COMETS AND ASTEROIDS WITH FIRST

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Abstract

The infrared and microwave domains have proved to be privileged tools to study the physical and chemical properties of small bodies of the Solar System. After a review of the recent results obtained on comets and asteroids in these wavelength ranges, we forecast the major outcomes that can be expected from their observations with the Herschel Space Observatory (hereafter referred as to FIRST, the former denomination). This prospect is focussed on: 1) observations of water rotational lines in comets to measure water outgassing and study water excitation in the coma and its kinematics; 2) observations of HDO in comets to constrain solar nebula models and formation scenarii of comets; 3) the study of surface properties of asteroids.

Key words: Solar System – Comets – Asteroids – Missions: FIRST

1. Introduction

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. A considerable amount of informations regarding some of the primordial processes that governed the formation and evolution of the Solar System is also "frozen" in the asteroid population.

Besides in situ explorations, to be achieved in the next decade (after the pioneering missions to comet Halley) and comet nucleus sample missions in a more remote 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, FIRST and its three instruments is expected to contribute significantly to these investigations. Indeed, submillimetre and far-infrared spectral ranges are of peculiar interest. Recent observations, especially of comets C/1996 B2 (Hyakutake) and C/1995 O1 (Hale-Bopp), resulted in a dramatic update of our knowledge of cometary volatiles. The number of known parent molecules has been multiplied by a factor of almost three these last four years. Table 1 lists all species (molecules, ions, radicals and atoms) observed in cometary atmospheres. One can see that spectroscopy at radio wavelengths got the lion's share. Other significant results came from infrared spectroscopy, either from the ground (at high spectral resolution with CSHELL or NIRSPEC) or from space with the Infrared Space Observatory (ISO). The first detection of the 557 GHz water line, in comet C/1999 H1 (Lee) by the Submillimeter Wave Astronomy Satellite (SWAS) (Melnick 2001), is very promising for the coming FIRST investigations of cometary water (Fig. 3).

The spectrum of thermal radiation from asteroids, which will be partly accessible to FIRST, carries important informations regarding the composition and thermophysical properties of their surface. Infrared observations with IRAS (Tedesco 1989), by permitting albedo measurements in a number of asteroids, led to a major advance in the asteroid taxonomy. Flux densities in the infrared to radio ranges have been measured for the larger asteroids (e.g., Altenhoff et al. 1994, Müller & Lagerros 1998, Redman et al. 1998). Informations regarding size, thermal conductivity, surface roughness and emissivity have been deduced.

In this paper, we present the prospect of FIRST for the study of comets and asteroids. Planets, satellites and Kuiper Belt objects are covered in this book by Lellouch (2001).

2. Comets with FIRST

2.1. H_2O observations

A major cometary programme which should be conducted with FIRST is the observations of water rotational lines. Water is the main constituent of cometary ices (Table 1) and the measurement of its production rate at 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 (Fig. 1). 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. Incidently, water production rates in splitting and dis-

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Table 1. Molecules, radicals, ions and atoms observed in cometary comae, with their means of detection: radio (rad.), infrared (IR), visible (vis.), ultraviolet (UV) spectrocopy. The production rates relative to water of the parent species in comet Hale-Bopp are listed from Bockelée-Morvan et al. (2000).

	rad.	IR	vis.	UV	abundance
H_2O	x	x			100
H_2O^+			x		
H_3O^+	x				
OH	x	x		x	
H			x	x	
O			x	x	
O^+				x	
CO	x	x		x	23
CO_2		x			6
CO^+	x		x	x	
CO_2^+			x		
C				x	
C_2		x	x		
C_3			x		
CH_4		x			0.6
C_2H_2		x			0.1
C_2H_6		x			0.3
CH		x	x		
CH^+			x		
H_2CO	x				1.1
HCO^+	x				
CH_3OH	x	x			2.4
HCOOH	x				0.090
CH_3CHO	x				0.02
$HCOOCH_3$	x				0.080
N_2^+			x		
NH_3	x	x			0.7
NH			x		
NH_2		x	x		
HCN	x	x			0.25
HNC	x				0.035
CN	x	x	x		
CH_3CN	x				0.020
HC_3N	x				0.021
HNCO	x				0.10
NH_2CHO	x				0.01–0.02
H_2S	x				1.5
CS	x			x	0.17
SO	x				0.29
SO_2	x				0.23
OCS	x	x			0.40
H_2CS	x				0.02
NS	x				
S_2				x	
S				x	
Na			x		
K			x		
Ar				x	
atoms[a)]			x		

[a)] Various atoms only observed in the sungrazing comet C/1965 S1 (Ikeya-Seki).

integrating comets provide valuable observations on the fragmentation process. Finally, measurements of the water production rate of short-period comets at different returns might permit us to study physical aging. Data on the nucleus sizes of comets are rapidly increasing. Water production rates provide information on the icy fraction of the nucleus surface. Water also plays an important role in the thermal balance of cometary atmospheres, as a cooling agent by the emission of its rotational lines (Bockelée-Morvan & Crovisier 1987).

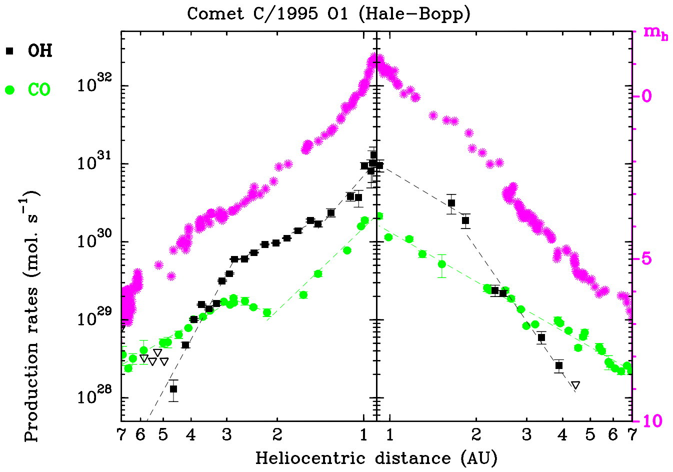

Figure 1. Heliocentric evolution of the H_2O (black squares) and CO (green dots) production rates in comet Hale-Bopp. CO data are from Biver et al. (1999b and 1999c). H_2O production rates determinations are from OH radio observations, OH ultraviolet observations from SWUIS and HST, and H_2O ISO data. The total heliocentric magnitude m_h is plotted for comparison (pink stars).

So far, production rates of water were inferred most of the time indirectly, by observations of its photodissociation products OH, H and O in the UV, visible or radio (Table 1). Occasionally, water was directly observed from in situ mass spectroscopy (Krankowsky et al. 1986), from air or space borne observations of its 2.7 and 6.3 μm bands in the infrared (Crovisier et al. 1999, Crovisier 1999), from ground based observations of several hot infrared bands (e.g. Dello Russo et al. 2000), and from observations of rotational lines in the submillimetric and far-infrared. Figs 2 and 3 show the only observations of water rotational lines available to date, besides a marginal detection of the 22 GHz line in comet Hale-Bopp (Bird et al. 1999): several lines in the 100–180 μm region in comet Hale-Bopp using ISO (Crovisier et al. 1999) and the 557 GHz line detected towards comet C/1999 H1 (Lee) with SWAS (Neufeld et al. 2000).

A comprehensive model of the excitation of the rotational levels of water has been developped (Bockelée-Morvan 1987) to prepare and interpret submillimetric ob-

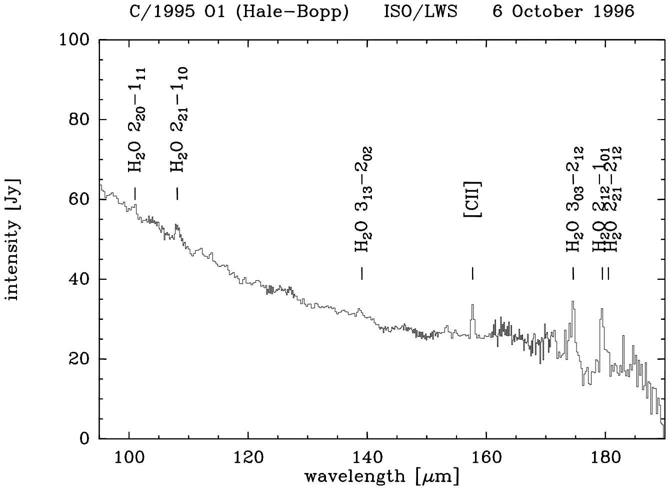

Figure 2. The rotational lines of water observed by the ISO long-wavelength spectrometer in comet Hale-Bopp at 2.9 AU from the Sun (Crovisier et al. 1999).

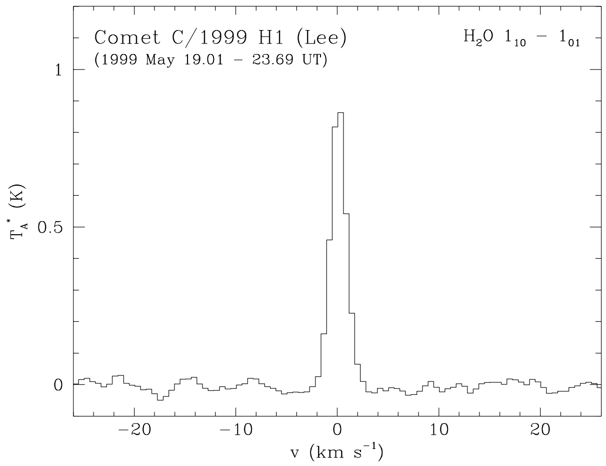

Figure 3. The H_2O 1_{10}–1_{01} line at 557 GHz observed by SWAS in comet C/1999 H1 (Lee) (Neufeld et al. 2000).

servations. This model includes collisional excitation and radiation trapping in the rotational lines, which are the prevailing excitation mechanisms in the inner coma, and radiative excitation by the Sun infrared radiation, which leads to a fluorescence equilibrium in the outer coma. Since cometary gas is cold (10 to 100 K depending of gas activity) and water is rotationally relaxed at fluorescence equilibrium, the rotational transitions occurring between the lowest energy states are the most intense. Synthetic spectra in the wavelength domains of HIFI, SPIRE and PACS are shown in Figs 4, 5, 6 and 7 for $Q[\mathrm{H_2O}] = 10^{27}$ and 10^{29} molecules s^{-1}. The 557 GHz line is the most favourable for detection in weak comets with FIRST, because it falls in a sensitive domain of the HIFI instrument: comets at r_h = 1 AU from the Sun and Δ = 1 AU from Earth with $Q[\mathrm{H_2O}] > 3 \times 10^{26}$ molecules s^{-1} should be detected in 1 hour integration or less. Several rotational lines should be easily detected in spectroscopy mode with the 3 instruments of FIRST for comets with $Q[\mathrm{H_2O}]$ larger than a few 10^{27} molecules s^{-1}.

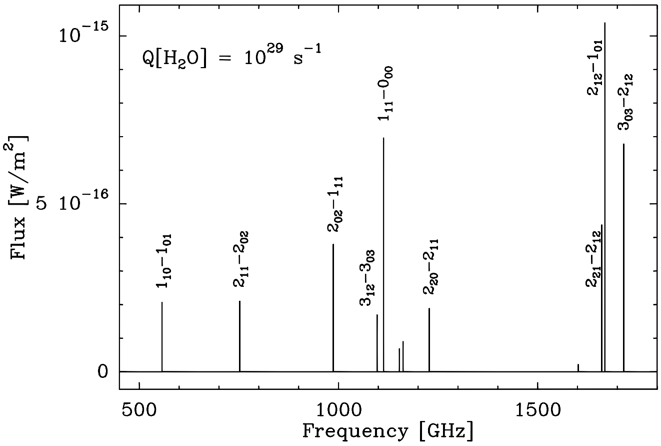

Figure 4. Synthetic spectrum of water for observations with HIFI and SPIRE. Intensities are computed for a comet at r_h = Δ = 1 AU with Q[H_2O] = 10^{29} molecules s^{-1} and FIRST diffraction limited beams. The excitation model of Bockelée-Morvan (1987) is used. Collisions with electrons are included (Biver et al. 1999a). The line transfer code for optically thick lines developped by Biver et al. (1999a) is used to compute the line intensities. The gas temperature and expansion velocity are taken equal to 60 K and 0.8 km s^{-1}, respectively.

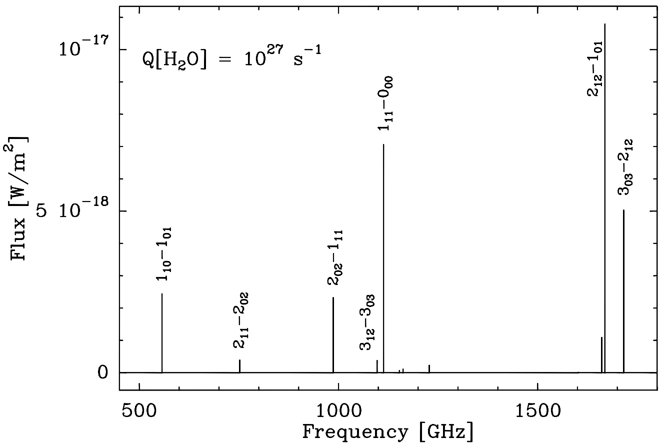

Figure 5. Synthetic spectrum of water for observations with HIFI and SPIRE. Model and comet parameters are the same as for Fig. 4, but with Q[H_2O] = 10^{27} molecules s^{-1}.

Observations of several rotational lines of water, when possible, are a requisite to well understand excitation processes and opacity effects and precisely infer water production rates. In bright comets, most of the detectable lines are expected to be thick somewhere in the coma and

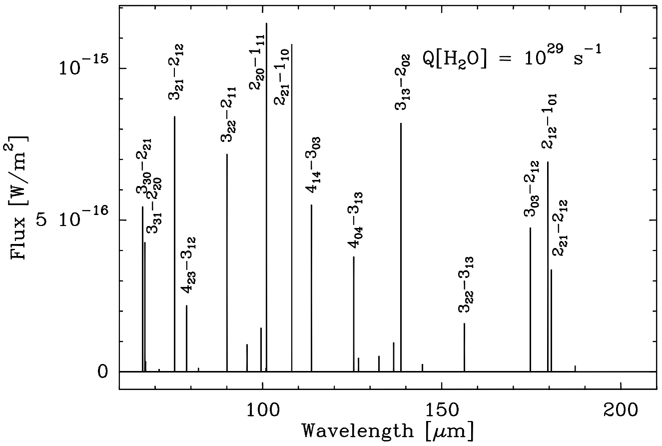

Figure 6. Synthetic spectrum of water for observations with PACS. Model and comet parameters are the same as for Fig. 4. The field-of-view diameter is taken to 9.4 ″.

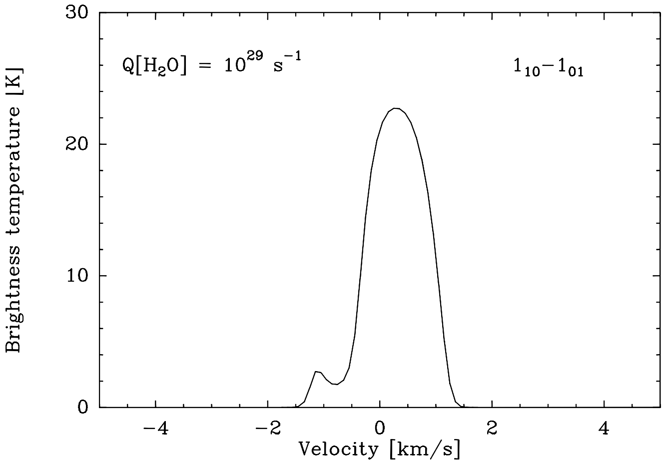

Figure 8. High resolution HIFI synthetic spectrum of the water 1_{10}–1_{01} line at 557 GHz. The model and comet parameters are the same as for Fig. 4. The line is asymmetric and has its centroid redshifted due to self-absorption in the front part of the coma. This illustrates the need of a high spectral resolution for understanding such line shapes.

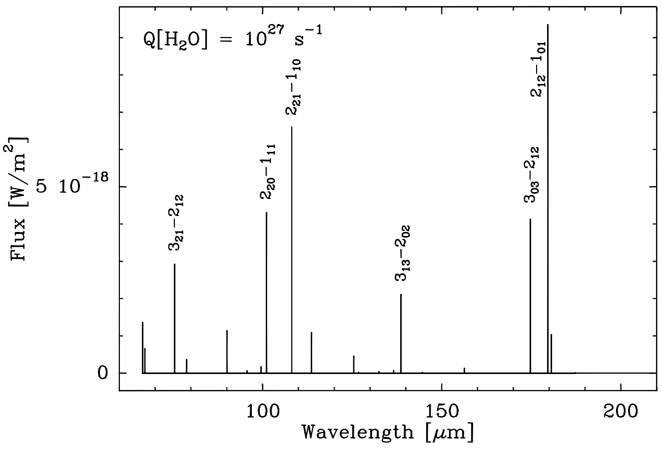

Figure 7. Synthetic spectrum of water for observations with PACS. Model and comet parameters are the same as for Fig. 4, but with Q[H_2O] = 10^{27} molecules s^{-1}. The field-of-view diameter is taken to 9.4 ″.

their brightness temperature is close to the excitation temperature at the nucleus distance where they become to be thick. These excitation temperatures are partly ruled by radiation trapping effects which delay radiative decay of the molecules to the lower rotational states, increasing the size of the region at thermal equilibrium (Bockelée-Morvan 1987). The gas temperature varies in the coma and collisions with neutrals, ions and electrons are not easy to model (Biver et al. 1999a), which adds to the complexity. We estimate the average opacity of the 557 GHz line to $\sim$ 6 for a comet at $r_h = \Delta = 1$ AU with $Q[\mathrm{H_2O}] = 1 \times 10^{29}$ molecules s^{-1} observed with FIRST. That of the strong 2_{12}–1_{01} line at 1669.9 GHz observable with HIFI and PACS (Figs 4 and6) is even larger ($\sim$ 20). The high spectral resolution of HIFI, by providing fully resolved lines, will allow to check opacity effects on the line profiles. Figure 8 shows a synthetic profile of the 557 GHz line under optically thick conditions: we expect an asymmetric line, more intense toward red velocities, in contrast to the symmetric profile expected for an optically thin line emitted by an isotropic water coma.

A good understanding of water excitation and opacity effects is also needed to well assess quantitatively the cooling rate of the coma due to water rotational emission (Bockelée-Morvan & Crovisier 1987). Indeed, the cooling becomes effective only in the outer coma, when the transitions become optically thin. Up to now, most thermodynamical models of cometary atmospheres use an heuristic formula for water rotational cooling. A significant progress in this topic is thus expected from the observation of water with FIRST. This study will benefit of measurements of the gas kinetic temperature, either obtained from the water lines themselves, or from ground-based millimetre observations of molecular thermometers such as methanol.

The observation of the water line shapes with HIFI will allow us to measure the gas expansion velocity, which is another important parameter for modelling the coma gas density and determining the water production rate. Gas velocity measurements from radio line shapes have been performed in a number of comets (e.g. Bockelée-Morvan et al. 1990, Biver et al. 1999b). Values between 0.5 and 2 km s^{-1} have been measured. The gas velocity increases with decreasing r_h and increasing $Q[\mathrm{H_2O}]$, due to the increasing size of the collisional region and more efficient photolytic heating. The high spectral resolution of HIFI, combined with its high sensitivity, will make possible velocity measurements in a large sample of comets. This will permit us to better investigate the dependences of the gas expansion velocity with $Q[H_2O]$ and r_h, and to constrain thermodynamical models. Asymmetries in the line shapes (provided that optical depth effects are well understood or that optically thin lines are observed) will provide informations on the outgassing pattern.

2.2. HDO OBSERVATIONS

The deuterium abundance is a key parameter for studying the origin and the early evolution of the Solar System and of its individual bodies. The D/H ratio in water was first measured in comet 1P/Halley from the mass spectrometers aboard Giotto (Balsiger et al. 1995, Eberhardt et al. 1995). HDO was observed from its 1_{01}–0_{00} line at 465 GHz in comets Hyakutake (Fig. 9) (Bockelée-Morvan et al. 1998) and Hale-Bopp (Meier et al. 1998). A ratio $[D/H] \sim 3 \times 10^{-4}$ was derived in these three comets. This value, which corresponds to an enrichment factor of ∼ 12 with respect to the protosolar D/H value in H_2 (Fig. 10), 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.

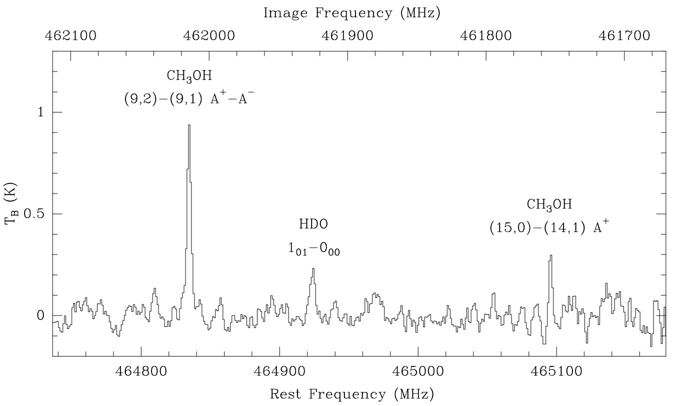

Figure 9. The HDO 1_{01}–0_{00} line at 465 GHz observed in comet C/1996 B2 (Hyakutake) at the Caltech Submillimeter Observatory (Bockelée-Morvan et al. 1998).

However, the deuterium enrichment in cometary water is by a factor of 2.5 lower than in the highly enriched deuterium component of the Semarkona and Bishunpur meteorites of LL3 class. This led Drouart et al. (1999) to suggest that this high D/H value in meteorites might be more representative of the grains in the presolar cloud. The lower value measured in comets would then result from isotopic exchange with H_2 in the solar nebula of the H_2O vapor originating from ices infalling from the presolar cloud. For kinetic reasons, the isotopic exchange could have been substantial only in the inner regions of the solar nebula. The D/H value measured in cometary water suggests that there was some mixing, by turbulent diffusion, between water vapor reprocessed in the inner regions of the solar nebula and the less processed component present in its outer regions (Drouart et al. 1999). Since the rate of isotopic exchange and the turbulent diffusivity both depend on the temperature and density radial profiles of the solar nebula, the D/H enrichments measured in comets and meteorites were used to constrain evolutionary solar nebula models (Drouart et al. 1999, Mousis et al. 2000, Hersant et al. 2001). Informations on the formation of cometary ices were also obtained. From the D/H ratios in H_2O and HCN measured in comet Hale-Bopp, Mousis et al. (2000) and Hersant et al. (2001) show that the microscopic grains which subsequently formed the cometesimals were produced in the Uranus-Neptune region and no later than a few 10^5 years after the formation of the Sun.

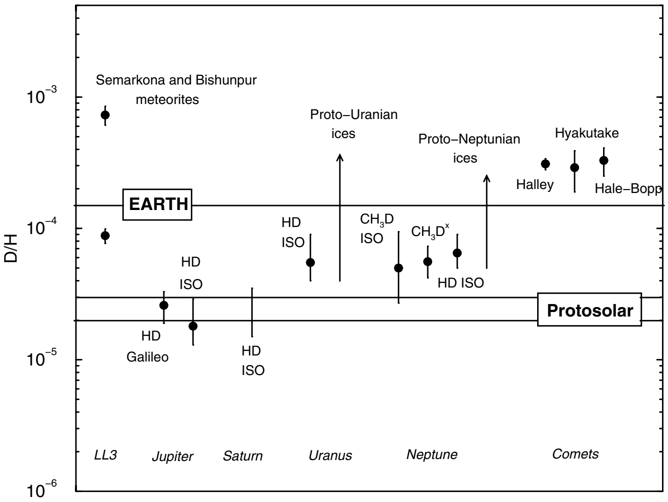

Figure 10. D/H ratios in the Solar System. From Hersant et al. (2001).

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, 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. 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.

Present ground-based instrumentation limits D/H investigations to bright comets. FIRST provides the opportunity to detect HDO in moderately active comets by observing its 1_{10}–1_{01}, 2_{11}–2_{02} and 1_{11}–0_{00} lines at 509, 600 and 894 GHz, respectively. The 509 GHz line should be detected with HIFI in ∼ 1 hr integration in comets with water production rates of 5×10^{28} molecules s^{-1}. Simultaneous observations of several H_2O lines will allow accurate determinations of the deuterium abundance.

2.3. Other cometary science

We mention here some other programmes to be conducted with FIRST.

2.3.1. Search for other species

Besides water, other cometary species could be studied by FIRST. Light hydrides are especially interesting to observe in the submillimetric range which covers their most promising rotational lines. This includes CH, CH_2, CH^+, OH, OH^+, NH_3 and of course H_2O^+. Most of these species are already known and studied in some detail by observations at other frequencies (e.g., in the visible). Submillimetric observations, by investigating their fundamental rotational lines, would complete our knowledge of the excitation state of these species. They would also, by determining line profiles with high spectral resolution, probe their kinematics. Some of these species have transitions at longer wavelengths (e.g., Λ-doubling lines of OH and CH, inversion lines of NH_3), but their submillimetre rotational lines are expected to be much stronger. A special mention should be made for H_2O^+. This species dominates with CO^+ the comet ion tail. Its visible spectrum is customarily observed, but radio observations would allow us to further investigate the formation and acceleration of this species. No detailed excitation model is still available for H_2O^+, and laboratory determinations of its rotational line frequencies are still pending.

2.3.2. Water ice signatures

Broad emission features at 44 and 65 μm were observed in the ISO/LWS spectrum of comet Hale-Bopp at $r_h = 2.9$ AU, and assigned to the signatures of crystalline water ice present on the grains (Lellouch et al. 1998, Fig. 11). Observations of the 65 μm band in other comets will be possible with PACS. These observations can provide informations on the contribution of icy grains to water production in the coma. They should focuss on distant comets because, at small heliocentric distances, the radial extent of the icy grain halo is expected to be very small.

2.3.3. Dust continuum emission

The thermal emission of cometary dust has been observed in a number of comets. Observations in the millimetric and submillimetric domains proved to be successful in measuring the dust mass loss rate of comets. Indeed, in contrast to visible observations, they are sensitive to large particles which comprise most of the mass. With respect to infrared observations, inferred mass loss rates are less dependent on the assumed dust temperature. Figure 12 shows the spectral energy distribution measured in comet Hale-Bopp with various ground-based telescopes (Altenhoff et al. 1999, Jewitt & Matthews 1999, de Pater et al. 1998). Visible observations of the dust coma suggest large variations in the dust-to-gas mass ratio from comet to comet, but these variations might rather reflect differences in the size distribution. It is thus interesting to pursue the investigation of the dust mass loss rate in the submillimetric domain. The high sensitivity of the FIRST instruments will allow measurements even in weak comets.

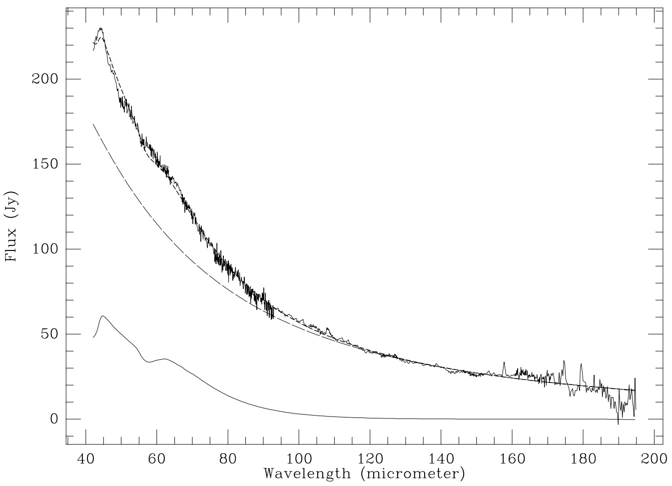

Figure 11. ISO/LWS spectrum of comet Hale-Bopp at 2.9 AU from the Sun showing evidence for spectral signatures of crystalline ice at 44 and 65 μm (Lellouch et al. 1998). Solid line: contribution of the ice. Long-dashed line: contribution of the dust. Short-dashed line: sum of the two components.

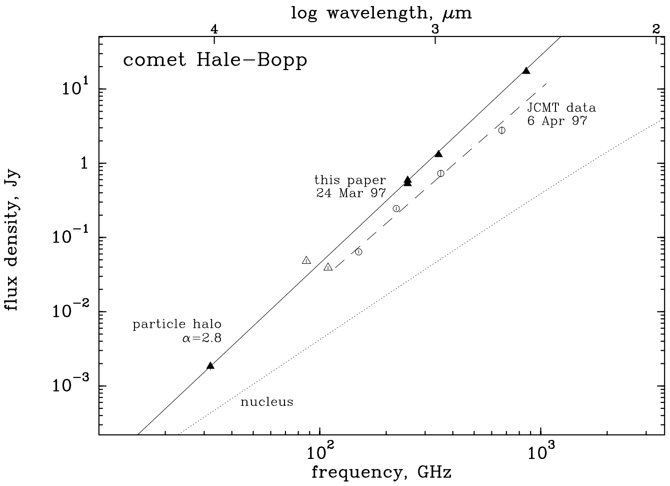

Figure 12. Spectral energy distribution of comet Hale-Bopp in the radio range showing the thermal emission of large grains. From Altenhoff et al. (1999).

2.4. A key programme for HIFI

A key programme, focussed on observations of H_2O and HDO in comets, has been proposed for HIFI. It has four distinct scientific goals:

1. Observations of the 557 GHz line of water in a large sample of comets for study of water production and kinematics.
2. Monitoring of the 557 GHz water line in selected comets for the study of water production evolution as a function of r_h.
3. Observations of several water lines in selected comets for constraining water excitation and physical conditions.
4. Observation of HDO for measuring D/H in water.

Known short-period comets will be selected according to their visibility with FIRST. The brightest comets are unexpected new comets. Their observation requires a flexible target-of-opportunity scheduling procedure. A crude estimation of the number of targets to be observed in one year of operation for each of the above scientific goals is:

1. $Q[H_2O] > 3 \times 10^{26}$ molecules s^{-1}: 10 comets;
2. $Q[H_2O] > 5 \times 10^{27}$ molecules s^{-1}: 4 comets;
3. $Q[H_2O] > 5 \times 10^{27}$ molecules s^{-1}: 4 comets;
4. $Q[H_2O] > 2 \times 10^{28}$ molecules s^{-1}: 2 comets.

A preliminary estimate of observing time for this programme is about 100 hours per year.

For extending the scientific return, this programme will have to be coordinated with observations with the other FIRST instruments: spectroscopic observations of other water lines with PACS and SPIRE, photometry with PACS and SPIRE for determination of the dust production rate and measurement of the dust/gas mass ratio in a large sample of comets.

3. Asteroids with FIRST

3.1. Search for water outgassing

There is now definite evidence that some asteroids are dormant cometary nuclei. Well known exemples are (3200) Phaeton, whose orbit presents similarity with that of the Geminid meteor shower, and (4015) Wilson-Harrington, identified to comet 107P/Wilson-Harrington. From orbital and dynamical considerations, it is also believed that a significant fraction of the population of Earth-crossing objects have been supplied by short-period comets. The detection of low levels of water outgassing in these objects of asteroidal appearance would provide important clues on the relationships between the comet and asteroid populations. High sensitivity observations of the 557 GHz water line should be performed with HIFI on a selected number of targets.

3.2. Surface thermal properties

The spectrum from asteroids in the thermal range carries important informations regarding the mineralogic composition and physical state of their surface and its thermophysical properties. An overview of the physical processes underlying the thermal emission of asteroids can be found in Lagerros (1996) and following papers, Müller & Lagerros (1998) and Redman et al. (1998). To zeroth order, observations of asteroids in the infrared and radio domains, combined with their optical magnitude, provide a mean to measure their size and albedo. At next order, the comparison of observations with thermophysical models which include heat conduction into the subsurface and infrared beaming allows one to constrain the thermal conductivity and surface roughness (Müller & Lagerros 1998).

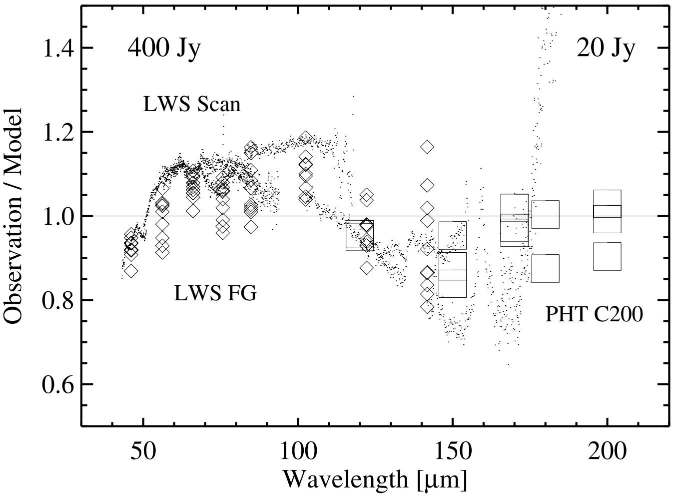

Figure 13. Observations of (1) Ceres with ISO/LWS and PHOT. Comparison between observations and a thermophysical model. From Müller et al. (1999).

While infrared radiation is emitted from the topmost layers of the asteroid surface, which undergo significant diurnal temperature variations, the radiation at longer wavelengths is emitted from deeper layers. If the depth sampled at these wavelengths exceeds or become comparable to the diurnal skin depth, the probed (diurnal average) temperature is colder than the dayside surface sounded in infrared observations at small phase angles. This effect, which leads to an apparent decrease of the spectral emissivity at long wavelengths, was observed on a few asteroids, and provides constraints on the opacity and density of the surface warm layer (Redman et al. 1998). The spectral emissivity in the infrared can also be affected by the presence of mineral bands. Large metal fractions in the surface minerals which make the asteroid surface to become reflective rather than emissive at long wavelengths can also profoundly affect the emissivity, and this was observed in a few M-type (metallic) asteroids as a steep decrease of the emissivity between 100 μm and 1 mm (Redman et al. 1998). Scattering by particles in the asteroid's regolith also reduces the efficiency of thermal emission in the far-infrared. This process has been proposed to explain the ~ 20 % decrease of the hemispherical emissivity of (1) Ceres from 20 to 200 μm deduced from ISO observations (Müller et al. 1999). Figure 13 shows the comparison between the spectrum of (1) Ceres obtained in the far-infrared and a comprehensive thermophysical model that specifies a wavelength dependence of the emissivity from 1.0 at 20μm to 0.83 at 200 μm (Müller et al. 1999).

The investigation of the thermal properties of asteroids requires high sensitivity and high flux accuracy. Up to now, this study has been performed on a limited number of asteroids, mainly the largest. The photometry capabilities of PACS and SPIRE will give the possibility to considerably enlarge the sample and promise important developments in this field.

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