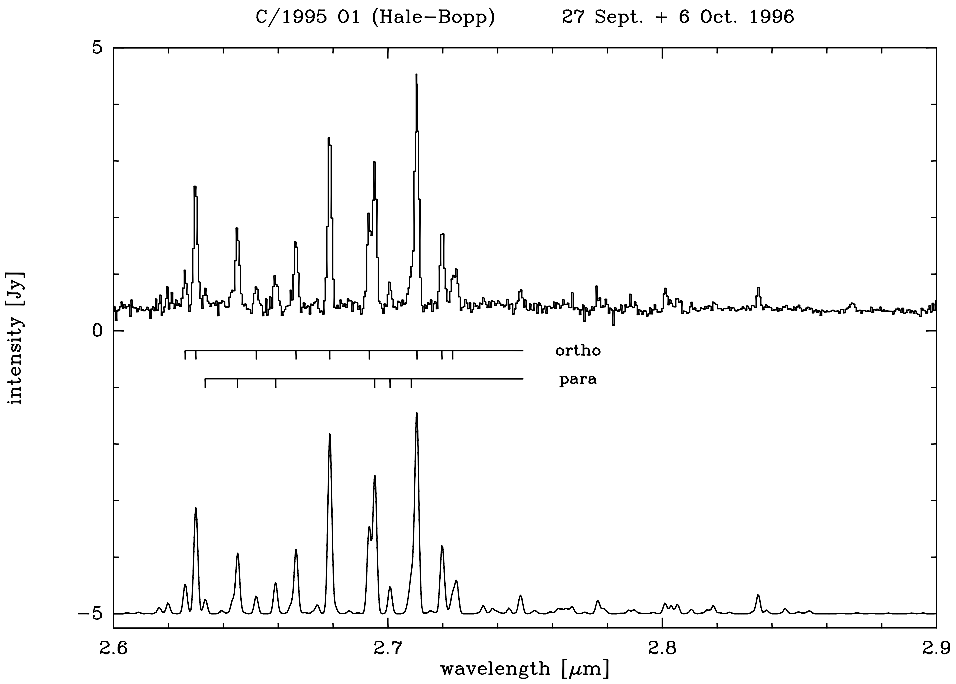

Figure 12. The spectrum of the 2.7 μm water band in comet C/1995 O1 (Hale-Bopp) observed by the short-wavelength spectrometer of *ISO* at 2.9 AU from the Sun. The resolution is $\lambda/\delta\lambda \sim 1500$ and the aperture is 14" $\times$ 20". The curve in the bottom shows a synthetic fluorescence spectrum of water computed for a rotational temperature of 28.5 K and an ortho-to-para ratio of 2.45. All the observed lines are due to water, except the line at 2.869 μm which is from OH (from [38]).

such as those of the *Halley family*.

Jupiter family comets are short-period comets ($P < 20$ years) with low-inclination orbits. They cannot come from the isotropic Oort cloud. It was postulated by Edgeworth and Kuiper that they should come from a reservoir beyond Neptune: the so-called *Edgeworth-Kuiper Belt* [104]. Confirmation of the existence of such a reservoir came recently with the detection of several tens of Kuiper Belt objects [68]. *Centaurs*, which are asteroids with highly eccentric, Saturn-crossing orbits (such as the enigmatic Chiron) (Table 2), could be intermediate objects, migrating from the Kuiper Belt to the Jupiter family.

These two reservoirs have quite different origins. Kuiper Belt objects are believed to be formed where they are now, in the trans-Neptunian outskirts of the Solar System. In contrast, the Oort cloud consists of objects formed in the inner Solar System and ejected by gravitational perturbation after formation of the giant planets. Hence, the two classes of comets, formed in different regions and having experienced different evolution, could be of

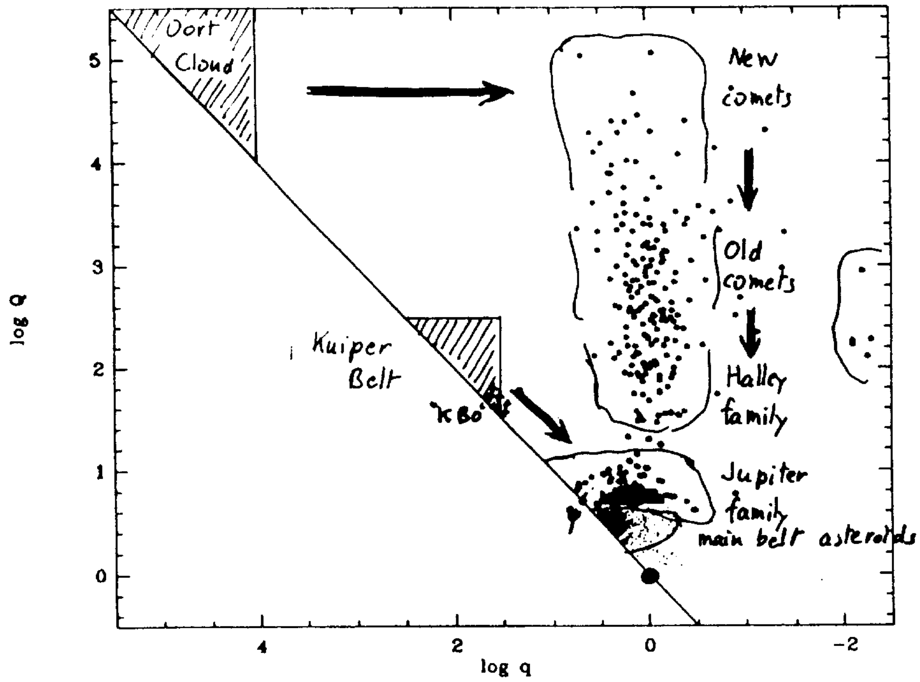

Figure 13. The different families of comets and their dynamical evolution. They are represented in a Q (aphelion distance) – q (perihelion distance) diagram. Adapted from [75].

quite different composition.

5. Conclusion

Our knowledge of comets has just been completely renewed with the exceptional observations of comets C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp). This course was given and written during the rush hours of the comet Hale-Bopp observing campaign. Thus it only reports on the highlights of the observations which were known at that time.

There is now a long series of pieces of evidence which show that cometary material is akin to interstellar matter: the composition of cometary ices compared to interstellar ices, the isotopic ratios and especially the high deuterium abundance, the high abundance of cometary HNC, the *ortho*-to-*para* ratio of cometary water. This seems to comfort the pioneering ideas of Greenberg who suggested that comets formed from unprocessed interstellar grains (e.g. [58, 59]). One cannot exclude, however, that part of the interstellar ices have been processed in the Solar Nebula, but this should have been done by processes mimicking interstellar processes.

The silicates of cometary dust are found to be in the crystalline form in about one comet out of two, and in the case of comet Hale-Bopp, crystalline forsterite has been more specifically identified. This is also the case for the dust contained in the discs surrounding Vega-type stars, which are believed to be akin to protoplanetary discs. Bona fide interstellar silicates, however, seem to be amorphous. We thus have to understand how cometary nuclei could have incorporated ices so similar to primitive interstellar ices together with processed silicates.

The next quantum leaps in our understanding of comets will probably be made with the expected results from the space missions which are at various steps of preparation.

- *NEAR*, launched in February 1996, is in fact aimed at asteroid (433) Eros. It will investigate how asteroidal material is related to cometary material.
- *Stardust*, a JPL/NASA mission, is to be launched on June 1999, to fly-by comet 81P/Wild 2 on March 2004 with a relative velocity of ~ 5 km s^{-1}, to collect samples of cometary dust and to return them on Earth on January 2006.
- *ROSETTA* is an ESA mission to be launched towards comet 46P/Wirtanen in 2003. It will meet the comet at 3.8 AU from the Sun in May 2012 and accompany it until perihelion at 1.05 AU in July 2013. This very elaborated mission will include remote sensing instruments at all wavelengths, *in situ* analysers for cometary atmosphere material, and a lander which will probe the composition and physical properties of the nucleus of the comet.
- *Champollion (DS 4)* is a mission under study at JPL, to be launched in 2003 on a solar-electric power carrier spacecraft. It would meet comet 9P/Tempel 1 on 2006, send a lander on its nucleus, for *in situ* analysis and returning samples to Earth on 2010.

However, one should not forget that cometary science cannot focus only on exceptional comets and on space mission targets. A thorough study of the whole population of comets requires observations of a large sample of these objects, for which long-term ground-based efforts are needed.

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