WATER IN COMETS

A key programme for Herschel/HIFI

Version 3 — March 2004

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Foreword. This programme is in the process of being coordinated or merged with programmes of other instruments. Its organization and strategy are thus likely to change. Because of the specificities of comets (known, short-period comets are unevenly distributed in time and unexpected, bright comets can only be observed as targets of opportunity) we propose to spread this programme over the nominal lifetime of Herschel.

Summary. We propose to study water in comets with HIFI and the other instruments of the Herschel Space Observatory. In a significant sample of comets, we will investigate the evolution of water production over a large range of heliocentric distances and its kinematics by observing the 557 GHz water line. In a selection of bright comets, we will study water excitation and physical conditions by observing several water lines, and the D/H isotopic ratio by searching for HDO. A total of 150 hours of observation is requested.

1 Scientific background

Having retained and preserved pristine material from the Solar Nebula at the moment of their accretion, comets contain unique clues to the history and evolution of the Solar System. Their study assesses the natural link between interstellar matter and Solar System bodies and their formation (Irvine et al. 2000).

Besides in situ explorations, to be achieved in the present decade (after the pioneering missions to comet Halley), and comet nucleus sample missions in a more distant future, remote sensing is presently the unique way to investigate the chemical and isotopic composition of cometary material. By providing a sensitive access to a still poorly observed spectral domain, the Herschel Space Observatory and its three instruments is expected to contribute significantly to these investigations (Bockelée-Morvan & Crovisier 2001). Indeed, the submillimetre and far-infrared spectral ranges are of particular interest. Recent observations, especially of comets C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp), resulted in a dramatic progress in our knowledge of cometary volatiles. The number of known parent molecules has been multiplied by a factor of almost three. In this investigation, spectroscopy at radio wavelengths got the lion's share (Bockelée-Morvan et al. 2000). Other significant results came from infrared spectroscopy, either from the ground (at high spectral resolution with CSHELL at the IRTF or NIRSPEC at the Keck telescope) or from space with the Infrared Space Observatory (ISO) (e.g. Mumma et al. 2003; Crovisier et al. 1997).

The observations of water rotational lines in comets is a major cometary programme which should be conducted with Herschel. Ironically, although being the most abundant cometary volatile, water is one of the species the most difficult to observe (e.g., Crovisier et al. 1997; Dello Russo et al. 2000). Since cometary gas is cold (10 to 100 K) and water is rotationally relaxed at fluorescence equilibrium, the rotational transitions occurring between the lowest energy states are the most intense. The 1_{10}–1_{01} water line at 557 GHz is thus expected to be among the strongest lines of the radio spectrum of comets (Bockelée-Morvan 1987). Its first dectection was achieved in comet C/1999 H1 (Lee) by the Submillimeter Wave Astronomy Satellite (SWAS) (Neufeld et al. 2000; Chiu et al. 2001; Fig. 1). The subsequent observations of several comets with SWAS and Odin (Lecacheux et al. 2003; Figs 2 & 3) are very promising for the coming HIFI investigations of cometary water.

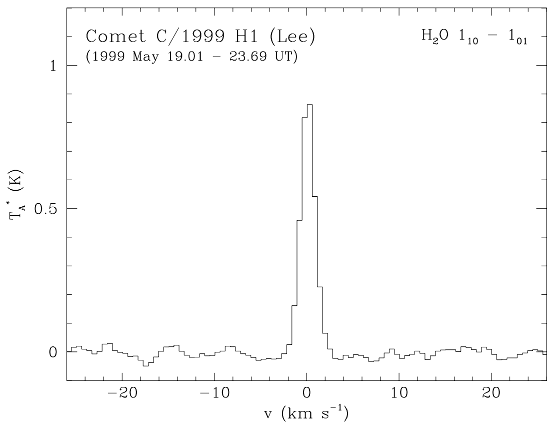

Figure 1: The historical detection of the H_2O 1_{10}–1_{01} water line at 557 GHz, observed by SWAS in C/1999 H1 (Lee). (From Neufeld et al. 2000.)

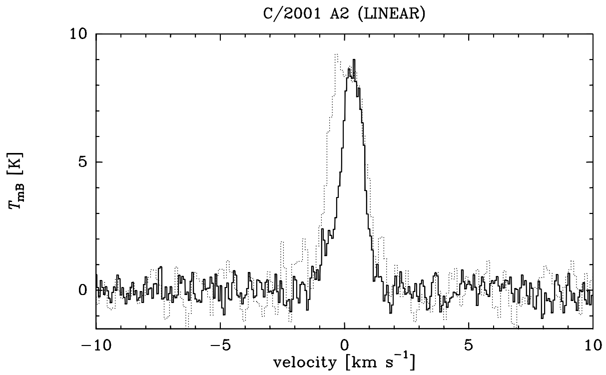

Figure 2: The 1_{10}–1_{01} H_2O line at 557 GHz observed by Odin in comet C/2001 A2 (LINEAR) on 2.2 July 2001 (full line). For comparison, the J(3–2) line of HCN observed at the *CSO* is also shown (scale expanded by $\times 10$, dotted line). The difference between the two profiles is attributed to self-absorption in the water line. This illustrates the benefit of high spectral resolution. (From Lecacheux et al. 2003.)

Water and cometary activity

Water is the main constituent of cometary ices and the measurement of its production rate from the surface of the nucleus is a requisite for abundance determinations of other species. In addition, water is the main driver of cometary activity at heliocentric distances less than 3 AU. By monitoring the water production rate, the onset and disappearance of water sublimation might be observed and one can expect to obtain important insights into the sublimation mechanisms at and under the nucleus surface. Gas production curves reveal also diurnal and seasonal effects and are required for the study of non-gravitational forces which modify cometary orbits. Data on the nucleus sizes are now available for many short-period comets (Lamy et al. 2004) and water production rates provide information on which fraction of the nucleus surface is active (the so-called *active areas*). This fraction is known for a small number of comets only. It varies much, with a tendency to be larger in short-period comets. Further measurements are required to confirm this trend and to elucidate the processes responsible for this diversity, which may be related to physical aging. Invoked processes are the formation of a crust protecting cometary ices, either by cosmic-ray irradiation (space weathering) or by the accumulation of large dust particles not dragged by the gas, and the subsequent blow-off of the crust during surges of activity.

Correlation with dust

Active comets release both gas (mainly water) and dust. Comparison of the water production with the dust production (which could be obtained by continuum observations, either in the thermal infrared with PACS, or from independent observations of the reflected sun light in the visible) provides us with the dust-to-gas ratio, a parameter which greatly varies from comet to comet and may reflect their formation in different regions of the Solar Nebula, or subsequent differentiation (the question is open).

In contrast to the data from the visible which is related to sub-micronic particles, observations in the far-infrared are sensitive to large-size particles (cf. Grün et al. 2001), which are suspected to be the dominant component in mass for cometary dust. The observation of this dust component with PACS would allow us to estimate the momentum losses of the nuclei in more detail than previously. Together with the determination (with HIFI) of the gas production and its kinematics, we will have information for improved modelling of the non-gravitational forces affecting the orbits of short-period comets, and better constraints on their masses.

Water and coma thermodymamics

Water also plays an important role in the thermal balance of cometary atmospheres, as a cooling agent via emission in its rotational lines. This role is crucial in determining the expansion velocity and temperature of the atmosphere, which are two fundamental parameters for the physical description of this medium. Indeed, cooling becomes effective only in the outer coma where the transitions become optically thin. Up to now, thermodynamical models of cometary atmospheres use an heuristic approach for rotational cooling (Combi 2002).

The observations with Herschel of several water lines will provide us with insights into the excitation of this molecule and optical depth effects. This will lead us to more realistic models of the thermodynamics of the atmosphere.

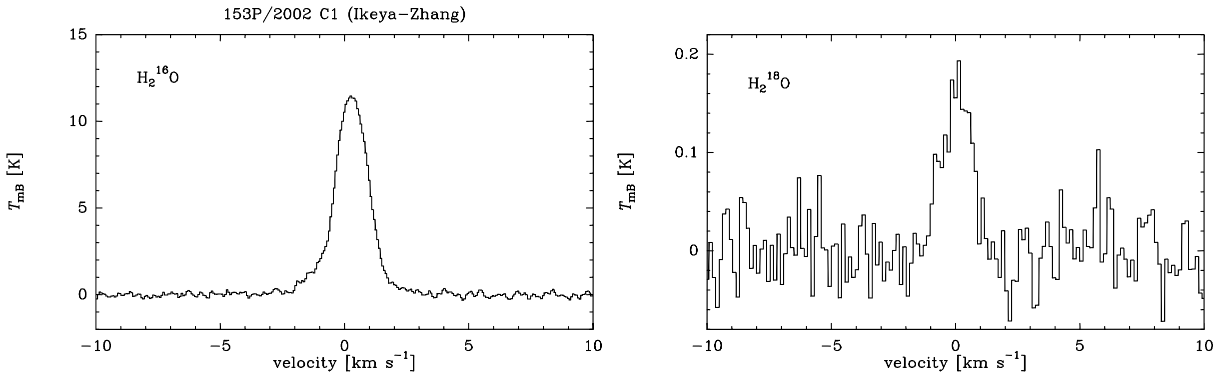

Figure 3: The 1_{10}–1_{01} lines of $H_2^{16}O$ (left) and $H_2^{18}O$ (right) observed in comet 153P/2002 C1 (Ikeya-Zhang) on 24–28 April 2002 by Odin. (From Lecacheux et al. 2003.)

The D/H ratio

The deuterium abundance is a key parameter for studying the origin and the early evolution of the Solar System and of its individual bodies. Simultaneous observations of HDO and H_2O determine D/H in cometary water. It was first measured in comet 1P/Halley from the mass spectrometers aboard Giotto; HDO was observed from its 1_{01}–0_{00} line at 465 GHz in comets

Hyakutake and Hale-Bopp (Altwegg & Bockelée-Morvan 2003). A ratio [D/H] $\sim 3 \times 10^{-4}$ was derived in these three comets. This value, which corresponds to an enrichment factor of $\sim$ 12 with respect to the protosolar D/H value in H_2, cannot be explained by isotopic exchanges between H_2O and H_2 in the solar nebula and reflects fractionation effects which took place through ion–molecule or grain surface reactions in the presolar cloud (Mousis et al. 2001). However, it is significantly below that measured and expected in dense molecular clouds. This suggests that comets incorporated material reprocessed in the inner Solar Nebula, which was transported outwards to the comet formation region by turbulent diffusion. This deuterium measurement was used by Hersant et al. (2001) to constrain evolutionary solar nebula models.

All three comets in which the D/H ratio in water was measured are long-period comets coming from the Oort cloud. Measurements of the D/H ratio in a larger sample of comets with HIFI, including short-period comets formed in the Kuiper Belt, would provide additional tests to the above proposed interpretation and further constraints to Solar Nebula models. Short-period comets could have formed outside the turbulent Solar Nebula and exhibit higher D/H ratios, as expected for unprocessed material. Comets formed close to the orbit of Jupiter are expected to have D/H ratios lower than those measured in comets Halley, Hyakutake and Hale-Bopp, presumably formed in the Uranus–Neptune region.

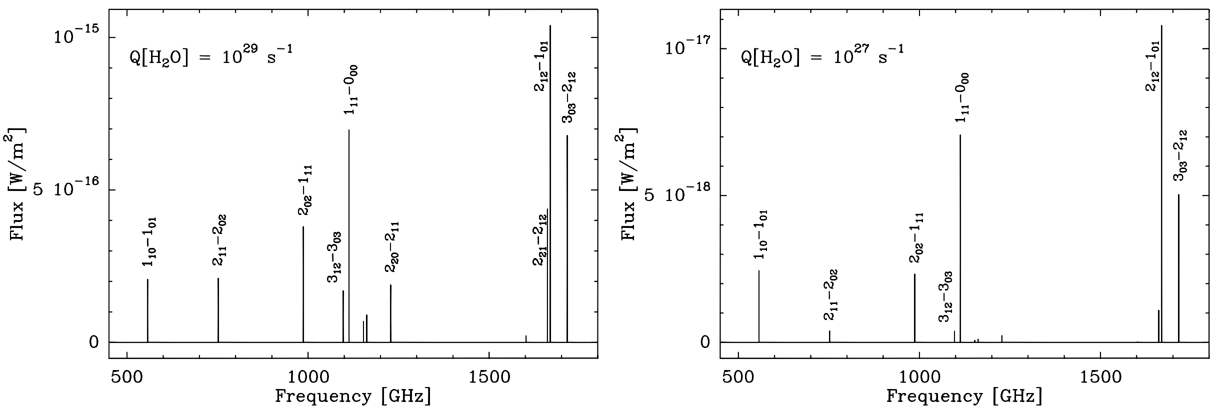

Figure 4: Synthetic spectra of water for observations with HIFI. Intensities are computed for a comet at $r_h = \Delta = 1$ AU and diffraction-limited beams. The excitation model of Bockelée-Morvan (1987) is used; collisions with electrons and optically thick lines are taken into account. The gas temperature and expansion velocity are taken equal to 60 K and 0.8 km s^{-1}, respectively. Left spectrum: bright comet with $Q[H_2O] = 10^{29}$ molecules s^{-1}. Right spectrum: weak comet with $Q[H_2O] = 10^{27}$ molecules s^{-1}. (From Bockelée-Morvan & Crovisier 2001.)

2 Observations with HIFI

Main goals

This programme is focussed on the study of water in comets: monitoring of water production rates, search for water production in low-activity objects, study of physical conditions, search for deuterated water. Other cometary science goals (such as the search for new molecular species), which need bright (unexpected) comets, will be performed on guaranteed time, open time or discretionary time. Some species, however, could be searched for serendipitously within the present programme using specific receiver setups. The specific case of a spectral survey is currently under study.

The first part of the programme is a systematic investigation of the water production rate and its evolution (survey and monitoring):

- a) Water in a sample of weak comets.

  Determination of the water production rate and water kinematics (from the line shape).

  Correlation with dust (from complementary observations with PACS): the dust-to-gas ratio and assessment of non-gravitational forces..

  Correlation with the nucleus size (from other oservations; cf. Lamy et al. 2004): the active fraction of the nucleus.

- b) Monitoring the water production as a function of distance to Sun.

  Investigating the onset of water sublimation. Correlation with dust (PACS).

- c) Search for water in distant comets and weakly active (dormant and/or extinct) objects.

  Relation between comets and asteroids.

The second part of the programme is a specific study of the physical conditions and D/H isotopic ratio in the brightest comets:

- d) Water excitation.

  Observation of several lines (with complementary observations with SPIRE and PACS).

- e) The D/H ratio and minor species.

  Search for HDO – especially in Jupiter-family comets.

  Serendipitous search for other species.

Details of observations

Due to the water excitation conditions in comets and the performances of the instrument, the 557 GHz water line is the most sensitive for a study with HIFI: it will permit a search for weak activity and observation of line profiles with high S/N. Due to the small line widths which are expected, HRS could be used with frequency switching. The detection limit (5–σ) achievable in one hour observation of the 557 GHz line corresponds to a water production rate of $\approx 10^{26}$ molecules s^{-1} for a comet at 1 AU from Earth and Sun (Table 2). This exceeds by far the sensitivity of other remote sensing techniques currently used to measure cometary gas productions.

Observations of the 557 GHz water line in a few comets with SWAS and Odin recently demonstrated the interest of such a study. They may serve as a basis for a feasibility evaluation of our project.

There are 5 distinct scientific goals in the programme we are proposing:

- a) Observation of the 557 GHz water line in a large sample of comets (single observation) for water production and kinematics. The sensitivity with HIFI is much better than with other techniques, giving access to a large sample of comets.

  The observation of the line profile with high resolution will allow us to study the kinematics of water sublimation and coma expansion for a large sample of comets, including weak objects. The high spectral resolution of HRS is needed, because we want to observe velocity offsets of the order of 0.1 km s^{-1}.

Correlation with dust. We wish to obtain complementary continuum observations with PACS. In this domain of wavelengths, we are sensitive to large-size particles. We will determine the dust-to-gas ratio relevant to this component of dust and, together with the gas production, we will assess the momentum loss of the nuclei in terms of non-gravitational forces.

Correlation with nucleus size: information on the nucleus size already exists for most numbered short-period comets (Lamy et al. 2004).

- b) Monitoring of the 557 GHz water line in selected comets for the study of the water production evolution as a function of heliocentric distance.

  This will permit the study of the sublimation mechanism of cometary ices, with a special look on the onset of water sublimation at $r \approx$ 3–4 AU. This should also be undertaken in relation with the observation of sublimation of other species (need for ground-based complementary observations at radio and IR wavelengths). The high sensitivity of HIFI is needed to search for water sublimation in distant objects.

- c) Search for water in weakly active objects.

  We wish to conduct a sensitive search for water outgassing in comet 29P/Schwassmann-Wachmann 1. This active comet has a nearly circular orbit at $\approx$ 6 AU from the Sun. CO (with $Q \approx 2. \times 10^{28}$ s^{-1}) is responsible for its activity. However, part of CO is observed to be released from and extended source, possibly icy grains (Gunnarsson et al. 2002). Such grains could be a source of water.

  Herschel/HIFI will also be very sensitive for searching water in Near Earth Objects (NEO's). Some of these objects might be extinct or dormant comets, with a low level of activity.

- d) Observations of several water lines in selected comets for constraining water excitation and physical conditions.

  This will be achieved by (nearly) simultaneous observations with HIFI, SPIRE and PACS of several rotational lines of water. It must be noted that although SPIRE and PACS cannot resolve the lines, they can measure several lines simultaneously.

  High resolution line profiles will also be measured to study asymmetric outgassing and velocity offsets, as well as self-absorption effects and temperature profiles (the temperature as a function of distance to nucleus). They should be obtained not only on the 557 GHz line, but on other lines less sensitive to optical depth effects. Mapping could also be made to study asymmetric outgassing and temperature profiles.

  One could also attempt to measure the ortho-to-para ratio, but it is a difficult challenge due to opacity effects and to the different fields of views used for observing the different transitions.

- e) Search for HDO for determining the D/H ratio in a selection of comets.

  Up to now, D/H $\approx 3. \times 10^{-4}$ has been measured in only three comets, which are "Oort cloud" comets. Herschel will give us access to the weaker "Jupiter-family" comets for which nothing is known.

  The strong 465 GHz line of HDO, previously observed in comets Hyakutake and Hale-Bopp, is difficult to detect from the ground, except in very bright comets. It is not covered by HIFI, nor by the baseline set of receivers of ALMA. The 509, 600 and/or 894 GHz lines are to be observed with HIFI which has an unprecedented sensitivity for this search.

Table 1: Cometary molecular lines for HIFI.

molec.	transition	ν [GHz]	E_u [cm^{-1}]	HIFI band
		water		
H_2O	1_{10}–1_{01}	556.9	42.3	1
H_2O	2_{11}–2_{02}	752.0	96.0	2
H_2O	2_{02}–1_{11}	987.9	70.1	4
H_2O	1_{11}–0_{00}	1113.3	37.1	4
H_2O	2_{21}–2_{12}	1661.0	134.9	6
H_2O	2_{12}–1_{01}	1669.9	79.5	6
H_2O	3_{03}–2_{12}	1716.8	136.7	6
		water isotopes		
HDO	1_{10}–1_{01}	509.3	32.5	1
HDO	2_{11}–2_{02}	599.9	66.2	1
HDO	1_{11}–0_{00}	893.6	29.8	3
$H_2^{18}O$	1_{10}–1_{01}	547.7	42.1	1
$H_2^{17}O$	1_{10}–1_{01}	552.0	42.1	1
		other parent molecules		
NH_3	1_0–0_0	572.5	19.	1
H_2S	2_{12}–1_{01}	736.0	38.	2
		radicals		
OH	$3/2^+$–$1/2^-$	1837.8	187.	6
OH	$3/2^-$–$1/2^+$	1834.7	187.	6
CH	3/2–1/2	536.7	17.9	1
CH_2	1_{11}–2_{02}	945.8	78.3	3
NH	1–0	974.6	32.	4
		molecular ions		
H_3O^+	0_0^-–1_0^+	984.6	37.	4
H_3O^+	1_1^-–1_1^+	1655.8	53.	4
H_2O^+	?–?	??	??	??
OH^+	1–2	971.8	32.4	4
CH^+	1–0	835.0	28.	3
CH^+	2–1	1670.1	56.	6

Comets with $Q[H_2O] > 5. \times 10^{28}$ molec. s^{-1} at $r_h = \Delta = 1$ AU should be easily detectable (Table 2).

Several minor species could be searched for serendipitously with specific receiver and back-end setups. For instance: NH_3 (572.5 GHz) with H_2O (556.9 GHz) — $H_2^{18}O$ (547.7) and HNC (543.9) with H_2O (556.9)...

Lines to be observed

Table 1 lists the H_2O and HDO lines we plan to observe. Lines of other water isotopes and of cometary molecules and molecular ions of interest are also listed.

Strategy

- a) will be performed by observing the 557 GHz line once on weak objects (typically $Q[H_2O] > 3. \times 10^{26}$ molec. s^{-1}). A good S/N is required to derive the line shape for kinematics.

Table 2: Expected line intensities and S/N for HIFI.

molec.	transition	ν [GHz]	$Q[H_2O]$ [s^{-1}]	$T_b dv$ [K km s^{-1}]	S/N
H_2O	1_{10}–1_{01}	556.9	10^{26}	0.035	5.1
H_2O	1_{10}–1_{01}	556.9	10^{27}	0.43	63.
H_2O	1_{10}–1_{01}	556.9	10^{28}	4.8	713.
H_2O	1_{10}–1_{01}	556.9	10^{29}	31.	4660.
H_2O	1_{10}–1_{01}	556.9	10^{27}	0.43	63.
H_2O	2_{11}–2_{02}	752.0	10^{27}	0.027	3.4
H_2O	2_{02}–1_{11}	987.9	10^{27}	0.21	23.
H_2O	1_{11}–0_{00}	1113.3	10^{27}	0.60	61.
H_2O	2_{21}–2_{12}	1661.0	10^{27}	0.050	1.7
H_2O	2_{12}–1_{01}	1669.9	10^{27}	0.57	20.
H_2O	3_{03}–2_{12}	1716.8	10^{27}	0.21	7.
HDO	1_{10}–1_{01}	509.3	$5. \times 10^{28}$	0.032	4.8
HDO	2_{11}–2_{02}	599.9	$5. \times 10^{28}$	0.016	2.2
HDO	1_{11}–0_{00}	893.6	$5. \times 10^{28}$	0.076	8.8

Line intensities are evaluated for a comet at $r_h = 1$ AU from Sun and $\Delta = 1$ AU from Earth, a coma with an expansion velocity of 0.8 km s^{-1} and a temperature of 30 K.
For HDO, $D/H = 3. \times 10^{-4}$ is assumed.
S/N is evaluated for 1 hour integration, frequency switch, a single polarization, and a line width of 1.6 km s^{-1}.

- b) will be performed on a smaller number of brighter objects (typically $Q[H_2O] > 5. \times 10^{27}$ molec. s^{-1}). But the monitoring will be pursued at large heliocentric distances to watch the onset/disappearance of water-governed activity (for $Q[H_2O] < 2. \times 10^{26}$ molec. s^{-1}).
- c) will be performed on a small number of specific targets (29P/S—W1 and NEO's).
- d) will also be performed on a smaller number of brighter objects (typically $Q[H_2O] > 3. \times 10^{27}$ molec. s^{-1}), possibly the same as b) .
- e) needs integration on still brighter objects (typically $Q[H_2O] > 5. \times 10^{28}$ molec. s^{-1}). Jupiter-family comets, for which no D/H information is available, will be preferred.

Targets

Short-period comets: They will be selected from the list of known short-period comets, according to their expected gas production rate, to their visibility with Herschel and to the confirmed launch date. A detailed list is provided in the Appendix. A synopsys is shown in Fig. 5.

Unexpected comets: They will be observed as targets of opportunity. Following the statistics of Hugues (2001) and the magnitude–$Q[H_2O]$ heuristic law of Jorda et al. (1992), one would expect an average of one comet per year with $Q[H_2O] > 10^{29}$ s^{-1} (but only one comet out of two at most would be in the visibility range of Herschel).

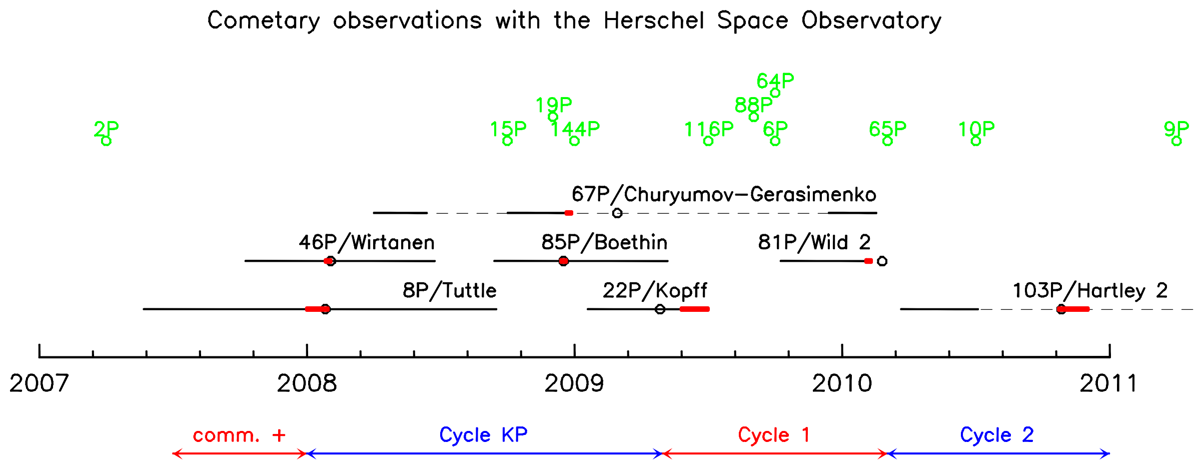

Figure 5: Short-period comets to be observed as a function of time. In green are weak comets for which a single observation is desirable. Targets qualified for more extensive studies have their observing windows shown by plain black lines, with the most favourable period indicated by thick red lines and their perihelion shown by a circle. The timelines for the various observing cycles are shown at the bottom for a launch in mid-2007.

3 Related work

Other observations

As stated above, this programme will be coordinated with complementary observations with the other Herschel instruments:

With SPIRE and PACS: simultaneous observations of several water rotational lines and mapping of some of the most intense ones to probe the excitation conditions of water.

With PACS: continuum observations in the far-IR to probe the dust component of the cometary material.

Supporting ground based observations will also be organized. Narrow-band photometry in the visible will be made to obtain production rates of radicals and dust. For the brighter comets, other spectroscopic radio observations with IRAM, CSO, and JCMT will be made to determine the chemical composition of the cometary ices and the kinematics of trace species. (Note that, in their frequency domains, these ground-based telescopes have instrumental beams comparable to those of HIFI.) Photometry in the infrared will also provide dust production and the silicate content.

Some comets which are (or were) the targets of space missions will be observed. This is the case for 46P/Wirtanen (previous target of Rosetta), 19P/Borrelly (Deep Space 1, flyby September 2001), 67P/Churyumov-Gerasimenko (target of Rosetta, encounter 2014–2015), 81P/Wild 2 (Stardust, flyby January 2004), 9P/Tempel 1 (Deep Impact, flyby July 2005). An increased scientific return is expected for these comets which are the objects of coordinated studies.

Related theoretical work

The scientific exploitation of this programme crucially depends upon modelling of water excitation and radiative transfer. A first generation of models has been initiated by Bockelée-Morvan (1987). They include collisional excitation and radiation trapping in the rotational lines (which are the prevailing excitation mechanism in the inner coma) and radiative excitation of the vibrational bands by the Sun infrared radiation (which leads to a fluorescence equilibrium in the outer coma). These models have recently been updated to consider collisional excitation by electrons following Biver (1997).

Such models were used for the interpretation of cometary water observations by ISO, SWAS and Odin. They were able to reproduce the rotational structure of the vibrational bands of water observed by ISO. They were also used to retrieve water production rates from the SWAS and Odin observations of the 1_{10}–1_{01} line,which were found to be in reasonable agreement with those obtained with independent methods (e.g. from radio and near-UV observations of OH).

These models will be refined and extended for the present project. The next generation of models will benefit from the knowledge of the excitation conditions resulting from the observations of several water rotational lines with Herschel. Such models are also needed for the in situ observations by Rosetta.

4 Estimation of time

Very crude estimation on the basis of a programme extended over three years.
(Comets to be observed are those of Table 4 plus unexpected comets as targets of opportunity.)

about 20 comets with $Q[H_2O] > 10^{26}$ molec. s^{-1}	
a) — search for the 557 GHz line —	**40 hours**
about 4 objects of weak activity	
c) — search for the 557 GHz line —	**10 hours**
about 8 comets with $Q[H_2O] > 5. \times 10^{27}$ molec. s^{-1}	
b) — monitoring of $Q[H_2O]$ in the 557 GHz line —	**30 hours**
d) — observation of other water lines —	**30 hours**
about 4 comet with $Q[H_2O] > 5. \times 10^{28}$ molec. s^{-1}	
e) — search for HDO —	**40 hours**
Total:	**150 hours**

APPENDIX A: Short-period comets to be observed

Table 3 lists short-period comets whose returns are expected in the first years of operation of Herschel.

Comets to be observed are to be selected according to their visibility for Herschel (solar elongation between 60 and 120°) and their expected gas production rate. For many comets for which information is sparse, this latter is not known. We have then to rely on the heuristic relation between heliocentric magnitude and water production rate

$$\log Q[H_2O] = 30.74 - 0.24\, m_h$$

(from Jorda et al. 1992).

A preliminary document discussing case-by-case the observability of the brightest comets from Table 3 is available. From this document, a selection of comets to be observed has been extracted and is listed in Table 4. Two comets are making close approaches to Earth, providing particularly good observing conditions: 8P/Tuttle ($\delta = 0.25$ AU) and 103P/Hartley2 ($\delta = 0.12$ AU).

Table 3: Short-period comets expected in 2006–2010.

Name	perihelion	q	P	H_p
132P/Helin–Roman–Alu 2	2006–Feb–15.00	1.924	8.28	15.7
98P/Takamizawa	2006–Mar–06.31	1.662	7.39	13.4
83P/Russell 1	2006–Apr–07.4	2.171	7.61	19.0
73P/Schwassmann–Wachmann 3	2006–Jun–06.65	0.939	5.35	7.5
71P/Clark	2006–Jun–06.86	1.562	5.51	12.5
102P/Shoemaker 1	2006–Jun–07.32	1.973	7.23	12.4
41P/Tuttle–Giacobini–Kresak	2006–Jun–11.37	1.047	5.41	10.8
45P/Honda–Mrkos–Pajdusakova	2006–Jun–29.74	0.530	5.25	6.8
84P/Giclas	2006–Aug–07.45	1.851	6.96	14.2
52P/Harrington–Abell	2006–Aug–14.76	1.757	7.53	11.9
114P/Wiseman–Skiff	2006–Sep–13.26	1.577	6.67	14.0
80P/Peters–Hartley	2006–Sep–26.08	1.633	8.13	12.3
112P/Urata–Niijima	2006–Oct–29.56	1.464	6.66	16.6
P/Lovas 2 (1986 W1)	2006–Nov–12.65	1.403	6.61	11.9
4P/Faye	2006–Nov–15.46	1.667	7.54	10.8
P/Shoemaker–Levy 6 (1991 V1)	2006–Nov–17.18	1.128	7.52	13.5
76P/West–Kohoutek–Ikemura	2006–Nov–19.86	1.603	6.47	14.1
99P/Kowal 1	2007–Jan–15.72	4.718	15.08	14.6
106P/Schuster	2007–Apr–02.19	1.556	7.30	15.4
96P/Machholz 1	2007–Apr–04.63	0.124	5.23	2.1
2P/Encke	2007–Apr–19.30	0.339	3.30	7.5
17P/Holmes	2007–May–04.50	2.053	6.88	14.7
135P/Shoemaker–Levy 8	2007–May–30.98	2.711	7.47	15.2
128P/Shoemaker–Holt 1	2007–Jun–13.64	3.068	9.58	13.4
156P/Russell-LINEAR	2007–Jun–17.	1.593	6.84	17.5
108P/Ciffreo	2007–Jun–19.	1.719	7.25	12.7
133P/Elst–Pizarro	2007–Jun–29.35	2.641	5.61	16.8
87P/Bus	2007–Jul–07.15	2.173	6.50	15.6
125P/Spacewatch	2007–Aug–10.72	1.523	5.52	15.7
70P/Kojima	2007–Oct–05.93	2.011	7.05	16.0
136P/Mueller 3	2007–Oct–23.91	2.960	8.57	15.7
50P/Arend	2007–Nov–01.18	1.924	8.26	13.7
75P/Kohoutek	2007–Nov–04.23	1.795	6.69	13.0
P/Jedicke (1995 A1)	2007–Dec–04.09	4.087	14.35	14.6
P/Shoemaker–Levy 1 (1990 V1)	2007–Dec–10.31	1.465	16.43	12.1
93P/Lovas 1	2007–Dec–17.36	1.704	9.20	12.8
8P/Tuttle	2008–Jan–26.96	1.027	13.61	8.3
46P/Wirtanen	2008–Feb–02.33	1.057	5.44	9.1
110P/Hartley 3	2008–Feb–03.49	2.488	6.88	13.9
44P/Reinmuth 2	2008–Feb–18.28	2.106	7.07	13.2
113P/Spitaler	2008–Mar–23.41	2.128	7.08	16.6
26P/Grigg–Skjellerup	2008–Mar–23.68	1.116	5.30	14.0
16P/Brooks 2	2008–Apr–12.55	1.466	6.14	11.7
139P/Vaisala–Oterma	2008–Apr–19.	3.402	9.54	15.3
124P/Mrkos	2008–Apr–27.21	1.468	5.74	14.8
11P/Tempel–Swift–LINEAR	2008–May–04.	1.553	6.37	16.9
146P/Shoemaker–LINEAR	2008–May–19.	1.418	7.88	16.5
P/Mueller 5 (1993 W1)	2008–May–19.32	4.214	13.62	16.2
86P/Wild 3	2008–May–20.01	2.301	6.91	16.4
148P/Anderson–LINEAR	2008–May–24.	1.702	7.05	14.8
79P/du Toit–Hartley	2008–May–28.35	1.230	5.27	16.9
51P/Harrington	2008–Jun–18.81	1.687	7.12	13.4
15P/Finlay	2008–Jun–22.52	0.970	6.49	9.7
33P/Daniel	2008–Jul–18.	2.170	8.07	17.0
19P/Borrelly	2008–Jul–22.34	1.354	6.85	6.5
6P/d'Arrest	2008–Aug–14.71	1.353	6.53	9.4
61P/Shajn–Schaldach	2008–Sep–06.02	2.107	7.04	14.4
147P/Kushida–Muramatsu	2008–Sep–23.03	2.756	7.42	14.3
7P/Pons–Winnecke	2008–Sep–26.64	1.253	6.35	12.7
150P/LONEOS	2008–Nov–25.	1.768	7.66	16.0
85P/Boethin	2008–Dec–16.36	1.147	11.53	7.7
57P/duToit–Neujmin–Delporte	2008–Dec–25.97	1.723	6.40	14.6

Table 3: Short-period comets expected in 2006–2010 (continued).

Name	perihelion	q	P	H_p
68P/Klemola	2009–Jan–20.98	1.759	10.82	12.4
144P/Kushida	2009–Jan–27.10	1.438	7.60	11.9
47P/Ashbrook–Jackson	2009–Jan–31.98	2.799	8.33	12.5
14P/Wolf	2009–Feb–27.25	2.724	8.73	15.2
67P/Churyumov–Gerasimenko	2009–Feb–28.36	1.246	6.44	10.5
59P/Kearns–Kwee	2009–Mar–07.60	2.355	9.50	12.6
145P/Shoemaker–Levy 5	2009–Mar–29.08	1.890	8.39	14.6
P/Shoemaker 4 (1994 J3)	2009–Apr–11.45	2.935	14.57	14.7
137P/Shoemaker–Levy 2	2009–May–14.78	1.915	9.55	15.7
22P/Kopff	2009–May–25.44	1.577	6.44	8.2
143P/Kowal–Mrkos	2009–Jun–13.	2.538	8.95	15.8
64P/Swift–Gehrels	2009–Jun–14.42	1.377	9.34	10.4
77P/Longmore	2009–Jul–07.82	2.310	6.82	14.1
116P/Wild 4	2009–Jul–18.67	2.175	6.48	11.2
74P/Smirnova–Chernykh	2009–Jul–30.36	3.557	8.52	12.7
24P/Schaumasse	2009–Aug–09.62	1.213	8.28	8.7
89P/Russell 2	2009–Aug–17.16	2.279	7.39	16.9
88P/Howell	2009–Oct–12.78	1.363	5.49	9.1
127P/Holt–Olmstead	2009–Oct–21.34	2.195	6.39	16.1
100P/Hartley 1	2009–Dec–06.18	1.982	6.29	15.4
54P/de Vico–Swift–NEAT	2009–Dec–06.48	2.171	7.37	16.9
118P/Shoemaker–Levy 4	2009–Dec–31.	1.984	6.51	13.0
82P/Gehrels 3	2010–Jan–10.	3.633	8.45	16.2
149P/Mueller 4	2010–Feb–19.	2.651	9.01	16.0
126P/IRAS	2010–Feb–24.	1.713	13.30	10.7
81P/Wild 2	2010–Feb–24.	1.598	6.39	10.1
65P/Gunn	2010–Mar–01.	2.440	6.83	10.8
94P/Russell 4	2010–Mar–31.	2.240	6.58	15.0
30P/Reinmuth 1	2010–Apr–20.	1.884	7.31	13.6
104P/Kowal 2	2010–May–05.	1.180	6.18	10.9
141P/Machholz 2	2010–May–25.	0.758	5.22	8.4
142P/Ge–Wang	2010–May–30.	2.488	11.20	17.5
10P/Tempel 2	2010–JUl–03.	1.422	5.47	10.9
43P/Wolf–Harrington	2010–Jul–03.	1.357	6.46	9.3
2P/Encke	2010–Aug–06.	0.339	3.30	7.5
31P/Schwassmann–Wachmann 2	2010–Sep–27.	3.424	6.39	15.7
103P/Hartley 2	2010–Oct–26.	1.059	6.39	8.4
9P/Tempel 1	2011–Jan–10.	1.510	5.51	10.0
27P/Crommelin	2011–Aug–03.	0.748	27.40	9.5
To be completed with comets in 2011–				
29P/Schwassmann-Wachmann 1				
95P/Chiron				
107P/Wilson-Harrington				

Comets are sorted by perihelion date;

q: distance to Sun at perihelion [AU];

P: orbital period [years];

H_p: total visual magnitude at perihelion, reduced to 1 AU from observer.

This list is incomplete for unnumbered comets. "D" comets are excluded.

(Compiled from HORIZONS data base — JPL.)

Table 4: Selection of short-period comets for Herschel.

Comet	observation	date
2P/Encke	d	Apr 2007
8P/Tuttle	b-d-e	Jan 2008 +
46P/Wirtanen	d	Feb 2008
15P/Finlay	a	Oct 2008
19P/Borrelly	a	Nov 2008
6P/d'Arrest	a	Oct 2009
85P/Boethin	b-d-e	Dec 2008 +
144P/Kushida	a	Jan 2009
67P/Churyumov-G.	a-b	Dec 2008 +
22P/Kopff	d-e	May 2009
64P/Swift-Gehrels	a	Oct 2009
116P/Wild 4	a	Jul 2009
88P/Howell	a	Sep 2009
126P/IRAS	(a)	Sep 2009
81P/Wild 2	d	Feb 2010
65P/Gunn	a	Mar 2010
10P/Tempel 2	a	Jul 2010
43P/Wolf-Harrington	(a)	Jul 2010
103P/Hartley2	b-d-e	Oct 2010 +
9P/Tempel 1	a	Apr 2011
To be completed with comets in 2011–		
Other weak comets	a	—
29P/Schwassmann-W.	c	several
NEO to be selected	c	—

a – just measurement of the 557 GHz line;
b – monitoring of the water production as a function of r_h;
c – search for water (557 GHz) in distant or weak objects;
d – observation of several H_2O lines;
e – search for HDO;
"date" corresponds to best observing period period; + indicate several observations (monitoring).

APPENDIX B: A spectral survey of a comet

There is presently no available comprehesive spectral survey of comets at radio wavelength. (For comet Hale-Bopp, which is the best studied comet at radio wavelengths, only $\approx 10\%$ of the microwave spectral range was covered, with observations spread over several months at various sensitivity levels, performed by different telescopes).

Such a spectral survey could be adequatly done with Herschel/HIFI on a resonably productive comet. It would provide an unbiased observation of water and its isotopes, of several other cometary species, and a serendipitous search for parent and daughter species.

We propose as a baseline an unbiased spectral survey such as the one proposed in the Star Formation HIFI core programme document:

- Survey restricted to the 500–1250 GHz spectral range (bands 1–5).
- Spectral resolution of 0.5 km s^{-1} (close to optimum for the detection of cometary lines).
- 25 hours of observation, yielding an rms noise of 25 mK.

Cometary lines (1.6 km s^{-1} wide) of area 0.11 K km s^{-1} are then observed at the 5–σ level.

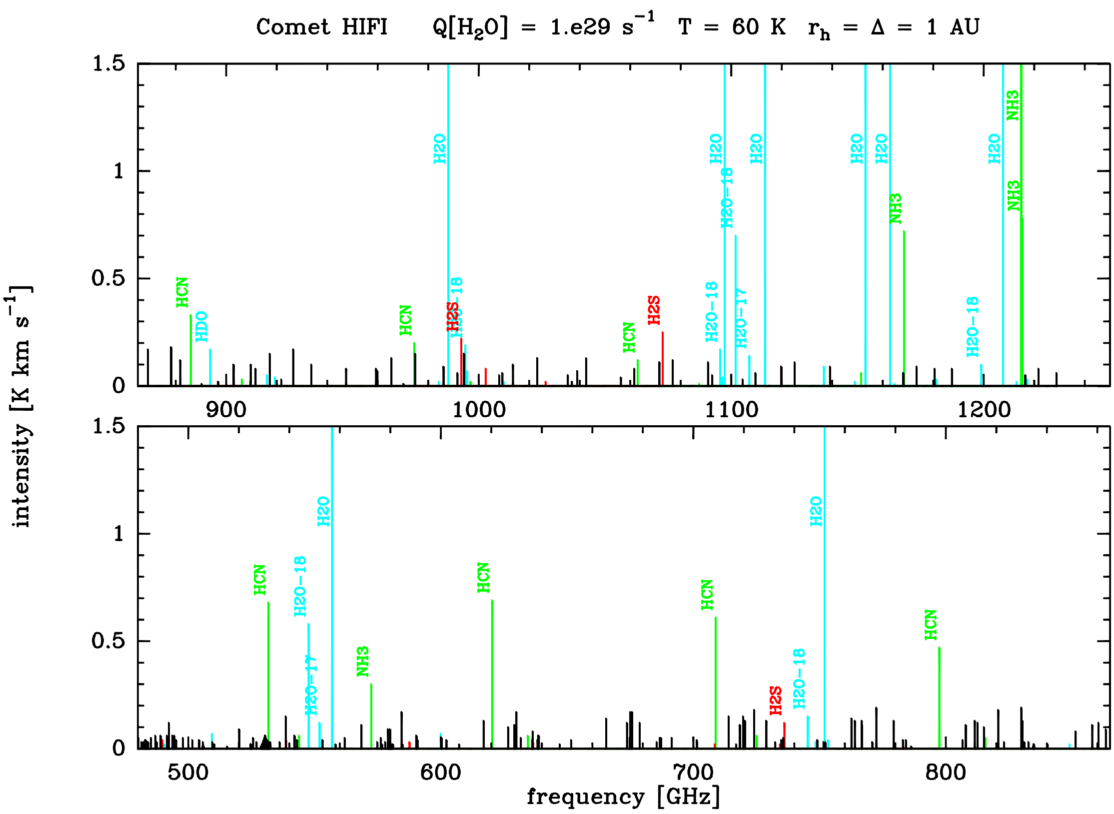

Figure 6: Comet spectral survey: synthetic spectrum. All black, unlabelled lines are due to methanol.

A cometary spectrum has been simulated using our software PAPSYNTHE. A basic water production rate of 10^{29} molecules s^{-1} was assumed. We have adopted a conservative list of molecules: water with water isotopes HDO (0.0006), $H_2^{18}O$ (0.002), $H_2^{17}O$ (0.0004), and other species HCN (0.002), NH_3 (0.01), H_2S (0.01) and CH_3OH (0.04) (the numbers in parentheses give the mixing ratios with respect to water $H_2^{16}O$). Simplistic thermal excitation at $T_{\rm rot} = 60$ K, a coma expansion velocity of 0.8 km s^{-1}, and a comet at $r_h = 1$ AU from the Sun and $\Delta = 1$ AU from the telescope are assumed.

The simulated spectrum (Fig. 6) shows that labelled lines of H_2O and isotopes, HCN, NH_3, H_2S, and many lines of CH_3OH will be detectable.

Of course, many other parent molecules, radicals or ions not considered here may be expected to show up: CH, CH_2, NH, H_2O^+, H_3O^+, OH^+, CH^+ and unexpected species that could be observed serendipitously.

Among short-period comets expected in 2007–2010, none is expected to exceed $Q[H_2O] = 10^{29}$ molecules s^{-1}. However, two comets will make close approaches to the Earth, the small Δ then compensating the weak $Q[H_2O]$ to yield signals comparable to those of Fig. 6:

- 8P/Tuttle with $Q[H_2O] \approx 3. \times 10^{29}$ s^{-1} at $\Delta = 0.25$ AU in January 2008.
- 103P/Hartley 2 with $Q[H_2O] \approx 1.2 \times 10^{29}$ s^{-1} at $\Delta = 0.12$ AU in October 2010.

We may also expect one or more unexpected comets with $Q[H_2O] > 10^{29}$ s^{-1} (and possibly much more) observable by Herschel during its lifetime and we must be prepared for valuable observations.

References

Altwegg, K. & Bockelée-Morvan, D. (2003). Isotopic abundances in comets. *Space Scie. Rev.*, **106**, 139–154.

Biver,N. (1997). Molécules mères cométaires : Observations et modélisation. PhD thesis, Université Paris VII.

Bockelée-Morvan, D. (1987). A model for the excitation of water in comet *Astron. Astrophys.*, **181**, 169–181.

Bockelée-Morvan, D,. & Crovisier, J. (2001). Comets and asteroids with FIRST. In *The Promise of the Herschel Space Observatory*, ESA SP–460, 279–286.

Bockelée-Morvan, D., Lis, D.C., Wink, J.E., et al. (2000). New molecules found in comet C/1995 O1 (Hale-Bopp). Investigating the link between cometary and interstellar material. *Astron. Astrophys.*, 353:1101–1114.

Chiu, K., Neufeld, D.A., Bergin, E.A., et al. (2001). Post-perihelion SWAS observations of water vapor in the coma of comet C/1999 H1 (Lee). *Icarus*, **154**, 345–349.

Combi, M. (2002). Hale-Bopp: What makes a big comet different? Coma dynamics: observations and theory. *Earth Moon Planets*, **89**, 73–90.

Crovisier, J., Leech, K., Bockelée-Morvan, D. et al. (1997). The spectrum of comet Hale-Bopp (C/1995 O1) observed with the Infrared Space Observatory at 2.9 astronomical units from the Sun. *Science*, **275**, 1904–1907.

Dello Russo, N., Mumma, M.J., DiSanti, M.A. et al. (2000). Water production and release in comet C/1995 O1(Hale-Bopp). *Icarus*, **143**, 324–337.

Grün, E., Hanner, M.S., Peschke, S. et al. (2001). Broadband infrared photometry of comet Hale-Bopp withISOPHOT. *Astron. Astrophys.*, **377**, 1098–1118.

Gunnarsson, M., Rickman, H., Festou, M.C., Winnberg, A., & Tancredi, G. (2002). An extended source of CO around 29P/Schwassmann-Wachmann 1. *Icarus*, **157**, 309–322.

Hersant, F., Gautier, D., & Huré, J.-M. (2001).A two-dimensional model for the Primordial Nebula constrained by D/H measurements in the Solar System: Implications for the formation of giant planets. *Astrophys. J.*, **555**, 391–407.

Hughes, D. (2001). The magnitude distribution, perihelion distribution and flux of long-period comets. *Monthly Not. Roy. Astron. Soc.*, **326**, 515–523.

Irvine, W.M., Schloerb, F.P., Crovisier, J., Fegley, B., and Mumma, M.J. (2000). Comets: a link between interstellar and nebular chemistry. In *Protostars and Planets IV*, V. Mannings, A. Boss and S. Russell (Edts), Univ. of Arizona Press, Tucson, Arizona, 1159–1200.

Jorda, L., Crovisier, J., & Green, D.W.E. (1992). The correlation between water production rates and visual magnitudes in comets. In *Asteroids Comets Meteors 1991*, LPI, Houston, 285–288.

Lamy, P.L., Toth, I., Fernández,Y.R., & Weaver, H.A. (2004). The sizes, shapes, albedos, and colors of cometary nuclei. In *Comets II*, Univ. Arizona Press, Tucson, Arizona, in press.

Lecacheux, A., Biver, N., Crovisier, J., et al. (2003). Observations of water in comets with Odin. *Astron. Astrophys.*, **402**, L55–L58.

Mousis, O., Gautier, D., Bockelée-Morvan, D., et al. (2001). Constraints on the formation of comets from D/H ratios measured in H_2O and HCN. *Icarus*, **148**, 513–525.

Mumma, M.J., DiSanti, M.A., Dello Russo, N., et al. (2003). Remote infrared observations of parent volatiles in comets: a window on the Early Solar System. *Adv. Space Res.*, **31**, 2563–2575.

Neufeld, D.A., Stauffer, J.R., Bergin, E.A., et al. (2000). SWAS observations of water vapor toward comet C/1999 H1 (Lee). *Astrophys. J.* **539**, L151–L154.