The planets and Titan observed by ISO [*]

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Abstract. Infrared spectroscopic observations of planets and Saturn's satellite Titan with the Infrared Space Observatory led to many significant discoveries that improved our understanding on the formation, physics and chemistry of these objects. The prime results achieved by ISO are: (1) a new and consistent determination of the D/H ratios on the giant planets and Titan; (2) the first precise measurement of the $^{15}N/^{14}N$ ratio in Jupiter, a valuable indicator of the protosolar nitrogen isotopic ratio; (3) the first detection of an external oxygen flux for all giant planets and Titan; (4) the first detection of some stratospheric hydrocarbons (CH_3, C_2H_4, CH_3C_2H, C_4H_2, C_6H_6); (5) the first detection of tropospheric water in Saturn; (6) the tentative detection of carbonate minerals on Mars; (7) the first thermal lightcurve of Pluto.

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1. Introduction

At the time of ISO (Kessler *et al.*, 1996; Kessler *et al.*, 2003) launch, the infrared spectrum of planets and Titan was not a virgin territory. Interplanetary spacecraft had carried infrared spectrometers in the vicinity of Mars, Jupiter, Saturn and Titan, Uranus, and Neptune. These instruments demonstrated the predominance of CO_2 in the martian atmosphere, N_2 on Titan, and H_2 and He on the giant planets, and gave insights on the planetary composition in minor species. Dedicated planetary missions were also specifically designed to provide spatial and temporal resolution on the atmospheric structure, in order to constrain the planets' dynamics and meteorology.

However, instruments aboard planetary spacecraft generally lacked spectral resolution and sensitivity. In this respect, ISO instruments gave planetary scientists a significant improvement that allowed them to obtain important results on the formation, chemistry, and dynamics of planetary objects. Hereafter we detail the major ISO achievements with emphasis on the measurement of the planetary isotopic composition and its significance for our understanding of Solar System formation,

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on the oxygen exogenic flux in the outer Solar System, and on the hydrocarbon photochemistry. Earlier reviews of ISO results can be found in Lellouch (1999), Bézard (2000) and Encrenaz (2003).

2. Isotopic composition

2.1. DEUTERIUM IN THE GIANT PLANETS

The D/H ratio is one of the most useful diagnostic of the formation and evolution of the giant planets. They formed in the protosolar nebula composed of gas, mainly H_2 and He, and icy grains, enriched in deuterium. Their current D abundances thus reflect the relative fraction of presolar gas and grains that participated in their formation. In Jupiter and Saturn, the majority of the mass came from the gaseous component of the presolar nebula. Their D/H ratios are therefore regarded as an estimate for the presolar D/H value. In contrast, the masses of Uranus and Neptune are dominated by ices, which have enriched their atmospheres in deuterium. For this reason, measuring their D/H ratios could yield the deuterium abundance in the proto-uranus and proto-neptunian ices, and help to constrain the condensation processes in the presolar nebula.

Prior to the ISO mission, the deuterium abundance had been measured in Jupiter and Saturn from near-infrared lines of HD (Smith *et al.*, 1989). However, the interpretation of these lines was complicated by some blending with absorptions from CH_4 and uncertainties on the cloud physical properties. Therefore, the most accurate value for Jupiter was obtained *in-situ* by the mass spectrometer aboard the Galileo probe (Niemann *et al.*, 1998). For the three other giant planets, we had to rely on measurements of the CH_3D/CH_4 ratio, and on the knowledge of the fractionation coefficient f induced by the isotopic exchange reaction $HD + CH_4 \rightleftharpoons H_2 + CH_3D$. The latter coefficient is quite uncertain as the reaction equilibrium constant and kinetics, and the planetary convection timescales are not well known.

As predicted by Bézard *et al.* (1986), ISO allowed the first detection of HD rotational lines (Encrenaz *et al.*, 1996; Griffin *et al.*, 1996; Feuchtgruber *et al.*, 1999a; Lellouch *et al.*, 2001). These lines enabled a simple and consistent determination of the deuterium abundance on the four giant planets. The LWS instrument (Clegg *et al.*, 1996; Gry *et al.*, 2003) detected the R(0) line on all giant planets. The SWS instrument (de Graauw *et al.*, 1996; Leech *et al.*, 2003) detected the R(2) line (37.7 μm) on each planet (Fig 1), while the R(3) line was only detected on Saturn. For Jupiter and Saturn, Lellouch *et al.* (2001) inferred D/H ratios in H_2

of $(D/H)_{H_2} = (2.4 \pm 0.4) \times 10^{-5}$ and $(D/H)_{H_2} = 1.85^{+0.85}_{-0.60} \times 10^{-5}$ respecively. Using CH_3D and CH_4 bands in the 7–9 μm range, Lellouch *et al.* also measured the D/H in methane, $(D/H)_{CH_4} = (2.2 \pm 0.7) \times 10^{-5}$ and $(D/H)_{CH_4} = 2.0^{+1.4}_{-0.7} \times 10^{-5}$, respectively for Jupiter and Saturn. Combining these two measurements yielded global D/H ratios of $(2.25 \pm 0.35) \times 10^{-5}$ and $1.70^{+0.75}_{-0.45} \times 10^{-5}$, respectively. Correcting for a small atmospheric enrichment in deuterium from ices that constituted the proto-cores of these planets, Lellouch *et al.* (2001) obtained a protosolar ratio of $(D/H)_{ps} = (2.1 \pm 0.4) \times 10^{-5}$

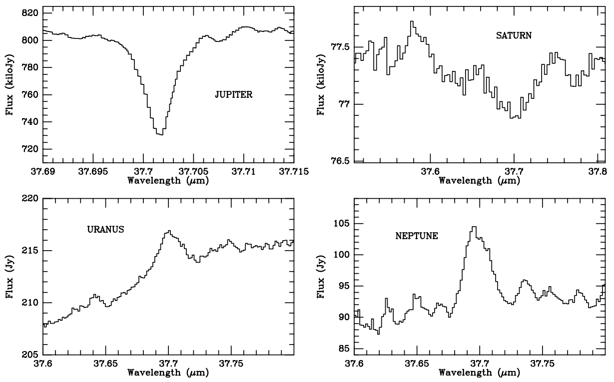

Figure 1. The HD R(2) rotational line observed on the four giant planets

Other estimates of the $(D/H)_{ps}$ ratio had been obtained analysing the evolution of the $^3He/^4He$ ratio from its protosolar value to its current solar value (Geiss and Gloeckler, 1998). The current solar ratio was measured in the solar wind, while the protosolar $^3He/^4He$ ratio was assumed equal to the current Jupiter ratio measured *in situ* by Galileo (Niemann *et al.*, 1998), or equal to the ratio measured in meteorites (Geiss and Gloeckler, 1998). These values led to protosolar deuterium composition, $(D/H)_{ps} = (1.94 \pm 0.5) \times 10^{-5}$ and $(D/H)_{ps} = (2.1 \pm 0.5) \times 10^{-5}$ respectively, in excellent agreement with the ISO measurement. This confirms that Jupiter is a reliable indicator of the protosolar D/H. The protosolar value also indicates a weak decrease of the D/H ratio in the Local Interstellar Medium (LISM) since the formation of the Solar System: $(D/H)_{LISM} = (1.5 \pm 0.1) \times 10^{-5}$ (Linsky, 1998).

For Uranus and Neptune, the retrieved isotopic ratios were larger than those measured in Jupiter and Saturn: $(D/H)_{H_2} = 5.5^{+3.5}_{-1.5} \times 10^{-5}$ and $(D/H)_{H_2} = 6.5^{+2.5}_{-1.5} \times 10^{-5}$, respectively (Feuchtgruber *et al.*, 1999a). This confirms that at least a fraction of the ices that constituted the proto-cores of these planets was mixed in their atmospheres. Using the interior models of Podolak *et al.* (1995), Feuchtgruber *et al.* were able to evaluate the deuterium composition of the proto-uranian and proto-neptunian ices: $(\mathrm{D/H})_{\mathrm{ices}} = 9.4^{+7.6}_{-4.2} \times 10^{-5}$ and $(\mathrm{D/H})_{\mathrm{ices}} = 10.8^{+8.5}_{-4.7} \times 10^{-5}$, respectively. These values differ by about a factor of three from the D/H ratios measured in cometary ices, $\sim 30 \times 10^{-5}$ (see Altwegg and Bockelée-Morvan (2003) for a review).

Drouart *et al.* (1999) and Hersant *et al.* (2001) used this D/H variability within Solar System objects as a chronometer of their formation. They argued that the various D/H ratios resulted from the different levels of isotopic exchange between water enriched in deuterium by interstellar chemistry and the hydrogen gas. The sooner ices condensed in the protosolar nebula, the higher were their D/H ratios. Using turbulent models of the nebula Drouart *et al.* (1999) and Hersant *et al.* (2001) calculated that comets formed in $\sim 10^5$ years, while Uranus and Neptune cores took $\sim 10^6$ years to agglomerate.

2.2. DEUTERIUM IN TITAN

In Titan, methane is the prime deuterium carrier. Using PHT-S (Lemke *et al.*, 1996; Laureijs *et al.*, 2003) and SWS data, Coustenis *et al.* (2003) observed both CH_3D and CH_4 between 7 and 9 μm to derive a D/H ratio of $(\mathrm{D/H})_{\mathrm{CH_4}} = 8.7^{+3.2}_{-1.9} \times 10^{-5}$. The ISO result is smaller than the value inferred from Voyager 1/IRIS spectra, $1.5^{+1.4}_{-0.5} \times 10^{-4}$ (Coustenis *et al.*, 1989), but agrees with the ground-based determination of $(7.75 \pm 2.25) \times 10^{-5}$ of Orton *et al.* (1992).

Two different scenarios have been proposed to explain this deuterium enrichment in Titan's atmosphere compared to that in the protosolar gas. Both scenarios account for the replenishment of Titan's atmosphere in methane, which is effectively photolysed in heavier hydrocarbons by the solar ultraviolet flux. In the first scenario, Lunine *et al.* (1999) proposed that methane evaporates from a local, small reservoir, located near the surface. In this case, over 4.5 byr, solar photolysis may have enriched the D/H in atmospheric methane up to a factor of 4. In the second scenario, Mousis *et al.* (2002) argued that the atmosphere could be replenished by cryovolcanism. In this case, Mousis *et al.* advocated that solar photolysis did not induce any fractionation, and that the observed deuterium enrichment is primordial. In this case, the D/H ratio in Titan could also be used as a chronometer for the condensation of ices at Saturn's heliocentric distance in an approach similar to that used by Drouart *et al.* (1999) and Hersant *et al.* (2001).

2.3. $^{15}N/^{14}N$ RATIO IN JUPITER

The value of the $^{15}N/^{14}N$ in the protosolar nebula had long been an unsolved mystery. Measurements in comets (Altwegg and Bockelée-

Morvan, 2003), in the solar wind trapped in the lunar regolith (Kerridge, 1993), *in situ* in the solar wind (Kallenbach *et al.*, 1998), and in meteorites (Pillinger, 1984) gave values ranging between 2.5×10^{-3} and 6.9×10^{-3} that were impossible to explain within the framework of a consistent, global scenario of the nebula. In addition, measurements in Jupiter's atmosphere yielded a ratio comparable to the terrestrial ratio $((^{15}N/^{14}N)_{\oplus} = 3.68 \times 10^{-3})$, but with uncertainties as large as a factor of 2 (Encrenaz *et al.*, 1978; Tokunaga *et al.*, 1980). Using ISO-SWS observations at 10 μm, Fouchet *et al.* (2000a) refined the measurement in Jupiter, yielding a $^{15}N/^{14}N$ ratio of $(1.9^{+0.9}_{-1.0}) \times 10^{-3}$, much smaller than the terrestrial ratio (Fig. 2). A similar result was found by the *in situ* measurements of Galileo (Owen *et al.*, 2001), and latter by the Cassini/CIRS observations (Abbas *et al.*, 2004; Fouchet *et al.*, 2004).

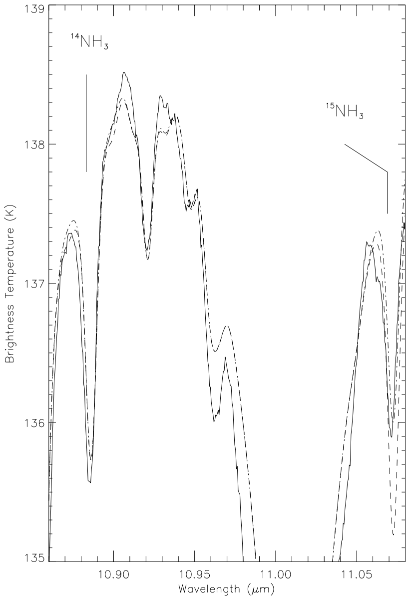

Figure 2. Comparison between Jupiter's ISO spectrum (solid line) and two synhtetic models with terrestrial (dashed line) and half-terrestrial (dotted line) $^{15}N/^{14}N$

Formation models of Jupiter (Owen *et al.*, 2001; Hersant *et al.*, 2004) suggest that the planet has retained most of the nitrogen present in its feeding zone. Therefore, the jovian nitrogen isotopic ratio can be seen as a tracer of the protosolar ratio. This view is supported by a recent reanalysis of lunar samples that gave an upper limit of 2.8×10^{-3} for the trapped solar wind (Hashizume *et al.*, 2000). Such a difference between the protosolar and the terrestrial $^{15}N/^{14}N$ ratios bears important consequences for the origin of the Earth atmosphere.

Terrestrial N_2 must originate from a minor nitrogen reservoir in the protosolar nebula, highly fractionated (a factor of 2) with respect to the largest reservoir. If interstellar chemistry seems the most probable culprit (Charnley and Rodgers, 2002; Aléon and Robert, 2004), the exact fractionation mechanism still remains to be identified, along with the main nitrogen carrier to the Earth.

3. Exogenic oxygen to the giant planets

One of the most striking results obtained from ISO observations is the discovery of H_2O in the stratospheres of the four giant planets (Feuchtgruber *et al.*, 1997; Feuchtgruber *et al.*, 1999b; Lellouch *et al.*, 2002), and Titan (Coustenis *et al.*, 1998), as well as the detection of CO_2 in the stratospheres of Jupiter, Saturn and Neptune (Feuchtgruber *et al.*, 1997; Feuchtgruber *et al.*, 1999b; Lellouch *et al.*, 2002). The presence of water above the tropopause cold trap can only be explained by an external influx. CO_2 also condenses at the tropopause of Saturn and Neptune, while internal sources on Jupiter are believed to be weak, since carbon-oxygen bonded species present in the planetary interior are effectively converted to CH_4 at shallow atmospheric levels. Therefore, the H_2O and CO_2 detections from ISO provided evidences for an exogenic supply of oxygen in the atmospheres of outer Solar System objects. Three different possible sources are possible: i.) infall of interplanetary dust particles (IDPs), ii.) sputtering from icy rings and satellites, and iii.) rare impacts from kilometre-sized bodies.

In Jupiter, CO_2 may orginates from the Shoemaker-Levy 9 (SL9) impacts that occured in 1994. The shock chemistry induced by the impacts produced CO and H_2O that were deposited by the plumes at atmospheric levels above the 100-μbar level. CO and H_2O can subsequently react to form CO_2, while all the chemical products are slowly transported, both horizontally from the location of the impacts (44°S), and vertically. The ISO-SWS $14'' \times 27''$ aperture allowed Lellouch *et al.* (2002) to crudely resolve the CO_2 latitudinal variation. They derived column densities, $(6.3 \pm 1.5) \times 10^{14}$ cm^{-2} in the southern hemisphere, $(3.4 \pm 0.7) \times 10^{14}$ cm^{-2} in the Equatorial Region, and $< 7 \times 10^{13}$ cm^{-2} in the northern hemisphere, reflecting the partial horizontal diffusion of SL9 products. Moreover, the ISO CO_2 abundance agrees with photochemical predictions computed using the CO latitudinal distribution observed in the millimeter range (Moreno *et al.*, 2003).

Since the ISO spectrometers apertures were similar to the Jupiter angular size at wavelengths longer than 20 μm, it was not possible to observe such a latitudinal gradient for H_2O. However, Lellouch *et* *al.* (2002) combined the SWS and LWS observations to demonstrate that Jupiter stratospheric H_2O most likely originates from the SL9 impacts. As shown in Fig. 3, the use of water lines with different intrinsic strengths in the two instrumental ranges led to the conlusion that water is restricted to pressures less than 0.5 ± 0.2 mbar. If H_2O originated from a continuous source like infall of IDPs, it would be present in the whole stratosphere. Rather, the water must originate from an event recent enough for H_2O not to have diffused downwards, i.e. most likely from the Shoemaker-Levy 9 impacts. The disk-averaged column density of $(2 \pm 0.5) \times 10^{15}$ cm^{-2} also agrees with predictions from shock chemistry models. In addition, Lellouch *et al.* put an upper limit of 8×10^4 cm^{-2} s^{-1} to the continuous exogenic flux of H_2O.

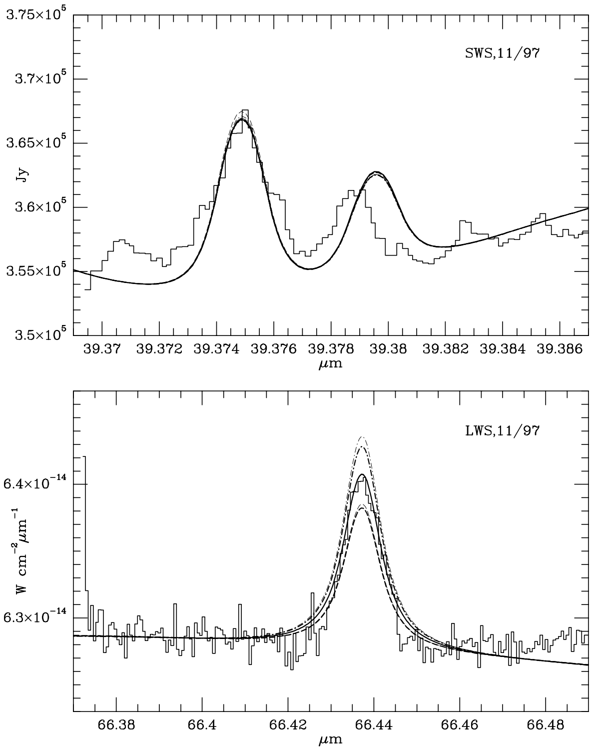

Figure 3. The Jupiter H_2O 39.38-μm and 66.44-μm line for different water vertical models. This shows that Jupiter water is restricted to pressures less than 0.5 ± 0.2 mbar.

In Uranus and Neptune, Feuchtgruber *et al.* (1997) derived water column densities of $(5 - 12) \times 10^{13}$ cm^{-2} and $(3 - 6) \times 10^{14}$ cm^{-2}, respectively. Using transport models for the upper atmospheres, these figures yielded estimates for continuous external fluxes of $(0.6 - 1.6) \times 10^5$ cm^{-2} s^{-1} and $(1.2 - 150) \times 10^5$ cm^{-2} s^{-1}. Such fluxes can be accounted for by IDPs if the flux measured at 1 AU is extrapolated to 30 AU. In Neptune, the CO_2 column density was estimated to 8×10^{14} cm^{-2}. Such an abundance can be accounted for by two different sources. IDPs constitute the first possible origin, since the CO_2/H_2O ratio in Neptune is consistent with the CO_2/H_2O ratio measured in comets. A second possible source is the reaction of H_2O with the neptunian stratospheric CO—whose origin remains uncertain.

On Saturn, Moses *et al.* (2000a) estimated column densities of $(6.3\pm1)\times10^{14}$ cm^{-2} and $(1.4\pm0.4)\times10^{15}$ cm^{-2}, for CO_2 and H_2O respectively. Using a photochemical model, Moses *et al.* matched the observed abundances with an exogenic O flux of $(4\pm2)\times10^{6}$ cm^{-2}s^{-1}. Moreover, Moses *et al.* found that, to reproduce the CO_2/H_2O ratio observed in Saturn's stratosphere, most of the exogenic oxygen must be delivered in the form of CO and/or CO_2, with a CO/H_2O ratio of ~ 3. Cometary ices do not match such a high ratio. On Titan, Coustenis *et al.* (1998) detected water with a column density of $2.6^{+1.9}_{-1.6}\times10^{14}$ cm^{-2}. Such an abundance could be achieved by an exogenic flux of $(0.8-2.8)\times10^{6}$ cm^{-2} s^{-1}.

The comparison between the exogenic oxygen fluxes derived for Jupiter, Saturn and Titan points towards a local source in the Saturn system. Indeed, the upper limit derived for the permanent flux at Jupiter, 8×10^{4} cm^{-2} s^{-1}, is much lower than the flux needed to account for the Saturn and Titan water. The variation of the IDPs flux with heliocentric distance is not well known, but it is expected to be lower at Saturn's distance, where cometary activity is reduced. A SL9-like event can also be rejected for Saturn, as on the long term, most of the O deposited by the impacts is converted to CO, with a CO/H_2O ratio of ~ 100 (Bézard *et al.*, 2002) higher than the ratio of ~ 3 derived for Saturn by Moses *et al.* (2000a). Instead, it is suggested that the rings could be an efficient source of oxygen for Saturn, as well as Hyperion for Titan. Assessing the external sources of oxygen in Saturn and Titan constitutes one of the goals of the Cassini mission.

4. Upper atmosphere

4.1. HYDROCARBON PHOTOCHEMISTRY

On the giant planets and Titan, the ultraviolet solar flux photolyses CH_4 to produce CH, CH_2 and CH_3 radicals in the upper stratosphere (~ 1 μbar). These radicals recombine in heavier hydrocarbons, such as C_2H_6, C_2H_4, C_2H_2, C_3- and C_4-species. Eddy diffusion then transports the newly formed molecules to the whole stratosphere. This hydrocarbon photochemistry still holds mysteries for theoretical modelers. In particular, some free parameters, such as the relative chemical production rates and the intensity of the eddy diffusion, require to be tuned. This can be achieved by measuring the relative abundance between different molecules, and observing how the abundance of an individual molecule evolves with altitude.

ISO-SWS allowed (Drossart *et al.*, 1999) to observe for the first time the CH_4 fluorescence at 3.3 μm on Jupiter and Saturn. The fluorescence probes low pressures, ~ 1 μbar, where the solar energy absorbed by methane is re-emitted before being thermalized by collisions. By chance, this pressure level coincides with the homopause, the level where molecular diffusion becomes as efficient as eddy diffusion, resulting, at higher altitudes, in the diffusive separation of the elements according to their mass. The intensity of CH_4 fluorescence constrains the CH_4 column density, and is therefore a diagnostic of the homopause level and eddy diffusion coefficient. Drossart *et al.* found $K_H = 6 - 8 \times 10^6$ and $K_H = 3 - 5 \times 10^7$ $\mathrm{cm}^2\,\mathrm{s}^{-1}$ for Jupiter and Saturn respectively. These values agree with previous determinations made from Voyager observations. CH_4 fluorescence thus provides a new method to determine eddy mixing coefficients in the outer Solar System.

The chain of reactions that produces hydrocarbons in the outer Solar System starts from radicals. However, these primitive blocks had never been observed prior to the ISO mission. For the first time, the SWS instrument allowed Bézard *et al.* (1998,1999) to detect a radical, CH_3, on Saturn and Neptune, from its ν_2 band at 16.5 μm (Fig. 4). The derived column densities are respectively $(1.5 - 7.5) \times 10^{13}$ and $1.6^{+1.2}_{-0.9} \times 10^{13}$ cm^{-2}. These values conflict with predictions from photochemical models, which overestimate the CH_3 abundance by a factor of ~ 5. Methyl is mostly sensitive to the eddy mixing coefficient at the homopause, and to the poorly known methyl recombination rate. Since eddy mixing coefficients at the homopause have been established consistently through various different means, Bézard *et al.* (1998,1999) stressed the need for new laboratory data on the three-body self-recombination of the CH_3 radical $2CH_3 \xrightarrow{\mathrm{M}} C_2H_6$.

The SWS and PHT-S instruments also led to the first detection of many products of the hydrocarbon photochemistry in the outer Solar System: C_2H_4 on Neptune (Schulz *et al.*, 1999), CH_3C_2H on Jupiter (Fouchet *et al.*, 2000b), CH_3C_2H and C_4H_2 on Saturn (de Graauw *et al.*, 1997), and benzene (C_6H_6) on Jupiter, Saturn and Titan (Bézard *et al.*, 2001; Coustenis *et al.*, 2003). (Benzene had been previously detected on Jupiter, but only over the polar regions (Kim *et al.*, 1985), whereas the ISO detection pertains to the whole planet.) ISO-SWS also

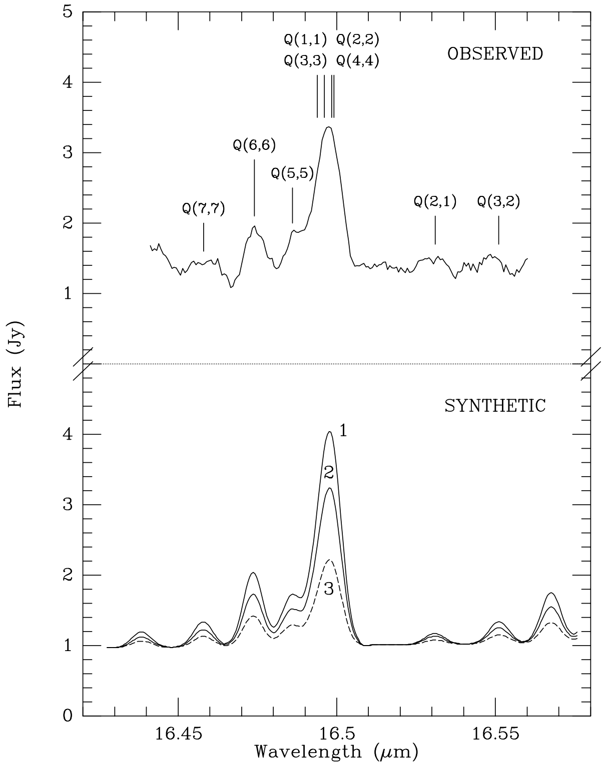

Figure 4. The first detection of CH_3 on Neptune compared with synthetic spectra.

allowed Fouchet *et al.* (2000b), Moses *et al.* (2000b), and Coustenis *et al.* (2003) to determine the vertical distributions of C_2H_6 and C_2H_2 on Jupiter, and C_2H_2 on Saturn and Titan. All these observations made possible the development of refined photochemical models, in particular for Jupiter and Saturn (Moses *et al.*, 2000b; Moses *et al.*, 2001). Models generally fit the abundances and vertical distributions observed by ISO, but with a few exceptions, such as benzene on Jupiter and Saturn, and ethylene on Neptune. In the case of benzene, the observed column densities, $9^{+4.5}_{-7.5} \times 10^{14}$ and $4.7^{+2.1}_{-1.1} \times 10^{13}$ cm^{-2} respectively, are larger than that predicted by photochemistry. Wong *et al.* (2000) proposed that benzene production could be induced by auroral particle precipitation, but their model also fails to predict the observed global abundance on Jupiter. Therefore, new laboratory studies for benzene production in the conditions relevant to the outer Solar System are needed. In the case of ethylene on Neptune, the column densities predicted by photochemical models strongly depend on the CH_4 branching ratios at Lyman α. The most recent laboratory measurements reproduce the observed column density, $(1.1-3)\times 10^{14}$, but the need for more laboratory work is still present.

On Uranus, Encrenaz *et al.* (1998) also improved the current photochemical models. From the non-detection of CH_4 and the observed signature of C_2H_2, Encrenaz *et al.* were able to constrain the eddy mixing coefficient at Uranus tropopause in the range $0.5-1\times 10^4$ cm^2 s^{-1}. This confirms that turbulent mixing is much less vigorous on Uranus than it is on Jupiter, Saturn and Neptune.

4.2. ATMOSPHERIC STRUCTURE

ISO-SWS observed the H_2 S(0) and S(1) quadrupole lines in the four giant planets. These lines probe pressures levels located between 10 and 1 mbar and allowed Fouchet *et al.* (2003) to determine the stratospheric hydrogen para fraction for the first time. In Jupiter, Saturn and Neptune, the measured para fraction present a significant departure from thermodynamic equilibrium. Fouchet *et al.* (2003) interpretated this situation as a result from the lagged conversion between the ortho and para states as H_2 is transported upward by eddy diffusion. In constrast, the uranian stratosphere lies close to thermodynamic equilibrium. Using a one-dimentional diffusion model, Fouchet *et al.* showed that the departure from the thermodynamic para fraction appeared anti-correlated with the density of stratospheric aerosols. This provided quantitative evidence for an equilibration mechanism dominated by conversion on aerosols rather than by conversion in the gas phase.

5. Tropospheric composition

With H_2 and He the two main constituents (over 98% by volume), the atmosphere of the giant planets constitutes a highly reducing environment, where elements are mostly present in reduced forms, i.e. CH_4, NH_3, H_2O, H_2S, PH_3... In the troposphere, the temperature decreases with increasing altitude to a minimum temperature of $\sim$ 110 K at Jupiter and down to $\sim$ 50 K at Uranus and Neptune. These low temperatures induce the condensation of gases: on Jupiter and Saturn, H_2O, H_2S, NH_3 do condense between 10 and 1 bar, while on Uranus and Neptune CH_4 also condenses out. This situation makes difficult the determination of the global composition, hidden below a thick cloud cover.

Using ISO-SWS observations at 5 μm and 10 μm, and ISO-LWS observations in the range 43–197 μm, Fouchet *et al.* (2000a) and Burgdorf *et al.* (2004) derived two sharply different ammonia vertical profiles. At

10 μm and in the ammonia rotational lines, the atmosphere appears slighlty under-saturated, with a NH_3 mixing ratio reaching the solar abundance at about 1 bar. In contrast, at 5 μm, Fouchet *et al.* found a highly dessicated atmosphere, with a NH_3 mixing ratio increasing with pressure to a solar abundance at $\sim$ 4 bar. This later vertical profile is quite similar to that measured by the Galileo Probe (Folkner *et al.*, 1998) on its specific entry point. These two independent measurements confirm the spatial heterogeneity of Jupiter, covered by a majority of wet, cloudy, regions, with some spots, highly dry and almost cloud-free, mostly located in the North Equatorial Belt. If ISO-SWS could not resolved these spots, also called the 5-μm hot spots, they still dominate Jupiter spectrum at this wavelength. Dynamical models experience some difficulties in reproducing this structure. Hueso *et al.* (1999) showed that a traditional convection pattern, with ascent of wet air and descent of dry air, is not able to generate the high level of dessication observed. Showman and Dowling (2000) suggested an alternative model, where the atmosphere and the gas vertical distributions are stretched by planeraty waves.

On Saturn, the ISO-SWS observations at 5 μm led to the first detection of tropospheric water (de Graauw *et al.*, 1997). The H_2O mixing ratio was found strongly undersaturated, similarly to NH_3 on Jupiter. This suggests that Saturn's dynamics generates the same hot spot features as observed on Jupiter. However, Saturn images at 5 μm do not reveal the high radiance constrast observed on Jupiter. The Cassini mission, especially the VIMS instrument, will provide new insights on this issue.

Phosphine was observed through its rotational lines both on Jupiter and Saturn (Davis *et al.*, 1996; Burgdorf *et al.*, 2004) using ISO-LWS. The retrieved vertical profiles (Burgdorf *et al.*, 2004) agree well with those derived from 10 μm observations (Fouchet *et al.*, 2000a; de Graauw *et al.*, 1997) and clearly show a cut-off at pressures below 300 mbar due to the ultraviolet photolysis as predicted by photochemical models.

From both the SWS and LWS spectrometers, Burgdorf *et al.* (2003) used the collision-induced H_2-He continuum to obtain a new determination of the He/H_2 ratio in Neptune. The derived helium abundance, $14.9^{+1.7}_{-2.2}\%$, confirms, with smaller error bars, previous determination obtained from the combined analysis of Voyager-2 IRIS and radio occultation experiment (Conrath *et al.*, 1991). This result is consistent with the protoplanetary estimate of the helium abundance, as expected from the internal models of Neptune which predict no differenciation (Marley, 1999).

6. Cloud structure

6.1. MARS

Dust plays an important role in the geologic and climatic history of Mars. As an efficient absorber, it strongly affects the atmospheric thermal balance, and hence the atmospheric dynamics, while it erodes and coats geologic and mineralogic features that hold insights into the planet's history. Therefore, the continuous monitoring of the martian dust, in particular of its spatial and temporal variations, constitutes an essential objective of the martian exploration. Using the ISO-SWS spectrum of Mars, Fedorova *et al.* (2002) applied a new method to sound the atmospheric dust. They used the optically thick 2.7-μm CO_2 band, where solar photons are absorbed before reaching the ground. In clear atmospheric conditions, the flux in the core of the CO_2 band is thus zero, whereas on dusty conditions a small fraction of the solar flux is reflected by aerosols at high altitudes before being absorbed.

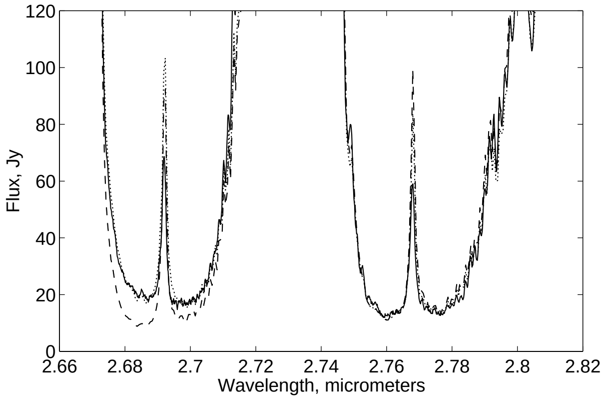

Figure 5. The spectrum of Mars at 2.7 μm observed by ISO (solid line). Dashed line : synthetic spectrum for grey aerosols model. Dotted line : synthetic spectrum for dust with phyllosilicates.

Indeed, ISO-SWS recorded a flux of $\sim$ 20 Jy at 2.68-2.70 μm and at 2.76-2.78 μm (Fig. 5), from which Fedorova *et al.* (2002) derived a dust optical depth of $\tau = 0.33 \pm 0.13$. Their analysis also revealed the existence of a sharp absorption band in the dust spectrum between 2.7 and 2.8 μm, that probably indicates the presence of hydrated minerals, most likely phyllosilicates, in the dust. Therefore, ISO observations led to the development of a new dust sounding method that will be used by current and future missions to Mars.

As a by-product, ISO observations of Mars were used to infer the mean water vapour vertical distribution, using both the SWS (Lellouch *et al.*, 2000a) and LWS (Burgdorf *et al.*, 2000; Sidher *et al.*, 2000).

6.2. Giant planets

As stated above, several chemical species (H_2O, H_2S, NH_3, CH_4) are expected to condense in the tropospheres of the giant planets. This condensation is well established from the measurement of subsaturated abundances above the theoretical condensation levels, and from the obvious thick cloud covers of these planets. However, ice spectral signatures had remained elusive. From the ISO-SWS spectrum at 3 μm, Encrenaz *et al.* (1996) and Brooke *et al.* (1998) first identified NH_3 ice on Jupiter. The best-fit model included an upper cloud located at 0.55 bar, with 10-μm NH_3 ice particles, above a grey thick cloud located between 1 and 2 bars. Since, the detection has been confirmed by Baines *et al.* (2002) from Galileo/NIMS observations, also at 3 μm. The spatial resolution provided by Galileo further demonstrated that pure NH_3 ice is restricted to some specific regions on the planet, associated with strong convective updrafts. The reason why particles are featureless on the rest of the planet remains to be explained.

In the case of Uranus and Neptune, the PHT-S spectra between 2.5 and 4 μm were used to constrain the cloud level and albedo (Encrenaz *et al.*, 2000). For both planets, the albedo was found to be very low $< 1\%$, while the cloud level was found to be at about 3 bars. Encrenaz *et al.* (2000) also found evidence for cirrus cloud above ~ 0.3 bar, presumably due to CH_4 particles. Burgdorf *et al.* (2003) also found that their 46–185 μm spectrum is best reproduced by invoking a CH_4 cloud in the upper troposphere with particle sizes lying between 15–40 μm.

7. Planetary surfaces

7.1. Mars

The Martian atmosphere is transparent at nearly all wavelengths, allowing the sounding of the martian surface from the near infrared to the thermal infrared. ISO-SWS indeed measured the albedo and emissivity of Mars from 2.4 to 45 μm (Lellouch *et al.*, 2000a). The spectrum shows the usual features due to hydrated minerals and silicates, but Lellouch *et al.* also tentatively identified carbonate signatures at 5.3, 6.3, 7.2, 11.1, 26.5, 31, and 43.5 μm. The four signatures between 5-12 μm had been already identified in Mariner 9/IRIS spectra, but were not attributed to carbonates. The ISO detection remains tentative as no single carbonate species can be uniquely identified from this association of features.

Since then, the detection of carbonates has been confirmed from MGS/TES observations by Bandfield *et al.* (2003). However, carbonate signatures were present only in a small fraction of the MGS/TES spectra. This leads Bandfield *et al.* to favour the presence of carbonates in the martian dust rather than on the surface itself. Such an origin was also supported from ISO observations (Lellouch *et al.*, 2000a). This issue is important for our views on the evolution of the Martian atmosphere, since carbonates could represent a significant sink for the initial atmosphere of CO_2. However, since carbonate minerals are currently only identified in the dust, they cannot yet be interpreted as the signature of a primordial thick atmosphere. More work remains to be done for current and future Martian orbiters.

7.2. PLUTO

Using ISO-LWS and PHT-S observations, Lellouch *et al.* (2000b) performed the first unambiguous detection of Pluto's 60- and 100-μm lightcurve, and the first detection of its 150- and 200-μm emission. These observations definitely demonstrated that Pluto's surface is non-isothermal. The infrared lightcurve is globally anti-correlated with the visible lightcurve, but not exactly. This lag was attributed to thermal inertia effects. Lellouch *et al.* (2000b) developed a model with three different geographical units that fits the complete set of visible and infrared observations. The three units are constituted of N_2-ice, CH_4-ice, and tholins. The latter two units show a small thermal inertia, $(1.5-10)\times10^4$ erg cm^{-2} s$^{-1/2}$ K^{-1}, and a high emissivity. This suggests that the shallow layer is made of porous ice. In this respect, Pluto seems similar to the icy satellites in the outer Solar System.

8. Conclusions

ISO observations of planetary objects proved extremely fruitful. ISO sensitivity and spectral resolutions led to the first detection of several chemical species, and to the development of new methods to probe planetary atmospheres. This brought new views on the formation, dynamics and chemistry of planets, and raised new questions.

The work undertaken with ISO observations will be carried on by several infrared instruments aboard Earth orbiting or interplanetary missions: the Spitzer, Hershell and Cassini missions, several martian missions. In particular, Hershell will continue the ISO legacy by measuring more precisely the giant planets composition in deuterium and helium through the observations of the HD rotational lines and the H_2 collision-induced continuum. Hershell, and Cassini specifically on the Saturn System, will bring more informations on exogenic water in the outer Solar System, in order to sort out the various possible sources. Laboratory work will be done to better constrain chemical reactions in the conditions relevant to planetary atmospheres, especially the methyl recombination reaction and the benzene production. In association with the wealth of infrared observations provided by Cassini, we can expect significant progesses in our understanding of the hydrocarbon photochemistry in the giant planets and Titan. On Mars, Mars Express will look for carbonates and monitor the dust opacity using new ways opened by ISO.

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