# OBSERVATIONS OF PLANETARY AND SATELLITE ATMOSPHERES AND SURFACES

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Abstract

The full opening of the submillimeter range with the operation of *Herschel* is expected to prove very useful for the study of planetary atmospheres and surfaces. Areas of anticipated progress include: (i) the origin and evolution of the Giant Planets, from improved determinations of the abundance of deuterium and helium (ii) the origin of the external source of oxygen in the Giant Planets and Titan (iii) several compositional and physical aspects of planetary atmospheres, especially the issue of vertical transport in Uranus and Neptune and the martian photochemistry and (iv) the thermophysical and compositional properties of planetary surfaces, including the size distribution of transneptunian objects. The high sensitivity of all instruments and the diversity of their spectral resolutions is well suited to the diversity of size and atmospheric pressure within the bodies of the Solar System.

Key words: Submillimeter observations – Planets and satellites: atmospheres and surfaces

## 1. Introduction

Since the first ESA meeting dedicated to a spaceborne submillimeter mission, held in Segovia in 1986 (ESA SP-260), Solar System science has made considerable progress, due to the development of ground–based and Earth-orbit instrumentation, and to the successful operation of several spacecraft probes. Therererefore, the objectives of a submillimeter cornerstone in the field of planetary science (Lellouch and Encrenaz 1986, Encrenaz 1997) have naturally evolved. Some of the objectives identified fifteen years ago are still valid, but in a new perspective, while others have become essentially obsolete (or will become so by 2007). In addition, new objectives have appeared, such as the study of objects that were not known 15 years ago, namely the transneptunian population (over 360 objects discovered by January 1, 2001). Recently, the operation of ISO has provided planetologists a wealth of new results, many of them being unexpected (Lellouch 1999). Attempting to guess whether the harvest with *Herschel*[1] will be as rich is a dangerous challenge, but based on recent developments in the field, one can reasonably identify four major areas where *Herschel* will bring an important contribution (i) the history of the Giant Planets (ii) the problem of the external source of oxygen in the outer planets (iii) several compositional and physical aspects of planetary atmospheres and (iv) the thermophysical and compositional properties of planetary surfaces.

[1] The new name for the FIRST mission is adopted here

## 2. Origin and evolution of the Giant Planets

### 2.1. Deuterium

Our understanding of the origin and evolution of the Giant Planets and of the Solar System as a whole will benefit from new and improved measurements of deuterium and helium abundance in the Giant Planets with *Herschel*. The abundance of deuterium in Giant Planets is one well-known key to understanding their history. The traditional view is that the deuterium abundance in Jupiter and Saturn represents that of the gaseous part of the protosolar nebula from which the Solar System was formed. In contrast, Uranus and Neptune may have been enriched in deuterium, during their formation, by the mixing of their atmospheres with comparatively larger cores containing D-rich icy grains. Therefore, comparing the D/H ratio in Giant Planets and using interior models may allow one to estimate the D/H ratio in these protoplanetary grains. In addition, the comparison of the D/H ratio in Jupiter and Saturn with the current local interstellar medium value constrains the evolution of deuterium over the last 4.55 billion years, and therefore extrapolating backwards in time, may provide information on the primordial D/H ratio.

Important observational progress has been obtained recently. The *Galileo* probe has measured *in situ* the D/H ratio in Jupiter's atmophere. ISO has obtained the first detection of the IR lines of HD, in particular SWS observed the 37.7 $\mu$m line on all four Giant Planets (Fig. 1), providing a coherent and direct determination of the bulk atmospheric D/H ratio in the four Giant planets (Feuchtgruber et al. 1999a, Lellouch et al. 2001). LWS also obtained some detections at Jupiter and Saturn (Griffin et al. 1996), but the analysis is still in progress. Fig. 2 compares the D/H ratio in the four Giant Planets, as determined by ISO/SWS, with that in other objects. Uranus and Neptune are clearly richer in deuterium than Jupiter and Saturn, but poorer than comets, which matches well

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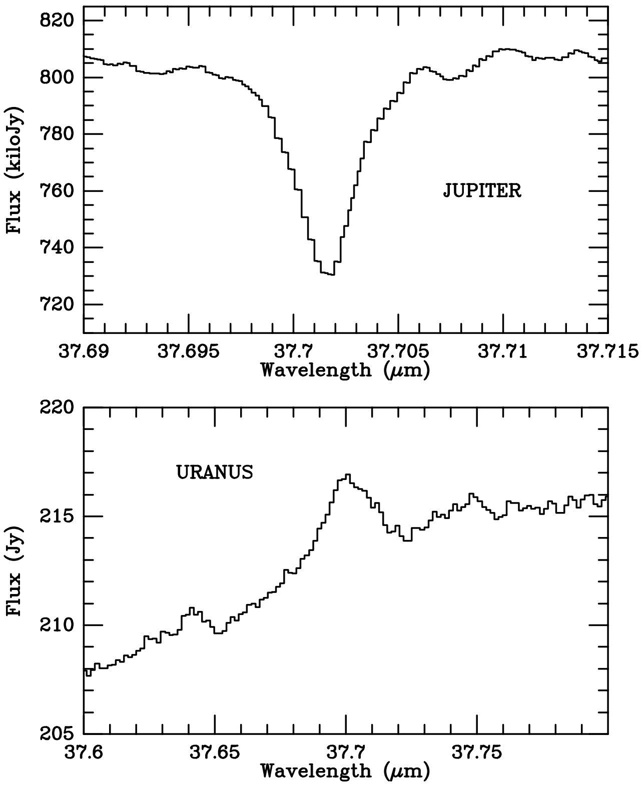


*Figure 1. The HD R(2) line at 37.7 μm detected by ISO/SWS on the Giant Planets*

the above idea of a mixing between two deuterium reservoirs. The Jupiter and Saturn abundances are consistent with an estimate of the protosolar D/H value deduced from solar wind measurements of $^3$He. They are also slightly higher than the abundances in the current Local Interstellar Medium, which points to a minor comsumption of deuterium in our Galaxy and, extrapolating backwards, is in agreement with relatively low D/H values in distant quasars.

Although the picture seems by now reasonably well settled, there is room for refinement. More cometary observations are needed, as current measurements only refer to long-period periods (Bockelée-Morvan, this volume). The Uranus and Neptune values are still fairly inaccurate (~60 % uncertainty). This, combined with uncertainties in the interior models, forbids to say firmly if really the protouranian and protoneptunian ices have the same composition as cometary ices. For Jupiter and Saturn, the problem must now be investigated at next order. Indeed, the deuterium abundance at Jupiter and Saturn deuterium must also be affected to some degree by the mixing of gas with ices. Recent interior and evolution models (Guillot, 1999) show that this contamination could be of about 10 % for Jupiter and 30 % for Saturn. Current data, which within error bars, show indistiguishable D/H ratio in the two planets, are clearly unsufficient to test these models. It is therefore necessary to measure the D/H ratio in all Giant Planets to an accuracy better than 10 %. This precision should be achievable from measurements with PACS, whose moderate spectral resolution and very high sensitivity will permit a high signal-to-noise detection of the HD R(0) and R(1) lines at 112 and 56 micron.

## 2.2. Helium

Helium is also an indicator of Giant Planet evolution. As the only source of helium in Giant Planets is the gaseous protosolar nebula itself, with no possible contribution from the icy grains, all four Giant Planets must have a bulk He/H ratio (as inferred from He/$H_2$) roughly equal to the protosolar value. However, there are two reasons why the apparent He/H in Giant Planets' atmospheres could depart from this value (e.g. Gautier and Owen 1989). The first effect, called differentiation, is due to the fact that a large fraction of Jupiter's and Saturn's interiors is probably composed of metallic ionized hydrogen. Helium is not miscible in such a medium and sinks, apparently depleting the observable atmosphere in helium. A possible inverse effect is due to the fact that the mixing of protoplanetary ices like CO with the gaseous part of the nebula is accompanied by a chemical reduction of carbon. This may lead to a significant depletion of molecular hydrogen in the case of Uranus and Neptune (where the carbon abundance is high), therefore to a higher helium–to–hydrogen ratio.

The helium abundance in Jupiter has been measured very accurately by the *Galileo* Probe and is indeed slightly

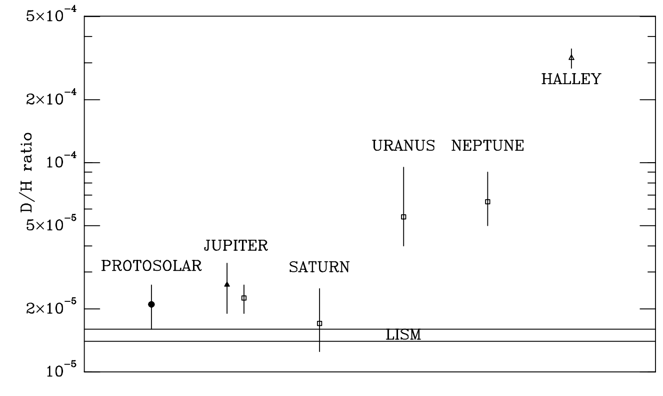


*Figure 2. The D/H ratio in the four Giant Planets (open squares indicate values from ISO/SWS; the triangle represents the* Galileo *measurement at Jupiter) and in comets (as represented by the value in 1 P/Halley; a similar value was measured in Hyakutake and Hale-Bopp), compared to the protosolar value (deduced from solar wind measurements of $^3He$) and to the current LISM value*

depleted with respect to the protosolar (as inferred from solar evolutionary models) value. For the other Giant Planets, for which the He/H values come from Voyager measurements, the situation is much less clear (Fig. 3). There is apparently a moderate depletion at Saturn as well and a possible moderate enhancement at Neptune. Spectroscopically, the way to measure helium in Giant Planets is to study the shape of the 20-200 $\mu$m continuum. The problem is complex because the spectrum also depends on the atmospheric thermal profile and on the ortho-to-para hydrogen ratio, so an accurate determination requires a large spectral interval. At Neptune, an attempt to derive the $He/H_2$ ratio from a combination of ISO/SWS and ISO/LWS data was recently performed by Orton et al. (2000), but not really conclusive because of signal-to-noise limitations. For Saturn, progress is expected from *Cassini*/CIRS observations at 7–1000 $\mu$m. For Uranus and Neptune, for which no spacecraft missions are foreseen, PACS and its high sensitivity will be very useful. It will however probably be necessary, for an unambiguous determination of the $He/H_2$ ratio, to combine the PACS data with shorter–wavelength observations that should be obtained earlier by SIRTF. Note that this also requires a very good data calibration (not exclusively based on Uranus and Neptune...)

## 3. The source of external oxygen in Outer Planets

Giant Planets possess *internal water*, which results from the oxygen incorporated during the planet formation, and *external water*, which originates from the delivery and vaporization of water ice or any other oxygen bearing material coming from the interplanetary medium or from planetary environments.

Observations with ISO/SWS have allowed the first detection of external water in all four Giant Planet stratospheres and Titan (Feuchtgruber et al. 1997, 1999b, Coustenis et al. 1998). CO and $CO_2$ are also present (except on Uranus), indicating that transport and chemical processing of water and/or simultaneous delivery of $CO/CO_2$ also take place. Water column densities are in the range (0.5–20)$\times10^{14}$ mol cm$^{-2}$ and incoming fluxes of order $10^5$–$10^7$ cm$^{-2}$s$^{-1}$. Remarkably, to within a factor of 10, the fluxes are the same on all five planets. More recently, SWAS has obtained the first detection, spectrally resolved, of the 556.935 GHz $H_2O$ line at Jupiter (Fig. 4) and Saturn. This provided in particular some information on the vertical distribution of water in Jupiter's stratosphere, whose abundance appears to increase with altitude (Bergin et al. 2000). There are several potential sources of external oxygen in the outer planets. The most likely one seems to be a continuous flow of interplanetary dust particles, but contributions due to local sources such as rings or planetary satellites are possible. Also, in Jupiter's case, the signature of the Shoemaker-Levy 9 impacts which delivered massive amounts of oxygen is still present, as proved by the existence of hemispheric variations of $CO_2$ (Feuchtgruber et

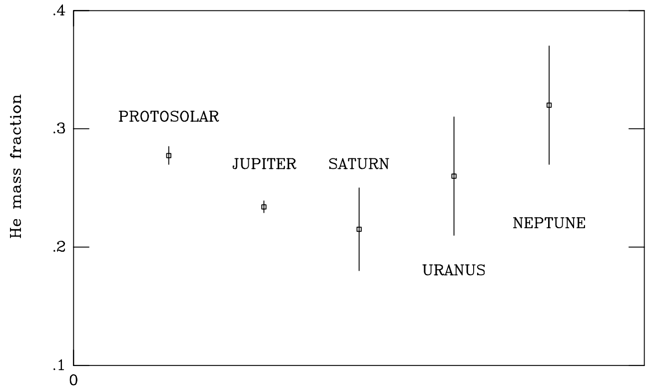


*Figure 3. The helium mass fraction in Giant Planets, compared to the protosolar value*

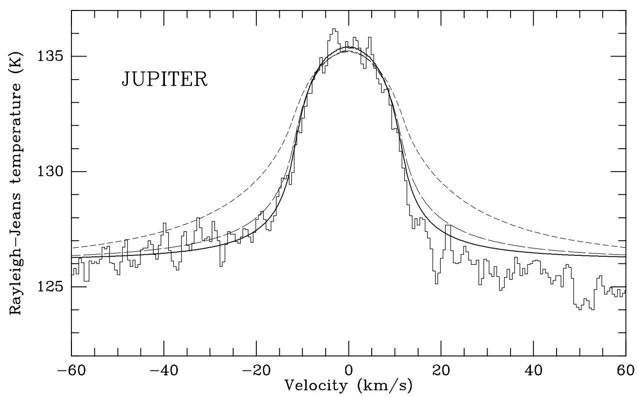


*Figure 4. The 556.935 GHz $H_2O$ line on Jupiter observed by SWAS (Bergin et al. 2000)*

al. 1999b). Knowing the ultimate origin of external oxygen is very important because it may bear implications for the production of dust at large heliocentric distances.

Yet, there remains considerably uncertainties in the input fluxes. First, the amount of water in each planet is typically known to within a factor of 2–3 only. Even more critical, inferring a flux from a column density is complicated and requires one to construct a full chemical model of the atmosphere, specifying sources and sinks of water. A key parameter in these models is the so–called eddy diffusion $K$ coefficient which describes the vertical transport in the stratosphere. $K$ is constrained by the vertical distribution of some trace gases. Such models are being currently developed (see Lara et al. 1996 for Titan, Moses et al. 2000 for Saturn). At the moment, a surprising result is that the influx rates at Saturn and Titan are identical to within a factor of 3, while we would expect Saturn to be much favored over Titan, given its much larger gravitational effect and the selective effect of a ring source (Titan being outside Saturn's rings).

*Herschel* will contribute to this problem in different manners. By observing the $H_2O$ rotational lines with a considerably higher S/N than did ISO and SWAS, it will improve the abundance and hence flux determinations. HIFI will resolve the lines, and for Jupiter, Neptune and Titan, this will give information on the vertical profile of $H_2O$, further helping the modelling in terms of the input fluxes. (At Saturn and Uranus, it is likely that the line profiles will be entirely defined by the planetary rotation). It might be also possible to retrieve vertical information by observing, with all three instruments, lines of different strengths. Monitoring the $H_2O$ lines with time could possible provide information about the permanent vs. episodic nature of the source. In the case of Jupiter, observations at high frequencies by HIFI and PACS will modestly (typically 5 measurements along a diameter) resolve the disk. Latitudinal variations of $H_2O$ would be highly interesting: for example, an increase at the two poles would probably be the signature of material coming from the satellites, which are connected to Jupiter's high latitudes ($> 65°$) through Jupiter's magnetic field. A possible by-product of a $H_2O$ mapping with HIFI would be the measurement of zonal winds in Jupiter's stratosphere, by determining the Doppler shift of the $H_2O$ line on the two equatorial limbs. This however, is a difficult measurement, both in terms of S/N and pointing knowledge. Finally, a dream but probably even more difficult measurement would be to combine these observations with a search for HDO (from *Herschel* or ALMA). Indeed, determining the D/H ratio in the external water would be a precious an elegant constraint on its origin.

## 4. Composition and physics of planetary atmospheres

Detecting new molecules in planetary atmospheres, or determining the spatial/vertical distribution of trace species, generally improves our knowledge of the physico-chemical phenomena at work. In this spirit, Herschell will be able to make some specific and unique contributions in our understanding of the Giant Planets and Mars.

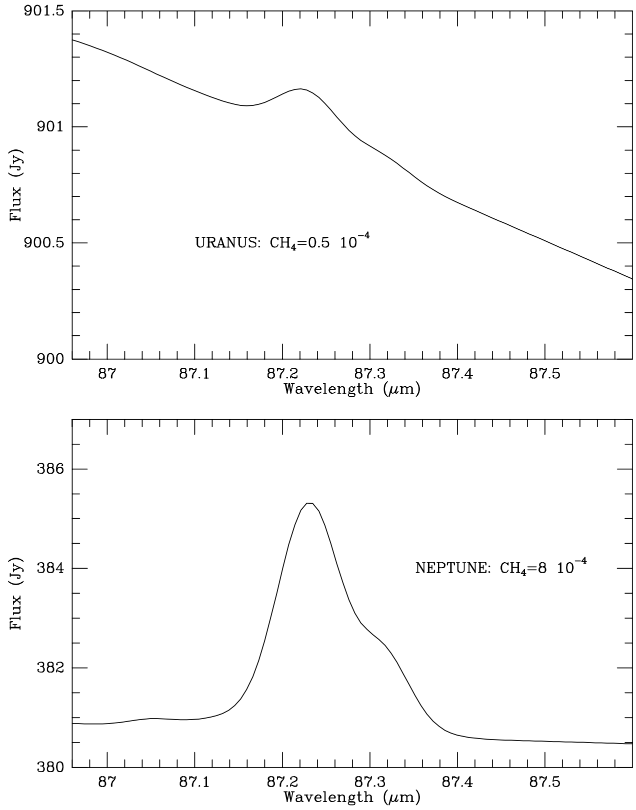


*Figure 5. Models of the 87.23 μm rotational line of methane at Uranus and Neptune. Assumed methane stratospheric mixing ratios are 0.5×$10^{-4}$ at Uranus and 8×$10^{-4}$ at Neptune*

### 4.1. Giant Planets

ISO has obtained many new results on the Giant Planets, with new information (in addition to that described above) about internal water, hydrocarbons, and cloud composition (see Lellouch 1999). Besides the already discussed HD and $H_2O$, species expected to show transitions in the submillimeter spectrum of Jupiter and Saturn include $NH_3$, $PH_3$ and $CH_4$, actually seen by LWS (Davis et al. 1996, 1997; Burgdorf et al., this volume), and, possibly, a number of species such as halides (HCl, HBr, HF, HI), $H_2Se$ and HCP. These species, called disequilibrium species, are, under the conditions of thermodynamical equilibrium, stable only at deep warm levels, but are expected to be transported to observable levels by vigorous upward convection. Detection of any of them would bring new information on the importance of vertical transport. This objective, which was identified already 15 years ago (Bézard et al. 1986), remains valid for *Herschel*; it must be noted however, that in the case of Jupiter, Saturn and Titan, the entire submillimeter spectrum will be explored by Cassini/CIRS prior to *Herschel* (currently, Jupiter; Saturn and Titan in 2004–2007). Although the *Herschel* instruments will have superior sensitivity and resolution capabilities compared to *Cassini*/CIRS (in particular the spectral resolution of both PACS and SPIRE appears very well suited to the study of relatively broad features originating in planetary tropospheres), it is clear that this this territory will not be virgin anymore by 2007.

Uranus and Neptune, in contrast, will not be visited by any spacecraft mission until then, and *Herschel* will contribute to understanding the intriguing difference in internal activity between Uranus and Neptune. There is evidence that Uranus is much more sluggish than Neptune. For example, as of today, there is no measurable internal heat source and no detectable CO in Uranus, unlike in Neptune; cloud activity is also much weaker in Uranus. *Herschel* will provide further insight into this problem by searching for $PH_3$ in Uranus and Neptune with SPIRE and by measuring the $CH_4$ abundance in their lower stratospheres with PACS. Both observations will be diagnostic of the vertical transport. Indeed, phosphine is also a disequilibrium species, and models (Bézard et al. 1986) predict that its rotational lines at 372 and 536 $\mu$m will be observable if the vertical transport is sufficient to replenish the upper troposphere in phosphine. A detection of $PH_3$ would also allow a first measurement of the P/H ratio in these objects, with implications for the composition of the protoplanetary grains. Similarly, the abundance of methane in the stratosphere is probably linked to the efficiency of its dynamical injection from the troposphere, where it is very abundant, through the tropopause cold trap. Based on current estimates of its abundance in Uranus and Neptune, synthetic spectra suggest that methane should be measurable in both planets (Fig. 5).

### 4.2. Mars

The composition of Mars' atmosphere is largely governed by the coupled photochemistry of $CO_2$ and water. Understanding the martian photochemistry in great details is important in a comparative planetology context (for example, on the role of couplings between chemistry and dynamics), but is also a necessary step for approaching the history of Mars' atmosphere with a firm grasp on key phenomena such as atmospheric escape.

HIFI will be well suited to the observations of the martian atmosphere, where lines are narrow. Using predictions from current photochemical models (e.g. Nair et al. 1994, Fig. 6), it is expected that HIFI will be able to detect $H_2O$, CO, $O_2$ and probably $O_3$ on Mars, and to obtain the first detection of a key species, $H_2O_2$ (e.g. at 1047 GHz) (see details in Encrenaz et al., this volume). Water vapor is known to vary dramatically in Mars' atmosphere

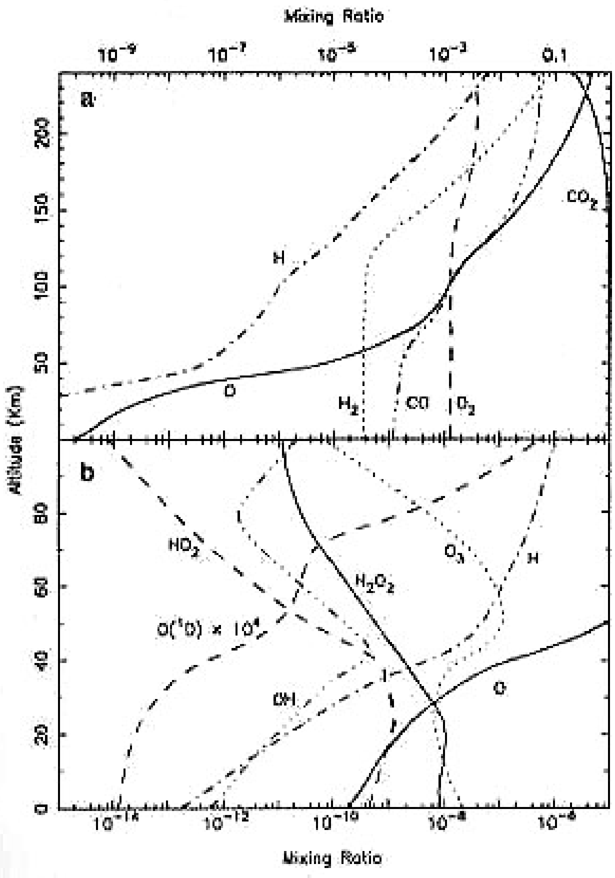


*Figure 6. Phochemical model predictions of the composition of Mars' atmosphere. From Nair et al. 1994*

and at periods of maximum water abundance, a first detection of OH (1835 GHz) could also be possible. In spite of the small size of the telescope compared to ground-based telescopes operating at millimeter wavelengths, the advantage of *Herschel* comes from the several orders–of–magnitude gain in line strength (for some species) when going to high frequencies. The vertical profile of water will be determined, as illustrated already by SWAS (Gurwell et al. 2000). A monitoring of this profile and of the abundances of the various compounds would be quite interesting because they are expected to exhibit correlated or anticorrelated variations (see Encrenaz et al., this volume), but might be in practice somewhat limited by the observability windows of Mars. Finally, using the strong lines of HDO, HIFI should provide a much more accurate measurement of the D/H ratio in Mars' atmosphere than is currently available. We know that this ratio is about 5 times larger than the terrestrial value, probably as an effect of massive photolysis and escape of hydrogen from an early denser atmosphere (Owen et al. 1988), although the quantitative interpretation (e.g. in terms of the initial atmospheric pressure) may not be trivial because of the existence of fractionation effects at each phase changes of water during the martian history.

## 5. Photometry and spectroscopy of planetary surfaces

*Herschel* will be a powerful tool to study planetary surfaces, addressing photometrically their bulk thermal properties and spectroscopically their composition.

### 5.1. Thermal photometry

Thermal photometry will be conducted with PACS and SPIRE on a variety of objects. Depending on pre-existing knowledge, this study can be performed at different levels of investigation.

#### 5.1.1. Size and albedos of transneptunian objects

At first order, by combining a measurement of the thermal flux at a given wavelength with a measurement of its visible magnitude, and using the classical equation relating the equilibrium temperature to the object albedo, one can separately retrieve (i) the object diameter (ii) its albedo and (iii) its mean temperature. Using observations over a large range of thermal wavelength can also help to determine the mean temperature (from blackbody fitting) independently of the object diameter. Such a study will be conducted for small irregular satellites of the Giant Planets, transneptunian objects (TNOs) and Centaurs. Regarding TNOs, a tentative detection of 2 objects (1993 SC and 1996 TL66) with ISOPHOT was reported (Thomas et al. 2000). Very recently (Jewitt and Aussel 2001) announced the detection of the 850 $\mu$m emission of a TNO (2000 WR106) from observations at JCMT. The photometric study of TNOs in the thermal range will constitute an important program for SIRTF, and all the more for *Herchel*. A dark 300-km diameter object at 50 AU from the Sun (T = 40 K) emits about 1.4 mJy at 170 $\mu$m, which typically represents 1.5 times the $1\sigma$, 1 hour detection limit of PACS in photometric mode. Thus, D = 300 km can be considered as a typical detection limit for TNOs with *Herschel*. The estimated corresponding population could be about 10000 (Davis and Farinella 1997). Thus, a large program for *Herschel* could consist of measuring the size and albedo of some 100–200 relatively bright objects with well-defined orbits and to study e.g. possible correlations with orbital characteristics. The size distribution of the "large" objects is particularly important to establish as it is likely to be primordial, i.e. unaffected by collisional disruption over the age of the Solar System.

#### 5.1.2. Lightcurves

At next order, when an object is well detected, its thermal lightcurve (i.e. the possible variation of its thermal flux with rotation) must be searched for. Variations of thermal flux may result from shape effects (in which case they are correlated with variations of visible magnitude; an example is Vesta (Redman et al. 1992)) or from albedo variations at the surface of the object (in which case they are anticorrelated with the visible lightcurve; an example is Pluto). In the second case, the detailed investigation of the lightcurve gives refined surface/subsurface properties, such as the thermal inertia and the spatial variations of albedo and emissivity. The thermal lightcurve of the Pluto-Charon system has been detected at 60 and 100 $\mu$m by ISO (Lellouch et al. 2000a) but so far not at millimeter wavelengths (Lellouch et al. 2000b) (Fig. 7). Pluto's thermal inertia was determined for the first time, and some constraints on the albedo and emissivity of the dark regions of Pluto's surface were inferred. Detecting more lightcurves at more wavelengths in the range 100-700 $\mu$m from repeated PACS and SPIRE measurements will provide, in a improved way, the spatial distribution of the dark units and their emissivity as a function of wavelength, providing further insight into their nature, which so far remains elusive.

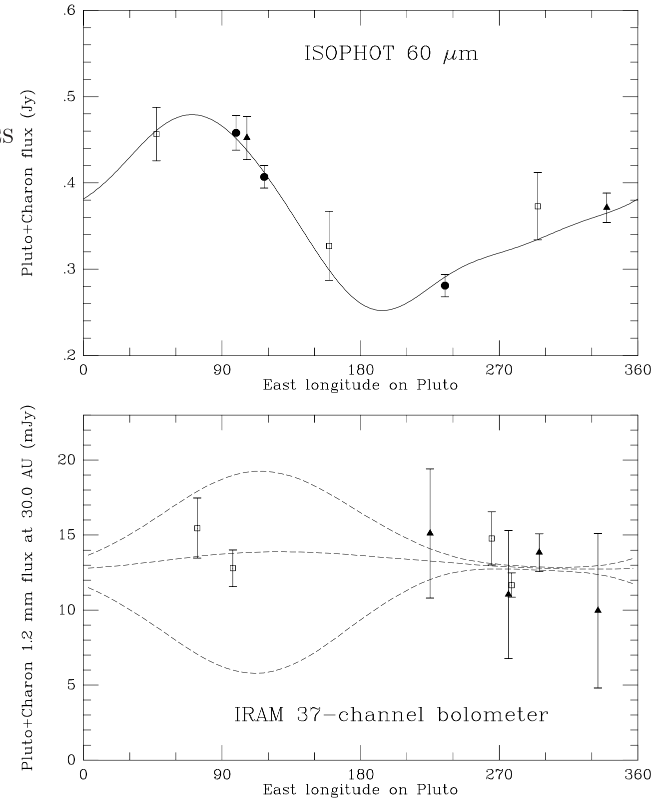


*Figure 7. Lightcurves for the Pluto-Charon system. Top: 60 $\mu$m lightcurve observed by ISO (from Lellouch et al. 2000a). Bottom: Unsuccesful search for the 1.3 mm lightcurve with the IRAM 30-m telescope. The three curves are models illustrating the influence on Pluto's dark terrain emissivity on the expected lightcurve Pluto dark terrains on the (from Lellouch et al. 2000b)*

### 5.2. Thermal spectroscopy

Mid–resolution spectroscopy of planetary surfaces in the thermal range provides information of surface composition, which can be in principle diagnosed from emissivity maxima or minima in the observed spectra. This has been exploited mostly in the 10 $\mu$m range, where, notably, the signature of silicates shows up on Mars (e.g. Christensen et al. 1998) and probably on asteroids (Dotto et al. 2000). In general, however, the quantitative interpretation of the spectra is made difficult by the pauciness of laboratory data (in particular, optical constants of candidate material are rarely available), and the complexity of radiative transfer effects in a solid surface at thermal wavelengths. This makes results often controversial. A recent example is provided by the tentative report of carbonates on Mars' surface from ISO/SWS observations (Lellouch et al. 2000c), in apparent contradiction with ISO/LWS (see Encrenaz et al., this volume), and the *Mars Global Surveyor*/TES dataset which essentially indicates the only presence of basalts/andesite and hematite (Bandfield et al. 2000).

The situation at submillimeter wavelengths is even more uncertain with the current quasi-absence of laboratory data of ices and minerals of planetological interest. Thus, the study of planet, large satellite, and asteroid surface continua with *Herschel* (PACS and SPIRE in spectroscopic mode) will be largely exploratory, given also the absence of instrumentation in this wavelength range on interplanetary spacecrafts (except on Cassini). Note however that $N_2$ and $CH_4$ ices are known to exhibit absorption bands in the submillimeter range (Fig. 8). Repeated measurements of Pluto's spectrum by PACS and SPIRE will therefore provide information on the distribution of these ices by repeated measurements. On Mars, the exploration of the submillimeter continuum may contribute to solving the carbonate issue. For all these continuum observations, it will be desirable to combine SPIRE and PACS measurements as much as possible.

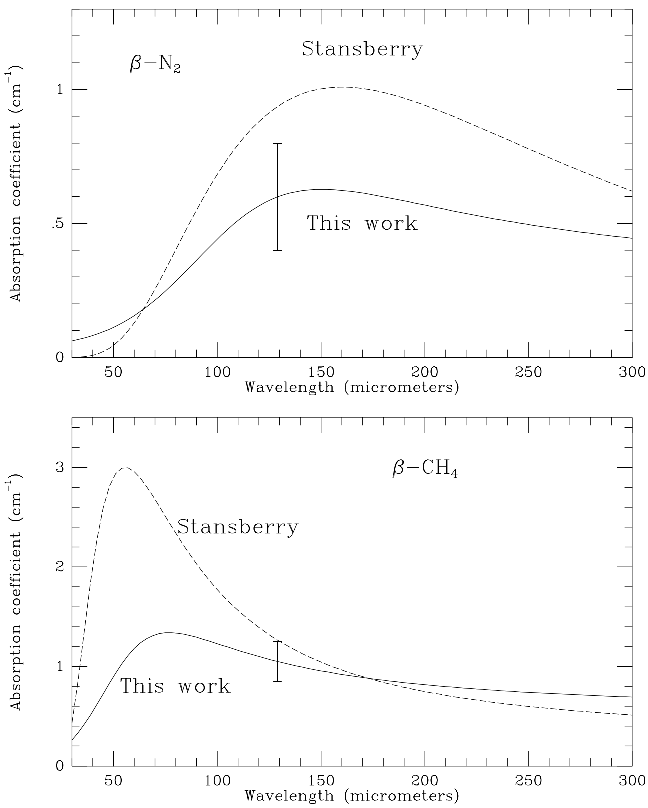


*Figure 8. The absorption coefficient for β-$N_2$ and β-$CH_4$ ices, showing the presence of broad bands near 150 and 60 μm respectively. Figure taken from Lellouch et al. 2000a*

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