Origin of solar systems: Organization

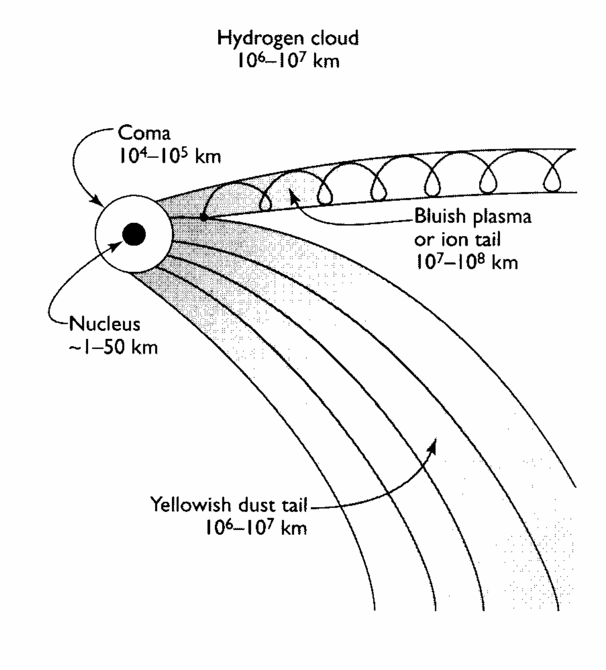
Lecture (KJ):	Student talks:
Introduction and overview Dense molecular clouds, photo-dissociation regions and protostars	Origin of the elements and Standard Abundance Distribution
Protoplanetary disks Equilibrium condensation of a solar nebula	Agglomeration of planetesimals and protoplanets
Meteorites and the early solar system	Isotope chronology of meteorites and oxygen isotopes
Origin of giant planets	Extrasolar planets
Comets and the early solar system	Transneptunian Objects

Comet Hale-Bopp in March 1997

"Best" image of the nucleus of comet Halley as obtained with the Halley Multicolor Camera

Parts of a comet:

- Nucleus
- Coma
- Plasma tail
- Dust tail
- Hydrogen cloud



Comet P/Halley on March 16, 1986 imaged with Bochum wide-field camera

Red continuum + H_2O^+ | CO^+ at 426 nm | CN at 388 nm

Crovisier J., Solids and volatiles in comets: From cometary nuclei to cometary atmospheres, in Greenberg, Li eds., Formation and evolution of solids in space, Kluwer, 1999, 389-426.

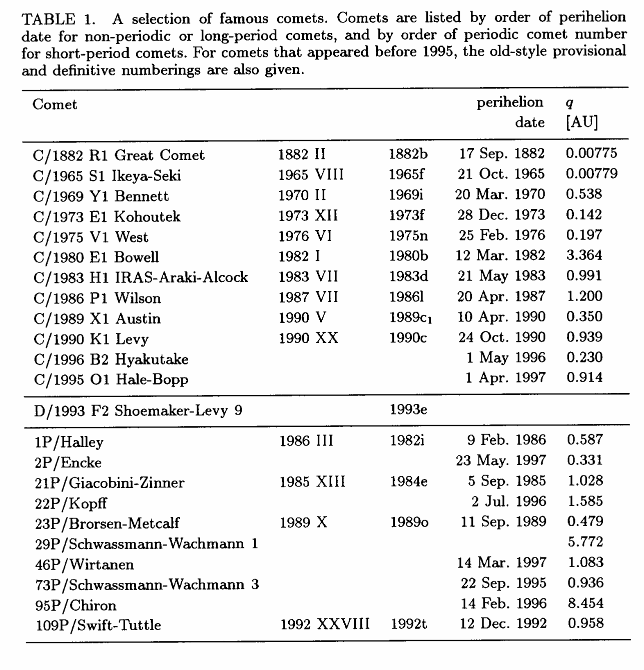


TABLE 1. A selection of famous comets. Comets are listed by order of perihelion date for non-periodic or long-period comets, and by order of periodic comet number for short-period comets. For comets that appeared before 1995, the old-style provisional and definitive numberings are also given.

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

Orbital elements of a solar system body (comet)

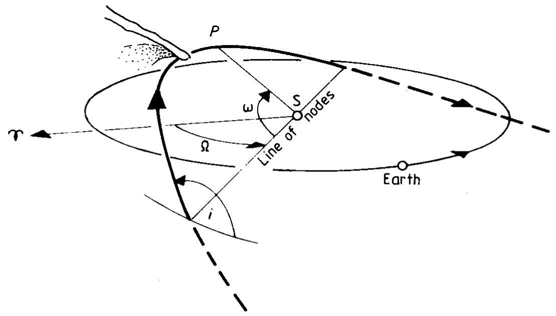


Figure 2. Main features of a comet moving on a typical very eccentric orbit. The symbols stand for: perihelion (*P*), inclination of the orbit with respect to the ecliptic plane (*i*), argument of perihelion (ω) and longitude of the ascending node (Ω) measured with reference to the vernal equinox (♈). Note that in this case the comet moves on a retrograde orbit with respect to the orbital motion of the Earth. Comet Halley moves on an orbit similar to the one represented here.

q: perihelion distance, e: excentricity (=1 parabola), a: semimajor axis

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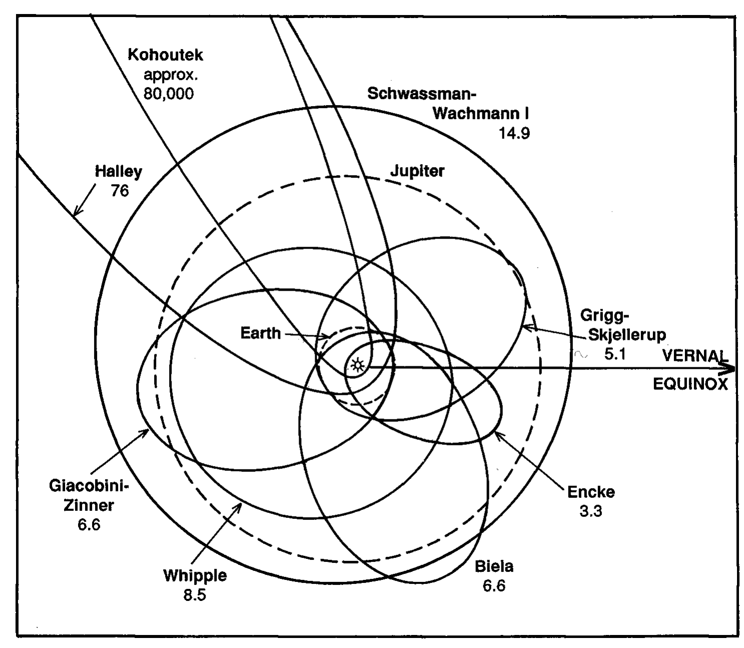
Cometary dynamics

J.A. Fernández, in “Encyclopedia of the solar system”,
Paul R. Weissman, Lucy-Ann MsFadden, Torrence V. Johnson (eds.),
Academic Press 1999, pp. 537-556.

Statistics of cometary orbits
Dynamical evolution of long-period comets
The Oort cloud
The Jupiter family
The trans-Neptunian belt (abbreviated)
Dynamical aspects of cometary origin

Orbits of selected comets.
Below their names are the orbital periods expressed in years.



Long-period, intermediate period, and short-period comets

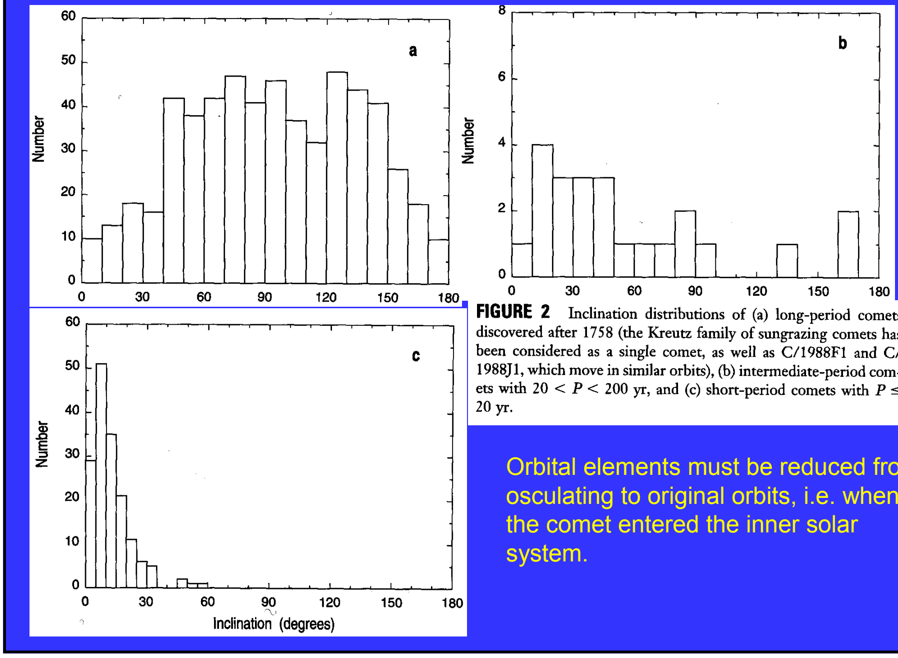
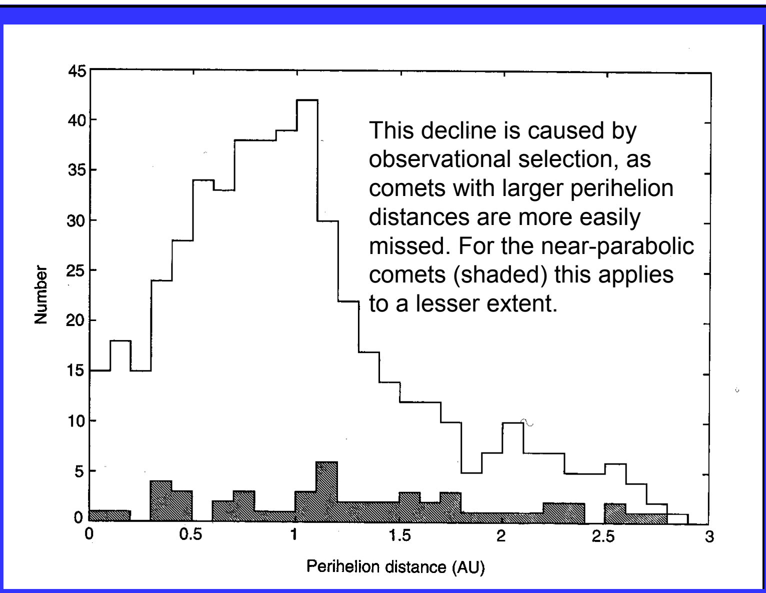


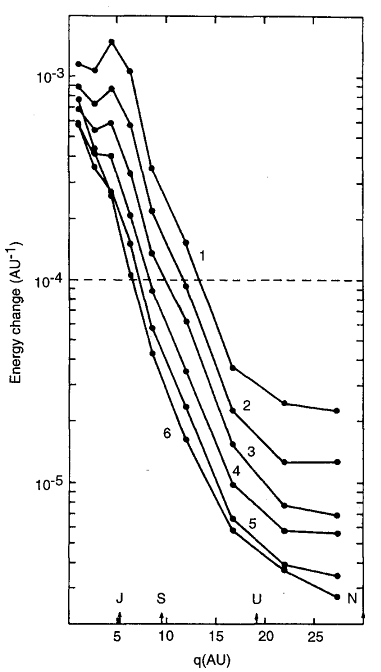
FIGURE 2 Inclination distributions of (a) long-period comets discovered after 1758 (the Kreutz family of sungrazing comets has been considered as a single comet, as well as C/1988F1 and C/1988J1, which move in similar orbits), (b) intermediate-period comets with $20 < P < 200$ yr, and (c) short-period comets with $P \leq 20$ yr.

Orbital elements must be reduced from osculating to original orbits, i.e. when the comet entered the inner solar system.



This decline is caused by observational selection, as comets with larger perihelion distances are more easily missed. For the near-parabolic comets (shaded) this applies to a lesser extent.

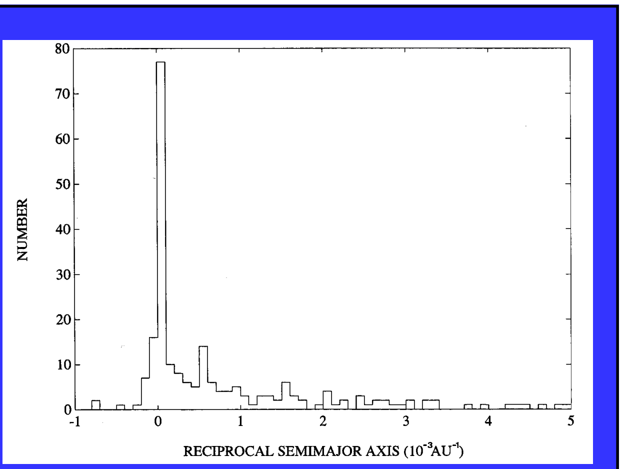
Distribution of perihelion distances of the same sample of long-period comets considered in the previous projection. The shaded histogram is for near-parabolic comets with original semimajor axes > 10^4 AU.



Typical energy change per perihelion passage as a function of a comet's perihelion distance and for different inclination ranges: curve 1 for $0<i<30^0$, ... , curve 6 for $150^0<i<180^0$.

Observations

Distribution of the original semimajor axes of observed long-period comets with $(1/a)_{orig} < 5 \times 10^{-3}$ AU^{-1}.



The spike with approximate width of $0 < (1/a)_{orig} < 10^{-4}$ AU^{-1} is smaller than the typical energy change by planetary disturbances, Oort argued that the comets in the spike enter the inner solar system for the first time, and therefore called these comets new. This finding let Oort to conclude that a huge swarm of 10^{11} comets surrounds the solar system at distances of 10^4-10^5 AU. This structure, called the Oort cloud, is the source of the long-period comets.

Not all “new” comets are new in the strict sense, as some of them will have been in the planetary region before.

Injection of new comets

The quasi-steady supply of new comets from the Oort cloud is due to the action of distant passing stars (typically at distances larger than ~5×10^4 AU) and galactic tides.

This mechanism should provide comets with a uniform distribution of perihelia q. But perturbations by the giant planets remove comets to different degrees.

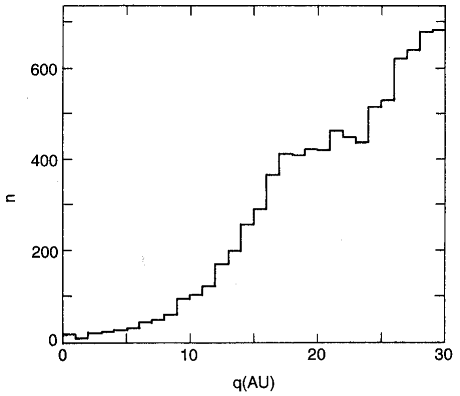


FIGURE 7 Computed distribution of perihelion distances of hypothetical “new” comets injected into the planetary region, obtained from Monte Carlo studies that included both planetary and stellar perturbations. [From J. A. Fernández (1982). *Astron. J.* **87,** 1318. Used with permission.]

Galactic tidal forces

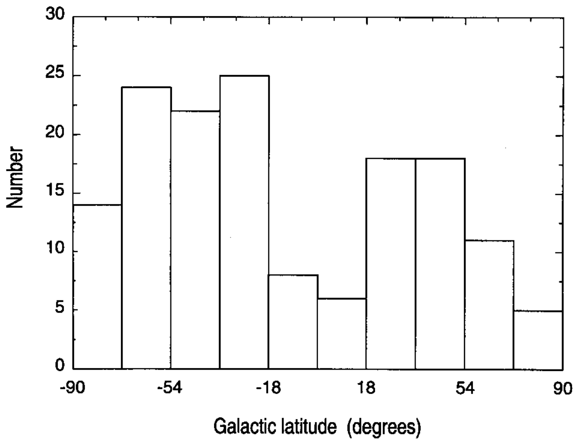
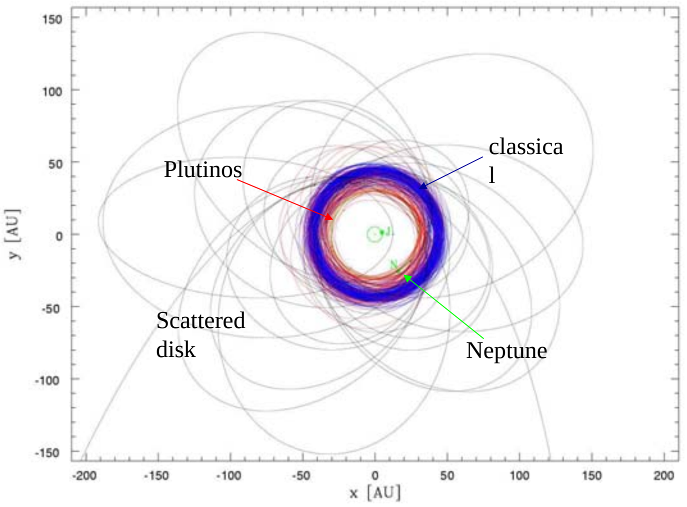


FIGURE 9 Number of aphelion directions in equal-area strips of the celestial sphere parallel to the galactic equator, taken from a sample of 151 "young" comets with $a_{\text{orig}} > 500$ AU.

The Kuiper belt, a vast population of small bodies orbiting the Sun beyond Neptune.

From DC Jewitt's Kuiper belt website



The Jupiter family comets

JF comets are moving on quite unstable orbits.
A large fraction of distant JF comets with perihelion q > 2 AU has still to be discovered.
JF comets could be the end products of the dynamical evolution of LP comets. But then we would expect rectograde JF comets. A more likely source for them is the trans-neptunian belt.
The Tisserand invariant of the restricted three-body problem is another useful criterion to clarify the origin of the JF comets.

$$T = \frac{1}{a} + 2\sqrt{2q\left(1 - \frac{q}{2a}\right)}\cos i$$

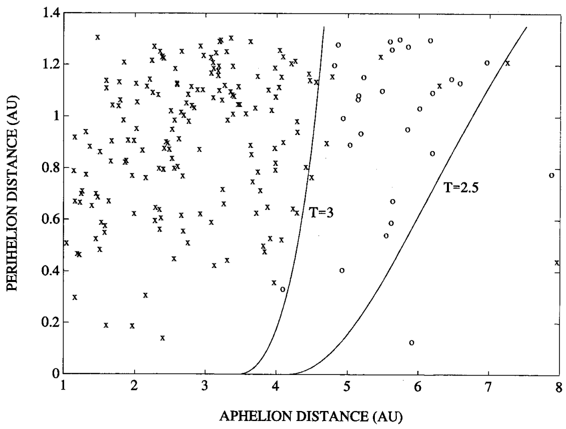
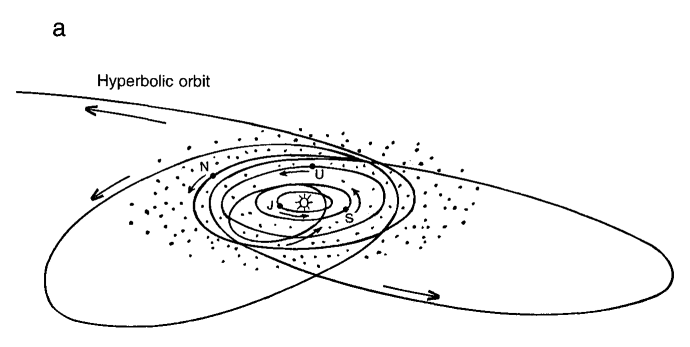
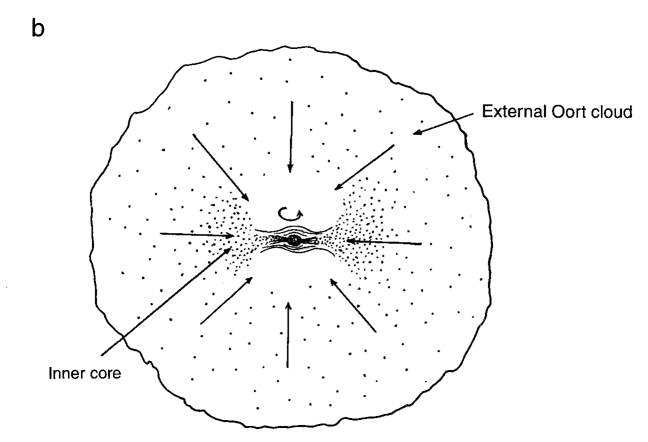


FIGURE 11 Plot of aphelion (Q) versus perihelion distances (q) for Apollo–Amor asteroids (x) and Jupiter-family comets with $q < 1.3$ AU (o). The solid curves are the loci in the (Q, q) plane, giving Tisserand parameters of $T = 2.5$ and $T = 3$ in the planar case.

JF with q<1.3 AU comets have a Tisserant invariant 2.5<T<3. By contrast LF comets have Tisserant invariants < 2. T is more or less conserved during the capture process. This argues against a field of near-parabolic comets from the Oort cloud as a suitable source.
Likewise, Apollo-Amor asteroids cannort be the end members of burnt-out comets.

FIGURE 14 Two possible scenarios of comet origin: (a) comets were the residues of the outer planets' accretion from where they were scattered to the Oort cloud by gravitational perturbations, mainly by Neptune; (b) comets formed in the outer parts of the primitive solar nebula as it collapsed, stretching perhaps from the edge of Neptune's accretion zone to some 10^4 AU.

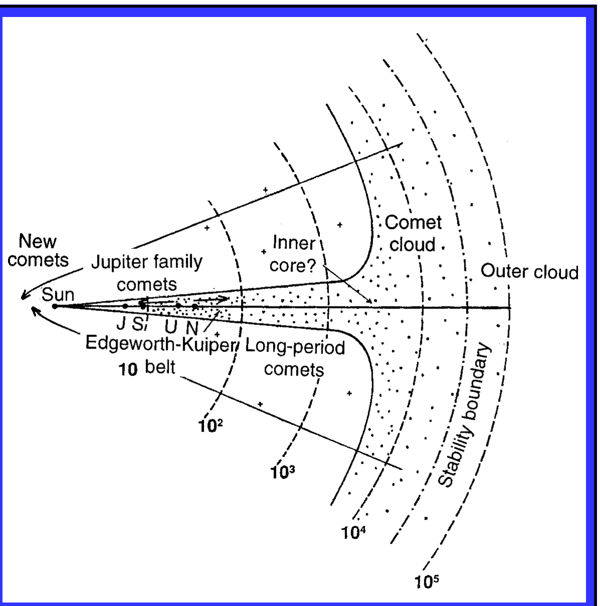




3 regions of the Oort cloud:

1. Inner core a < 3000-4000 AU, concentrated toward ecliptic, if comets formed in the protoplanetary disk. Its mass should then be constrained to a few 0.1 MEarth.
The mass should be considerably larger (up to several 100 MEarth, if comets formed in situ.

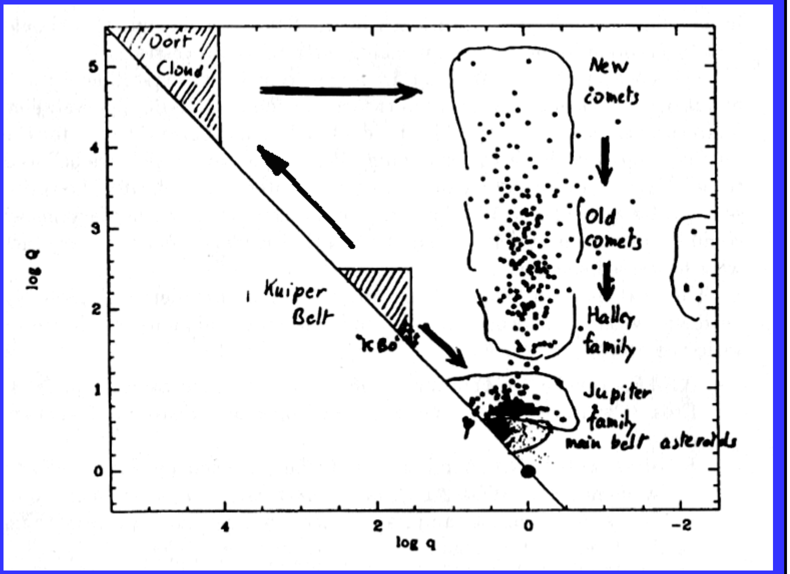
2. A spherical, stable Oort cloud 4000 < a < 30000 AU, containing comets stable over periods comparable or larger than the age of the solar system (4.6 x 109 yr).



3. An outer Oort cloud, for a>30000 AU, whose population has dynamical lifetimes shorter than the solar system age; it therefore needs to be continuously replenished with comets from the inner regions of the Oort cloud.

All observable comets have their origin in the Kuiper Belt

Plot of q (perihelion distance versus Q (aphelion distance). The arrows denote evolutionary pathways.



Adapted from Crovisier 1999, in Greenberg & Li (eds): Formation and Evolution of Solids in Space, Kluwer.

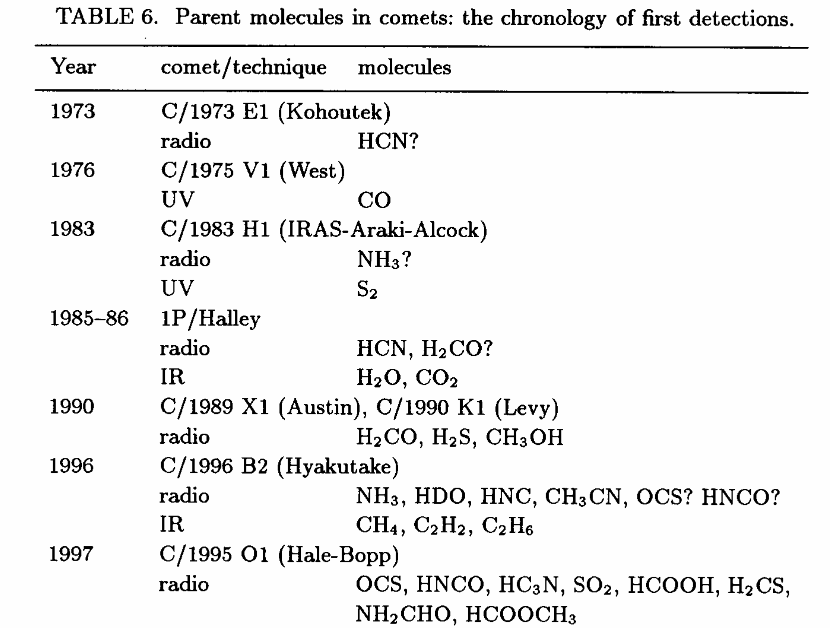


TABLE 6. Parent molecules in comets: the chronology of first detections.

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, $HCOOCH_3$

Crovisier J., in Greenberg, Li eds., Formation and evolution of solids in space, Kluwer, 1999, 389-426.

Crovisier J., Solids and volatiles in comets: From cometary nuclei to cometary atmo-spheres, in Greenberg, Li eds., Formation and evolution of solids in space, Kluwer, 1999, 389-426.

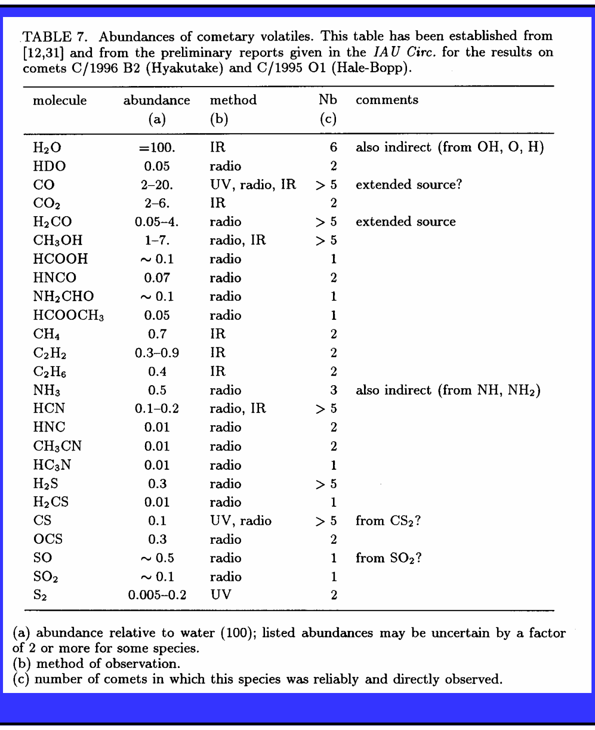


TABLE 7. Abundances of cometary volatiles. This table has been established from [12,31] and from the preliminary reports given in the *IAU Circ.* for the results on comets C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp).

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.

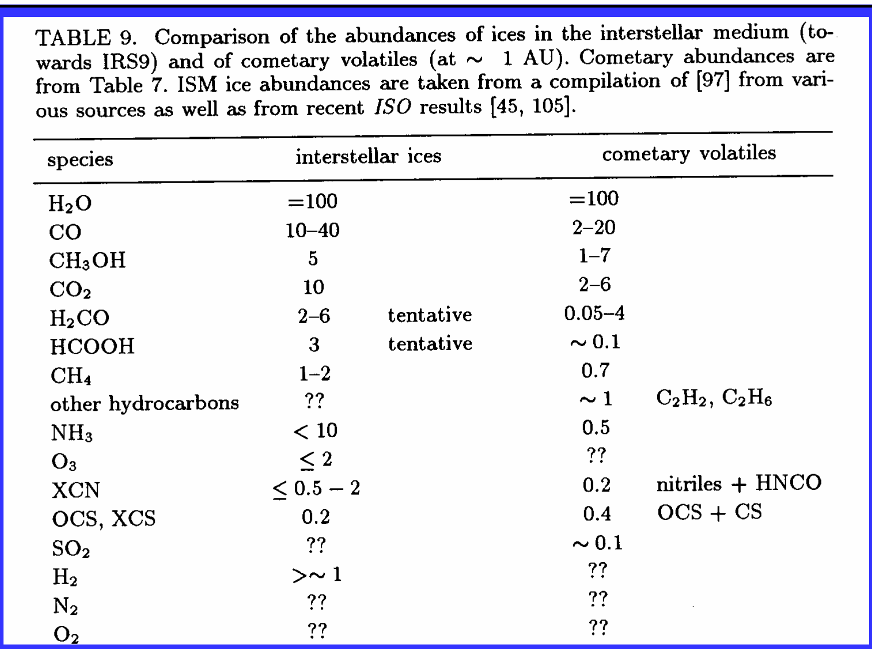


TABLE 9. Comparison of the abundances of ices in the interstellar medium (towards IRS9) and of cometary volatiles (at ~ 1 AU). Cometary abundances are from Table 7. ISM ice abundances are taken from a compilation of [97] from various sources as well as from recent *ISO* results [45, 105].

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	$\lesssim 2$		??	
XCN	$\lesssim 0.5 - 2$		0.2	nitriles + HNCO
OCS, XCS	0.2		0.4	OCS + CS
SO_2	??		~ 0.1	
H_2	$>\sim 1$		??	
N_2	??		??	
O_2	??		??	

Crovisier J., in Greenberg, Li eds., Formation and evolution of solids in space, Kluwer, 1999, 389-426.

The similarity of composition of comets and dense interstellar clouds suggests that possibly comets contain unaltered interstellar material.

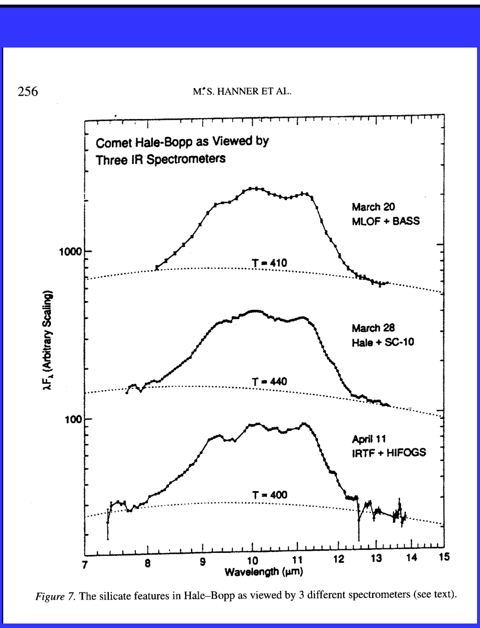
But the at least in the outer solar system the environment may be quite similar so the similarity may come from the fact that the chemical processes are similar.

Fegley B. jr. and Prinn R.G.: “Solar nebular chemistry: Implications for volatiles in the solar system” in
Hal A. Weaver, Laura Danly (eds.) “The formation and evolution of solar systems”, Cambridge Univ. Press 1989, pp. 171 - 211

Hanner M.S. et al.: Thermal emission from the dust coma of comet Hale-Bopp and the composition of the silicate grains.

Earth, Moon and Planets, 79, 247-264, 1997

Silicate peak was very strong in comet Hale-Bopp and the particles in this comet are believed to be smaller than average.



256 M. S. HANNER ET AL.

Figure 7. The silicate features in Hale–Bopp as viewed by 3 different spectrometers (see text).

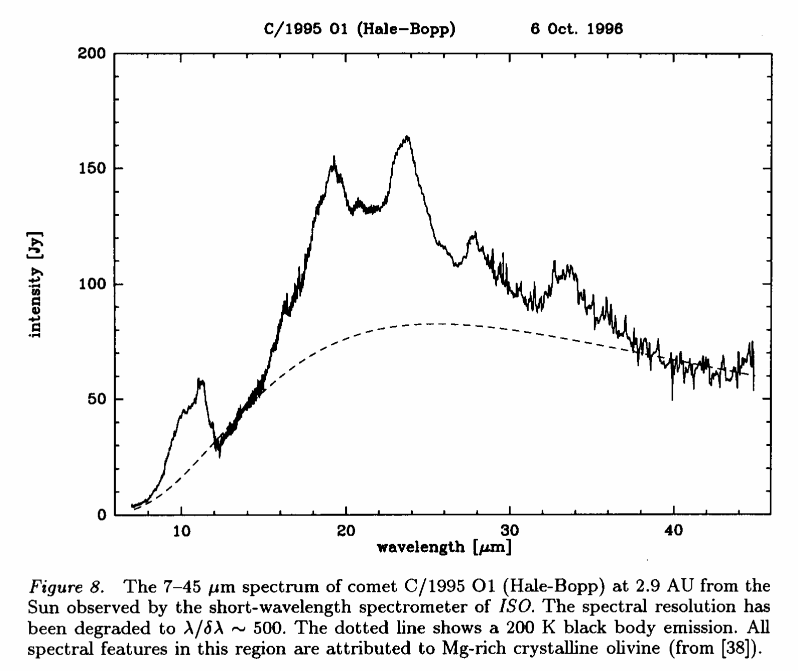


Figure 8. The 7–45 μm spectrum of comet C/1995 O1 (Hale-Bopp) at 2.9 AU from the Sun observed by the short-wavelength spectrometer of *ISO*. The spectral resolution has been degraded to $\lambda/\delta\lambda \sim 500$. The dotted line shows a 200 K black body emission. All spectral features in this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

Crovisier, in Greenberg and Li (eds.) Formation and Evolution of Solids in Space, Kluwer 1999, p. 389.

Crystalline silicates were found in come Hale-Bopp!

Diane Wooden gave colloquium talk here in the beginning of December 2005!

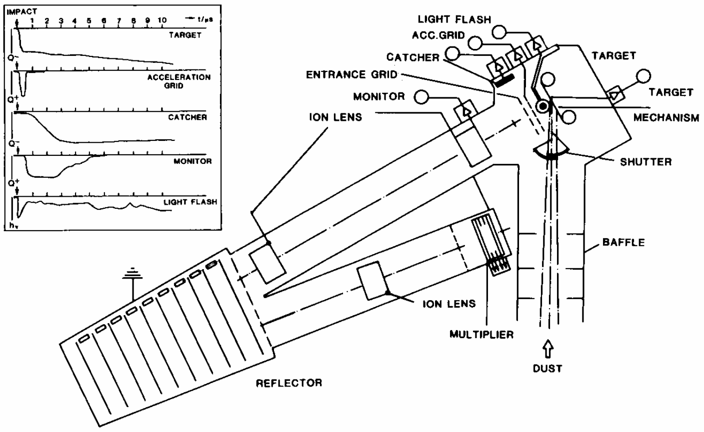


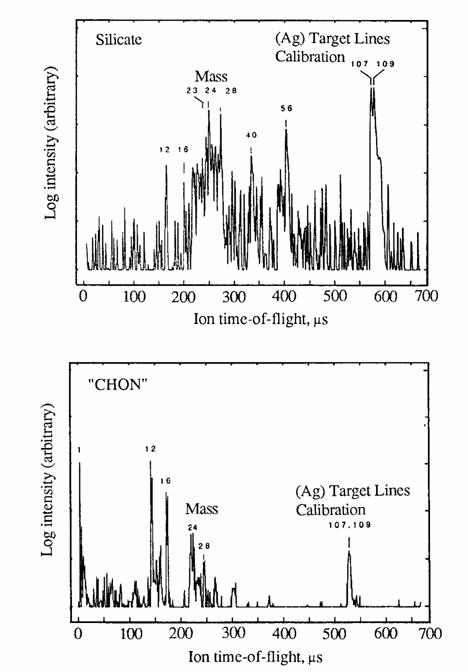
Figure 1. Schematic view of the particulate impact analyzers on board Giotto and VEGAs and 2. The inset shows characteristic front-end signals. From Kissel (1986).

Jessberger E.K., Kissel J., in Newburn et al. (eds.) Comets in the Post-Halley Era, Kluwer 1991, pp. 1075-1092.
Particle impact analyzer: Particles impact on a silver target (upper right), are evaporized and ionized immediately. The ions enter the time of flight system which produces a mass spectrum.

Impact spectra from the Giotto PIA instrument are shown.
Two particle types are illustrated, namely the silicate and carbonaceous CHON classes. CHON particles consist only of carbon, hydrogen, oxygen and nitrogen.

The comet's total content of organic material was higher than the mineral content by a factor 3-10.

Spectra from
McDonnel et al., in Newburn et al. (eds.) Comets in the Post-Halley Era, Kluwer 1991, pp 1043-1073



Dust composition measurements in comet 81P/Wild 2 with CIDA (Cometary and Interstellar Dust Analyzer)

In contrast to measurements in comet 2P/Halley negative ions were measured as well.

Because of the low encounter speed of 6 kms^{-1} organic compounds are much better preserved than they were in comet 1P/Halley. But in 81P not the whole particle is destroyed and the ions come from the outer layers of the particle.

The 29 spectra obtained during the flyby of Comet 81P/Wild 2 confirm the predominance of organic matter. In moving from interstellar to cometary dust, the organic material seems to lose most of its hydrogen and oxygen as water and carbon monoxide. These are now present in the comet as gas phases, whereas the dust is rich in nitrogen-containing species. No traces of amino acids were found.

Kissel et al., The cometary and interstellar dust analyzer at comet 81P/Wild 2, 2004, Science 304, 1774-1776.

CIDA positive ion spectrum measured in the coma of comet 81P/Wild 2

1. Three spectra like Fig. 1 →
CH^+ + traces of N^+, NH^+, O^+, OH^+
N-heterocyclic fragment ions,
$C_3NH_x^+$ (x=2, 4, 6, 8).
no complex O-containing species

2. Na^+, K^+ (contaminants of Ar target),
$C_6NH_4^+$ (H2- loss from $C_6NH_6^+$),
abundance of heterocyclic, probably annealed rings as backbones of most of the organic structure

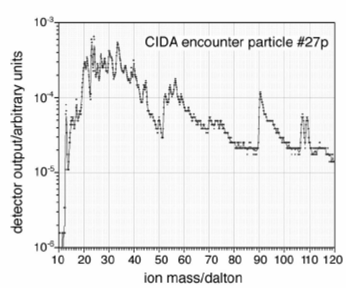


Fig. 1. A positive-ion spectrum, converted from time of flight into a linear mass scale. The amplitude scale is logarithmic. The spectrum is typical for nitrogen organic chemistry. The $m/z = 107, 109$ doublet is due to the Ag^+ from the target.

Negative ion spectra from comet 81P Wild 2 (Fig. 2) and from 3 interstellar particles (Fig. 3)

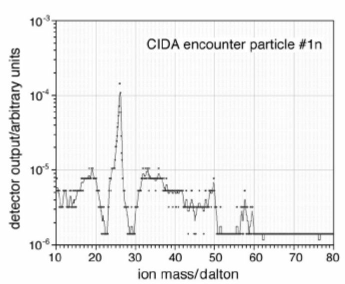


Fig. 2. A negative-ion spectrum, converted like Fig. 1. The dominating ion is CN^-, as is typical for nitrogen organic chemistry. The oxygen region ($m/z = 16, 17$) is surprisingly low; however, the SH^- ($m/z = 33, 35$) is high. The shift of the H^- line is a known instrumental effect.

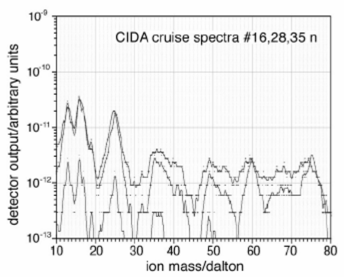


Fig. 3. Three negative-ion spectra, converted like Fig. 2, are shown for comparison with Fig. 2. The spectra are from three interstellar dust particles. The carbon-oxygen region is dominant, and the major peak in the mass range from 20 to 30 daltons is clearly 25, not 26.

Crovisier, in Greenberg and Li (eds.) Formation and Evolution of Solids in Space, Kluwer 1999, p. 389.

Note N deficiency in comets.

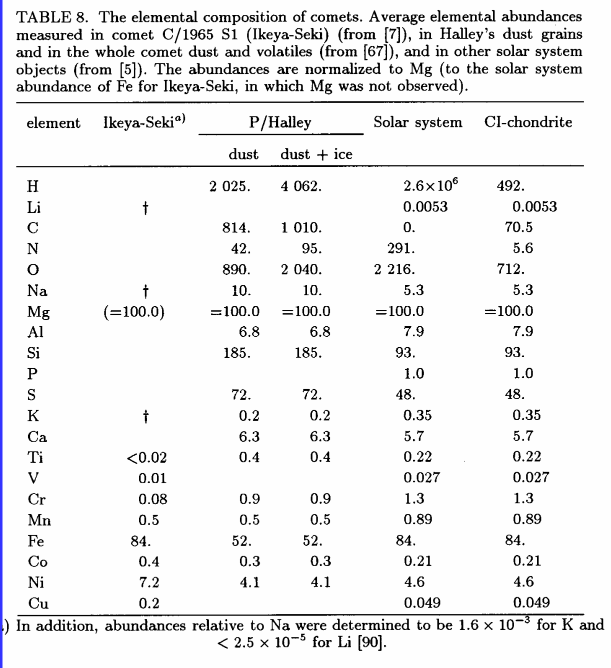


TABLE 8. The elemental composition of comets. Average elemental abundances measured in comet C/1965 S1 (Ikeya-Seki) (from [7]), in Halley's dust grains and in the whole comet dust and volatiles (from [67]), and in other solar system objects (from [5]). The abundances are normalized to Mg (to the solar 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

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

Crovisier J., in Greenberg, Li eds., Formation and evolution of solids in space, Kluwer, 1999, 389-426.

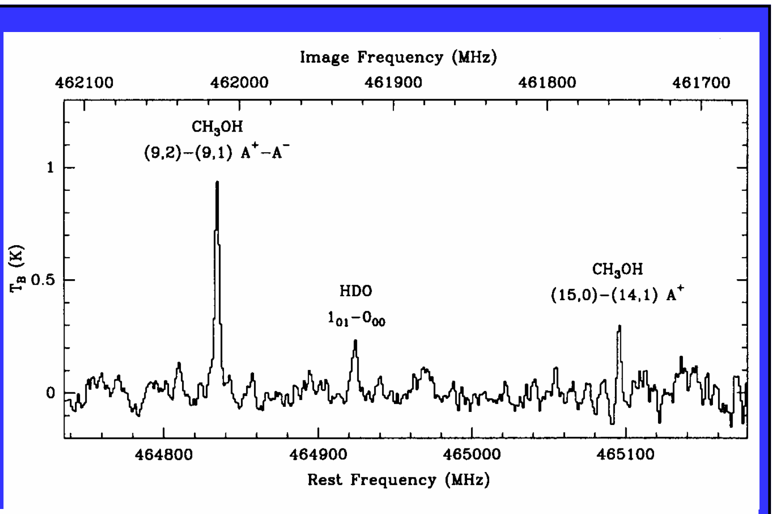


Figure 9. The $1_{10}-0_{00}$ HDO line at 465 GHz observed in comet C/1996 B2 (Hyakutake) at the Caltech Submillimeter Observatory. Two lines of methanol were observed in the same spectrum (from [13]).

The HDO transition observed in this spectrum corresponds to a very strongly forbidden ortho-para-transition in H2O which is allowed in HDO.

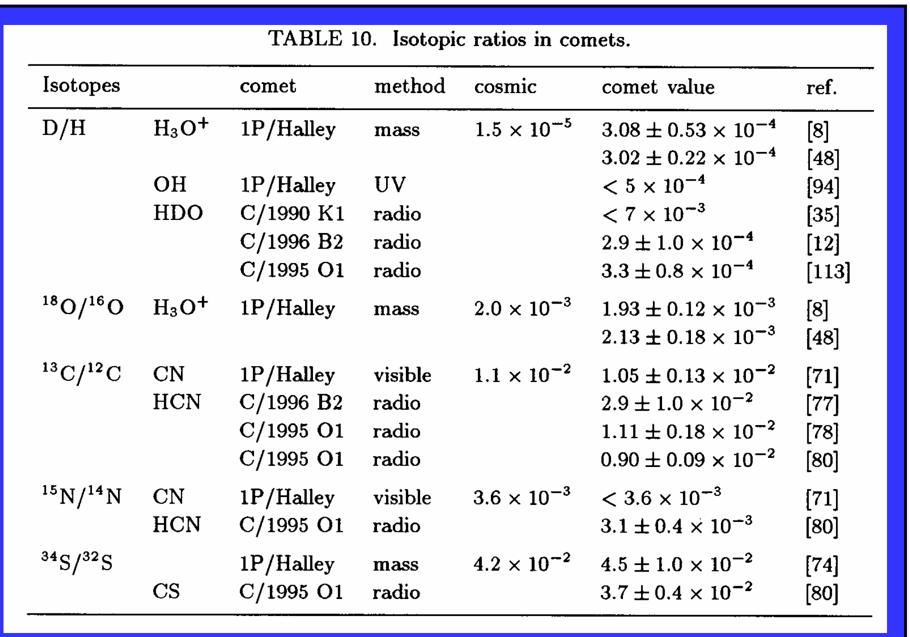


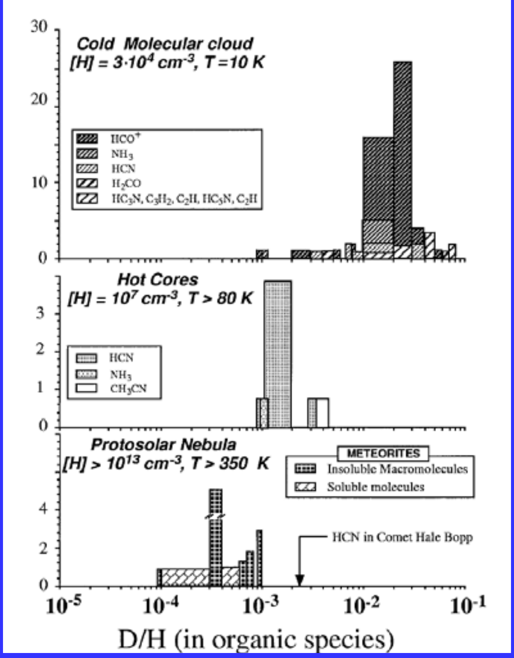
TABLE 10. Isotopic ratios in comets.

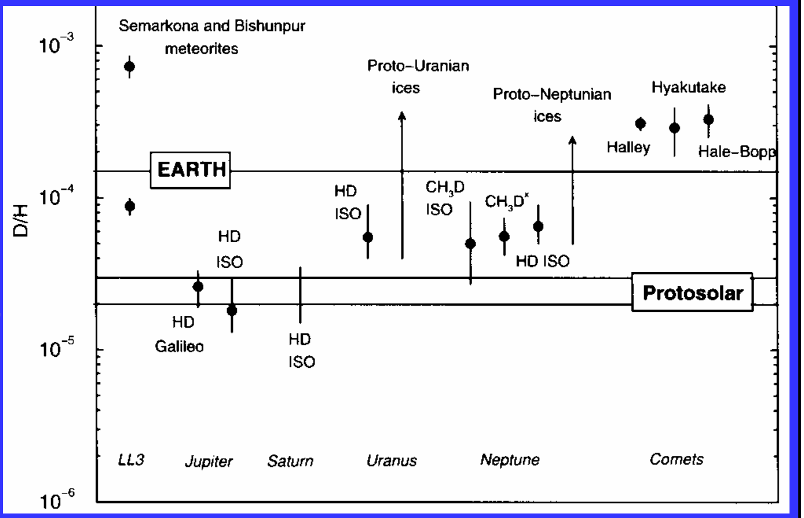
Isotopes		comet	method	cosmic	comet value	ref.
D/H	H_3O^+	1P/Halley	mass	1.5×10^{-5}	$3.08 \pm 0.53 \times 10^{-4}$	[8]
					$3.02 \pm 0.22 \times 10^{-4}$	[48]
	OH	1P/Halley	UV		$< 5 \times 10^{-4}$	[94]
	HDO	C/1990 K1	radio		$< 7 \times 10^{-3}$	[35]
		C/1996 B2	radio		$2.9 \pm 1.0 \times 10^{-4}$	[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]

Crovisier J., in Greenberg, Li eds., Formation and evolution of solids in space, Kluwer, 1999, 389-426.

Robert F., Gautier D., and Dubrulle B.: “The solar D/H ratio: Observations and theories”, Sp. Sci. Rev. 92, 201-244, 2000

When temperature and density increase, the deuterated molecules formed at 10-20K become isotopically lighter and lighter via an isotopic exchange with H2 (or H). Solar system organic compounds would also reflect such an isotopic processing occurring during the formation and evolution of the solar nebula.





D/H ratios in the solar system, from Hersant F. et al., Astrophys. J. 554, 391-407, 2001.

According to these authors, interstellar icy grains with high D/H ratio remained unprocessed during the formation of the protosolar nebula. They are found unprocessed in LL3 meteorites like Semarkona and Bishunpur. Otherwise they were mixed into a protosolar cloud with D/H = 2.5 10^{-5} with mixing ratio depending on heliocentric distance.

Questions to students:

- Was the topic of the lecture interesting?
- What kind of other topics you would find interesting?
- Was the level of the lecture ok?
- What about the presentation? Should the lecturer think in front of his audience? What about the powerpoint format? Long texts on the viewgraphs? Suggestions for improvements?
- What about the block format of this lecture? Suggestions for improvements?
- What about the student lectures?
- Opinion of the lecturers? Did you learn something? Would you like to do it again?
- Opinion of the audience?