COMETS AND ASTEROIDS WITH THE HERSCHEL SPACE OBSERVATORY

Jacques Crovisier

Observatoire de Paris, Place Jules Janssen, 92195 Meudon, France, `jacques.crovisier@obspm.fr`

This paper is dedicated to Caroline Herschel (1750–1848), sister of William Herschel, one of the first professional women astronomers, and discoverer of no less than 8 comets.

ABSTRACT

This review discusses the prospects for the observations of small bodies in the Solar System with the Herschel Space Observatory. Herschel, and especially its heterodyne instrument HIFI, is well suited to study cometary water, the evolution of its production, its kinematics, its excitation in relation with collisions and cooling processes. The D/H ratio of cometary water could be investigated in several objects (and especially Jupiter-family comets) to constrain the history of the Solar Nebula. The good sensitivity of HIFI could allow us to search for very low levels of water outgassing in distant comets and in comet–asteroid transition objects. HIFI, SPIRE and PACS, by observing several lines of water, could investigate the rotational energy distribution of this molecule. Several other cometary molecules such as light hydrides and their ions could also be studied in the Herschel spectral domain. Sensitive continuum observations with the PACS and SPIRE instruments, combined with visible photometry, could lead to the determination of the size and albedo for a variety of trans-Neptunian objects, Centaurs and asteroids.

Key words: asteroids, comets, Herschel Space Observatory.

1. INTRODUCTION

The Herschel Space Observatory will open the study of Solar System small bodies to the submillimetric domain. This spectral domain is unique for the observations of the rotational transition of light molecules (Table 1) and of the thermal emission of large-size particles.

The observation of water rotational lines is a major possibility offered by the Herschel Space Observatory for the study of comets. Ironically, although being the most abundant cometary volatile, water is one of the species the most difficult to observe (see, e.g., Crovisier et al. 1997 and Dello Russo et al. 2000 for a description of ISO and ground-based observations of this species). 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 detection 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). Subsequently, about ten comets were observed with SWAS and the Odin satellite (Lecacheux et al. 2003; Hjalmarson et al. 2004; Figs 2 & 3). The same water line was also observed in comet C/2002 T7 (LINEAR) by the microwave instrument MIRO aboard the Rosetta spacecraft during its commissioning (Gulkis 2004). This is very promising for the coming Herschel investigations of cometary water.

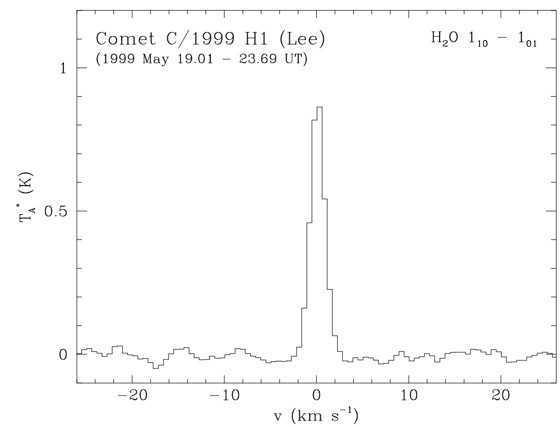

Figure 1. The historical detection of the H_2O 1_{10}–1_{01} water line at 557 GHz, observed by SWAS in C/1999 H1 (Lee). (From Neufeld et al. 2000.)

This paper is a sequel to previous reviews on the same topic by Encrenaz et al. (1982), Crovisier (1986), Crovisier & Bockelée-Morvan (1997),

Table 1. Selected cometary molecular lines in the submillimetric range.

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_{01}–0_{00}	464.9	15.5	–
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
NH_3	2_1^+–1_1^-	1168.5	56.	4
NH_3	2_0^-–1_0^+	1214.9	60.	4
NH_3	2_1^-–1_1^+	1215.2	56.	4
H_2S	2_{12}–1_{01}	736.0	38.	2
		radicals		
OH	$3/2^-$–$1/2^+$	1834.7	187.	6
OH	$3/2^+$–$1/2^-$	1837.8	187.	6
OH	$5/2^+$–$3/2^-$	2509.9	84.	–
OH	$5/2^-$–$3/2^+$	2514.3	84.	–
OH	$1/2^+$–$3/2^-$	3786.1	126.	–
OH	$1/2^-$–$3/2^+$	3789.2	126.	–
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.	6
H_2O^+	?–?	??	??	??
OH^+	1–2	971.8	32.4	4
CH^+	1–0	835.0	28.	3
CH^+	2–1	1670.1	56.	6

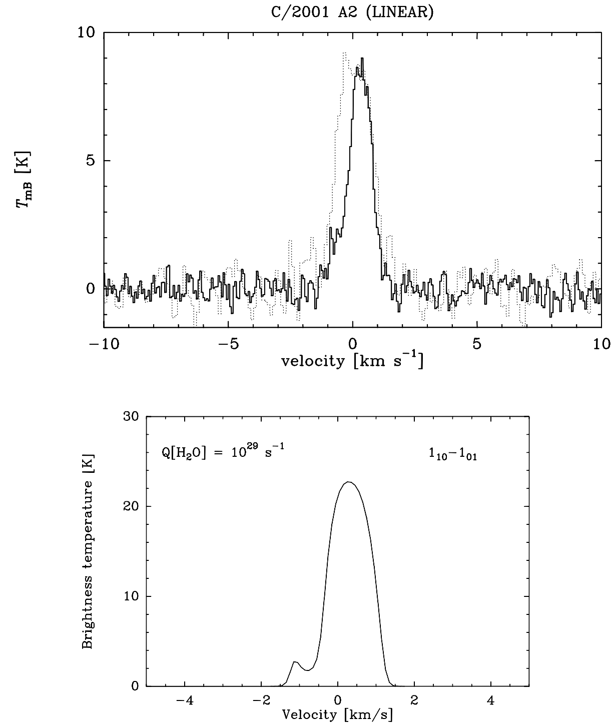

Figure 2. ***Top:*** *The 1_{10}–1_{01} H_2O line at 557 GHz observed by Odin in comet C/2001 A2 (LINEAR) on 2.2 July 2001 (full line). For comparison, the thin J(3–2) line of HCN observed at the CSO is also shown (scale expanded by $\times 10$, dotted line). The difference between the two profiles is attributed to self-absorption in the water line. This illustrates the benefit of high spectral resolution. (From Lecacheux et al. 2003.)* ***Bottom:*** *A synthetic spectrum of the same line, showing its asymmetry expected from optical depth effects. (From Bockelée-Morvan & Crovisier 2001.)*

Bockelée-Morvan & Crovisier (2002) and a complement to the more general review of Encrenaz et al. (2004).

2. PROSPECTS FOR COMETS

2.1. Water in comets

Due to its high sensitivity, HIFI can measure very low production rates of water (Table 2), making it one of the best tools for the detection of cometary activity. This will permit the investigation of weak comets, distant comets, and asteroid–comet transition objects.

Cometary molecular lines are narrow (≈ 1.5 km s^{-1} wide with occasionally features as narrow as ≈ 0.2 km s^{-1}). The high spectral resolution of HIFI will permit to investigate the kinematics of water outgassing, and to probe optical depth effects and excitation conditions by observing the line shapes (Fig. 2). It is highly desirable to observe a strong line with significant optical depth effects, such as the 557 GHz line, and a weak, thin line (e.g., oxygen isotope water line) for comparison.

Retrieving water production rates from the observation of a single, saturated line such as the 557 GHz rotational transition is highly model-dependent. The models presently used for the interpretation of the water observations by SWAS (Bensch & Bergin, 2004) or Odin (Lecacheux et al. and references therein) take into account radiative excitation by the Sun, collisional excitation by neutrals and electrons. Radiative transfer effects are addressed either by the escape probability formalism or by a Monte Carlo method. The water production rates are found to be in good agreement with those obtained from other, less direct means, indicating that these models are re-

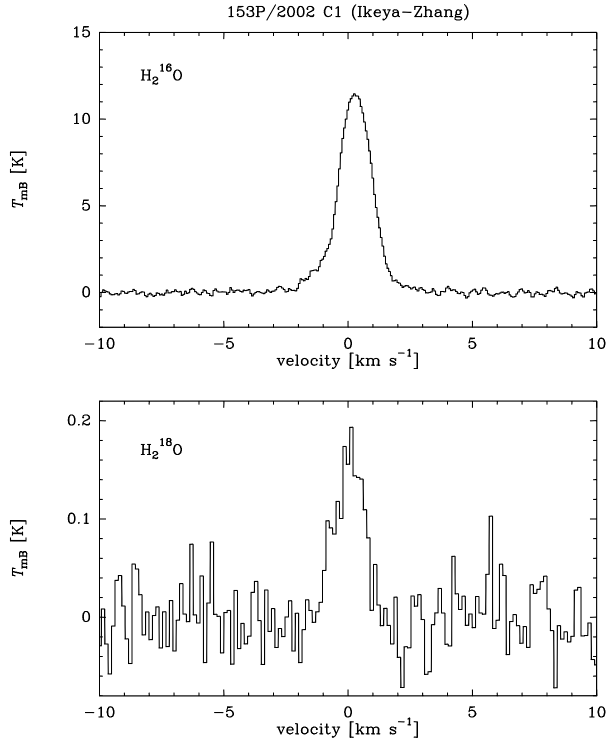

Figure 3. The 1_{10}–1_{01} lines of $H_2^{16}O$ (top) and $H_2^{18}O$ (bottom) observed in comet 153P/2002 C1 (Ikeya-Zhang) on 24–28 April 2002 by Odin. (From Lecacheux et al. 2003.)

liable at least in first approximation. However, these models, which are based upon several ill-known parameters, need to be improved.

The water excitation conditions and its radiative cooling mechanism may be probed by observing several rotational lines. PACS is required for higher frequency lines. HIFI may not easily observe different lines simultaneously, resulting in potential problems with inter-calibration and comet variability. SPIRE, although less sensitive, could observe the whole 490–1500 GHz spectrum at the same time, encompassing several water lines.

Investigating the ortho-to-para ratio of water in comets, which is poorly understood (Crovisier 2000), is an important goal. However, it will be difficult to probe from water rotational lines, because some of these lines are saturated.

2.2. 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 and references therein). 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.

2.3. Oxygen isotopes

Oxygen isotopes could be investigated in bright comets from the lines of $H_2^{17}O$ and $H_2^{18}O$ (Table 1). The observations of three comets with Odin (Lecacheux et al. 2003; Hjalmarson et al. 2004; Fig. 3) lead to a ratio $^{16}O/^{18}O$ close to the terrestrial value (499).

Up to now, only small variations of the $^{16}O/^{18}O$ and $^{16}O/^{17}O$ ratios were observed in the Solar System. However, some models (e.g., Yurimoto & Kuramoto 2004) predict oxygen rare isotope enrichments up to 5–20 % for cometary water, which could be checked with Herschel.

2.4. Other molecular species

The submillimetre spectral range covered by Herschel is not well suited for the observation of rotational lines of complex molecules, which are better studied at longer wavelengths (e.g., with ALMA; Biver 2004). However, an appealing possibility is the observation of the low frequency bending modes of species such as carbon-chain molecules (Cernicharo 2004).

Many lines of light hydrides, expected to be cometary parent molecules, radicals or ions, could be observed

Table 2. Expected water line intensities 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 the Sun and $\Delta = 1$ AU from the Earth, a coma with an expansion velocity of 0.8 km s^{-1} and a temperature of 30 K. The excitation model is described in Lecacheux et al. (2003) and references therein. For HDO, D/H = $3. \times 10^{-4}$ is assumed. The signal-to-noise ratio S/N is evaluated for 1 hour integration with HIFI, frequency switch, a single polarization, and a line width of 1.6 km s^{-1}.

Table 3. Some "good" comets for Herschel.

Comet	date	r [AU]	Δ [AU]	$Q[H_2O]$ [10^{28} s^{-1}	
8P/Tuttle	Jan 2008	1.1	0.25	3.	
46P/Wirtanen	Feb 2008	1.1	0.9	1.	
85P/Boethin	Dec 2008	1.1	0.9	3.	
67P/Churyumov-Gerasimenko	Dec 2008	1.5	1.7	0.5	Rosetta comet
22P/Kopff	May 2009	1.6	1.0	2.5	
81P/Wild 2	Feb 2010	1.6	0.9	1.3	Stardust comet
103P/Hartley2	Oct 2010	1.1	0.12	1.2	
unexpected long-period comet	1–2 per year	≈ 1	≈ 1	$> 10.$	

"date" corresponds to the best observing period.

by Herschel (Table 1). As an example, the 1_0–0_0 line of NH_3 was tentatively detected by Odin in C/2001 Q4 (NEAT) (Hjalmarson et al. 2004). Herschel could, in addition, observe the 2_0–1_0 and 2_1–1_1 lines of ammonia and measure its ortho-to-para ratio which, like that of water, is the subject of debates (Kawakita et al. 2004).

An unbiased spectral survey could also be attempted if a really bright comet does show up.

2.5. Investigating cometary dust and ice

The submillimetre continuum of comets is mainly due to the thermal emission of large-size dust particles, which cannot be probed at shorter wavelengths (Grün et al. 2001). The observation of the spectral energy distribution from 57 to 670 μm with SPIRE and PACS will allow us to constrain the properties of cometary dust. Spectral features of ice and minerals are expected to show up (Kerschbaum et al. 2004).

2.6. Selection of targets

When selecting comets for observations, one must have in mind that Herschel can only operate at solar elongations between 60° and 120°, which is a stringent constrain for Solar System observations.

Short-period comets may 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 synopsis of comets expected in 2007–2010 is shown in Fig. 4. Among peculiarly interesting targets (Table 3) are 9P/Tuttle and 103P/Hartley 2, which

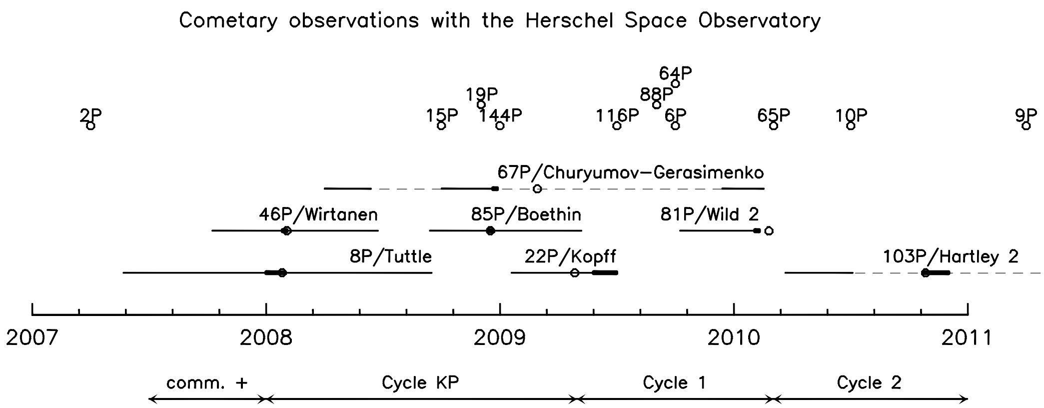

Figure 4. Short-period comets to be observed by the Herschel Space Observatory as a function of time. At the top, weak comets for which a single observation is desirable are indicated by a circle plotted at their perihelion date. Below, targets qualified for more extensive studies have their observing windows shown by plain lines, with the most favourable period indicated by thick lines and their perihelion shown by a circle. The schedule of the various observing cycles is shown at the bottom for a launch in mid-2007.

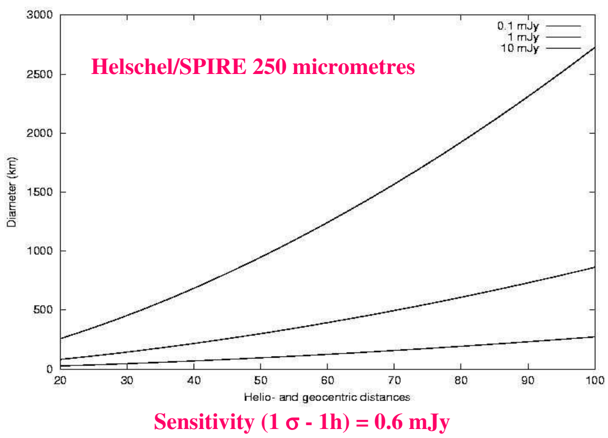

Figure 5. Detectability of TNOs with Herschel/SPIRE (courtesy of E. Lellouch).

are to make a close approach to Earth (at Δ = 0.25 and 0.12 AU, respectively). 67P/Churyumov-Gerasimenko should be specially mentioned. Although this weak comet is unsuited for detailed observations with Herschel, it is the target of the Rosetta mission. It could be observed on three time slots, allowing us to determine its water production rate for three different heliocentric distances.

Unexpected comets will have to 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 or two comets 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).

3. ASTEROIDS, CENTAURS AND TRANS-NEPTUNIAN OBJECTS

The combination of photometric measurements in the visible (or near-infrared) range and in the thermal range (submillimetric) allows us to determine independently the diameter and albedo of an asteroid, a Centaur, or a trans-Neptunian (TNO) object. Up to now, the sizes of TNOs are estimated using a priori assumptions on their albedos and very little is known on their true size distribution.

Due to its larger telescope size, Herschel is more sensitive for this project than the Spitzer Space Telescope, but not as much as ALMA will be (Jorda & Groussin 2004). TNOs with a diameter larger than 300 m could be detected with SPIRE up to 40 AU from the Sun (Fig. 5).

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