HIFIPLANETS:

A GT-KP planetary program proposed for Herschel/HIFI

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Note: time estimates need to be refined

Summary: HIFIPLANETS is a program for Herschel/HIFI in the field of planetary atmospheres, which is proposed as a Guaranteed Time Key Program to the HIFI consortium. It is focussed on the general theme of water in planetary atmospheres with two main parts: (1) The origin of water in the upper atmosphere of the Outer planets (2) The martian water cycle and atmospheric chemistry. The total requested time, including some provision for follow-up observations, is 150 hours.

1 Introduction

Water is ubiquitous in the Solar System, being present in gaseous form in all planetary and cometary atmospheres, and in the form of ice on the surface and subsurface of Mars, comets, and most planetary satellites and distant bodies. This proposal focusses on the general subject of water in planetary atmospheres, which is well suited to investigation by HIFI. Water is present in most planetary atmospheres. In terms of science objectives, it is convenient to discuss separately on the one hand the Outer Planets (i.e. the Giant Planets and Titan), and on the other hand Mars.

2 WATER IN THE OUTER PLANETS

2.1 Summary

We propose to study external water in the four Giant Planets and Titan with HIFI and the other Herschel instruments. The goal is to obtain high signal-to-noise observations of a few (3 or 4) strong lines of H_2O with HIFI, and full range spectra and/or targetted line observations with PACS and SPIRE. For each of the five objects, this will provide an accurate measurement of the H_2O abundance and vertical distribution. High-frequency lines will be mapped on Jupiter to search for horizontal variations. Observations should be repeated about once a year during the mission in search of a possible temporal variability.

2.2 Scientific background

Water in Giant Planets can be clearly separated as two distinct components: (i) internal water, present at warm deep levels (deeper than a few bars), and originating from the incorporation of ices during the planet formation and (ii) external water, present in the upper stratospheres, and which may have several sources. While the first component is too deep to be accessible to sub-millimetre spectroscopy, the second one results in narrow H_2O lines well suited to observations by Herschel. It is the subject of this investigation.

The detection of water in the upper atmospheres of the four Giant Planets and Titan was a major discovery of ISO. It gives a definite proof of the existence of external source(s) of oxygen into the outer planet atmospheres. CO and CO_2 are also present (except CO_2 in Uranus), indicating that transport and chemical processing of water, and/or the simultaneous delivery of CO and CO_2 also takes place. The measured water column densities are in the range 1×10^{14}–1×10^{15} H_2O molecules cm^{-2} and the equivalent input fluxes are typically of order 1×10^{5}–1×10^{7} cm^{-2} s^{-1} (Feuchtgruber et al. 1997, Coustenis et al. 1998, Lellouch et al. 2000). Heterodyne observations by SWAS have resulted in the detection of the 557 GHz line at Jupiter and Saturn, and proved that information on the vertical profile of water can be inferred from line spectral resolution (Bergin et al. 2000, Fig. 1). Several sources are thought to contribute to the oxygen supply to the Giant Planets : (1) the permanent interplanetary dust (IDP) particle flux (2) local sources from planetary environments (rings, satellites) (3) the cometary collision, "Shoemaker-Levy 9 type" impacts. Disentangling between the various sources is highly important as bearing consequences on our understanding of a variety of phenomena such as the production of dust at large distances from the Sun, the transport and ionization of solid/gas material in planetary magnetospheres, or the frequency of cometary collision events in the Outer Solar System, all of which are presently poorly known. The post-ISO and SWAS situation is however very complex and surprising in this respect. Indeed, it seems that most of the jovian stratospheric water and CO_2 was delivered by the Shoemaker-Levy 9 impacts in 1994 (Lellouch et al. 2002), and that older similar cometary events are responsible for the presence of CO in Jupiter's stratosphere (Bézard et al. 2002). The flux of IDP particles into Jupiter is surprisingly small, and the comparison with the oxygen flux into Saturn points to an important role of local sources (notably rings) in maintaining water in Saturn's upper atmosphere (Moses et al. 2000, Lellouch et al. 2002). At Uranus and Neptune, which have much less significant satellite and rings environments than Jupiter and Saturn, IDP particles are expected to dominate the supply of oxygen, but it remains to explain why the fluxes are larger than at Jupiter. A possible, but unconfirmed solution would be to invoke the role of Kuiper Belt dust. A very recent related result is the detection of CO in Uranus (Encrenaz et al. 2004a), but the origin of this presumably external CO and its relevance to the H_2O problem remain uncertain. Another puzzle is that the currently estimated fluxes at Saturn and Titan, although still uncertain by factors of several are apparently similar (Coustenis et al. 1998, Moses et al. 2000), while a larger flux is expected at Saturn because of gravitational focussing and ring contribution. Here, a possibility is that Saturn's satellite Hyperion is a significant source of dust and water to Titan (Banaszkiewicz and Krivov 1997). In this extremely confusing situation, improved and repeated measurements of the water abundance, horizontal and vertical distribution, as well as of its possible short-term (years) variability are clearly desirable.

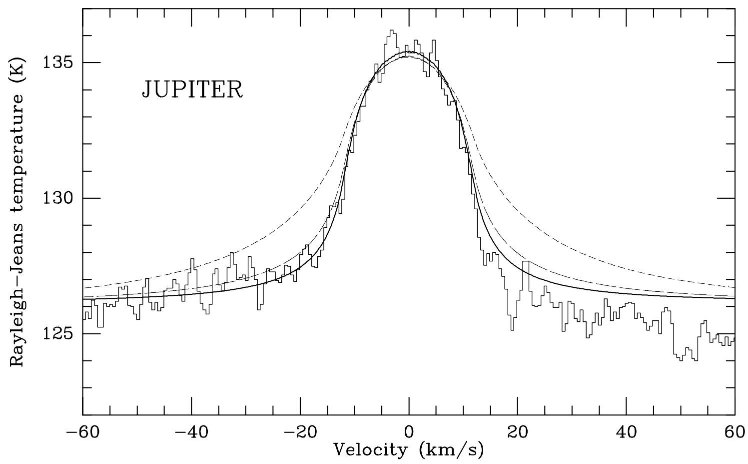

Fig. 1. The detection of the H_2O 556.935 GHz line by SWAS on Jupiter (Bergin et al. 2000). Different lines indicate models with different water distributions.

2.3 HIFI observations

2.3.1 Goals

The main goal of this program is to obtain a better characterization of the water in the four outer planets and Titan. Specifically, we want to :

(i) improve the accuracy on the disk-average water abundances (known from ISO to only within factors of 2-3 for each planet, given S/N limitations), which is necessary for refining the estimates of the input fluxes.
(ii) determine the vertical profiles whenever possible. Indeed, different vertical distributions are expected for water resulting from a permanently diffusing flux from the upper atmosphere and from water originating from a recent cometary impact.
(iii) perform a rough mapping of the horizontal distribution of H_2O at Jupiter, to measure the latitudinal variability of H_2O. In particular, an increase of water at the poles would be the signature of material coming from the satellites, which are connected to Jupiter's high latitudes (>65 degrees) through Jupiter's magnetic field.
(iv) search for temporal variability of all the above parameters as could result from variations of the external water fluxes or from the long-term evolution of Shoemaker-Levy 9 delivered material.

Another possible goal (feasibility to be assessed) would be to attempt the detection of $H_2{}^{18}O$. Millimeter observations have revealed an anomalous $^{18}O/^{16}O$ isotope ratio in Titan CO (Owen et al. 1999, IAU Circ. 7306). We also note that when ALMA will become operational, it might be able to detect HDO, which would by combination of concomitant Herschel observations provide the D/H ratio in this water, an elegant and unmistakable signature of its origin.

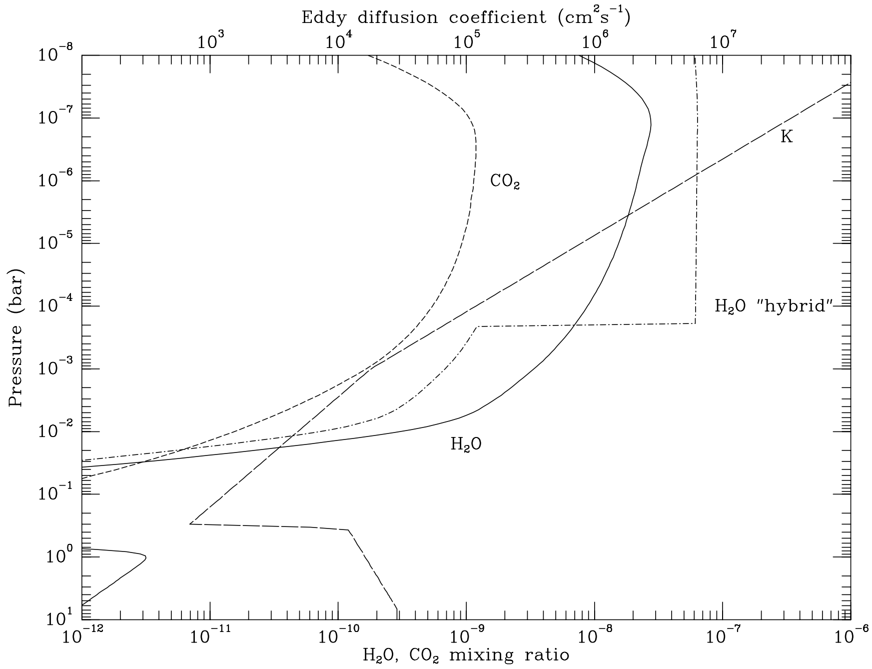

Fig. 2. Possible H_2O distributions of water in Jupiter's atmosphere. The solid line corresponds to water provided exclusively by a permanent interplanetary dust source. The dashed line marked "hybrid" corresponds to the combination of such a source with water deposited at 0.2 mbar by a cometary impact such as SL9. The ISO observations tentatively favor the second model, and confirmation by HIFI/Herschel observations is needed.

2.3.2 Strategy and target lines

The observations will consist of high S/N integrations with HIFI on several (typically three or four) H_2O lines, of different intrinsic strengths. These observations will be complemented by full spectra obtained by the other two Herschel instruments. In addition to precise abundance measurements for all five targets, in the case of Jupiter, Titan, and probably Neptune, high S/N profiling of the H_2O lines - and in particular accurate measurement of linewidths - will provide information on the vertical profile of water. At Saturn and Uranus, in which water must be restricted to very tenuous levels (< 0.3 mbar) due to a particularly cold stratosphere, it is likely that the line profiles will be entirely defined by the planetary rotation, preventing information on the residence level of water to be retrieved. Nonetheless, it may be possible to infer vertical information by observing lines with different strengths (study to be performed). In the case of Jupiter, H_2O will be mapped at 1716.8 GHz by HIFI (and at 2640 GHz by PACS). The spatial resolution (9–13") will make it possible to observe $\sim$9 points on the jovian disk (5 different latitudes, plus east and west limbs). The latitude distribution (PACS and HIFI) will be used to determine the Shoemaker-Levy 9 contribution and to separate it from a possible polar (auroral) oxygen source. ISO observations of CO_2 performed in 1997 have revealed a clear SL9 signature, with a factor of 10 contrast between 45 S and 45 N latitudes. Horizontal (eddy or organized) transport is expected to progressively erase the contrasts however, and extrapolating the transport/chemical model of Lellouch et al. (2002), a contrast of about 10 % in the water abundance is expected to remain between 45 S and 45 N latitudes in 2008. This is small but certainly measureable; in addition, Cassini/CIRS observations of Jupiter, obtained in Dec. 2000, reveal a much larger contrast than anticipated from the model of Lellouch et al. (2002), and in particular a surprising, probably dynamical in origin (isolation of a high-latitude vortex), factor-of-4 higher abundance of CO_2 at 65 S compared to 45 S. Note that a technique of "balanced position switch" - with reference on a position symetric with respect to Jupiter's center - can be used in the mapping observations, improving the instrumental baseline. Moderate resolution (1 MHz) should be sufficient for all the HIFI observations because of planetary rotational smearing. All of the measurements will be repeated once per year to search for temporal evolution.

Table 1: Water in Giant Planets: Possible target lines for HIFI (preliminary)

molec.	transition	GHz	band
H_2O	$1_{10} - 1_{01}$	556.9	1
H_2O	$2_{11} - 2_{02}$	752.0	2
H_2O	$2_{02} - 1_{11}$	987.9	4
H_2O	$3_{12} - 3_{03}$	1097.3	4
H_2O	$1_{11} - 0_{00}$	1113.3	4
H_2O	$2_{12} - 1_{01}$	1669.9	6
H_2O	$3_{03} - 2_{12}$	1716.8	6

2.4 Related work

2.4.1 Other observations

As mentioned above, full range spectra and/or targetted line observations by the other two Herschel instruments in spectroscopic mode are necessary for complementarity. They will address the five objects in the case of PACS, while for SPIRE, saturation issues will leave only Uranus, Neptune, and Titan observable. For Jupiter, mapping of H_2O at 2640 GHz (and possibly other shorter-wavelengths lines, in which case Saturn could be resolved too) by PACS will also be performed. Integration times for PACS and SPIRE will amount to a few minutes per line and object for selected line observations, and perhaps a few hours per object for full range spectra. It is anticipated that the PACS and SPIRE consortia will contribute to providing this time.

2.4.2 Related laboratory and theoretical work

A proper analysis will require a good knowledge of the H_2O spectral parameters, particularly of the Lorentzian linewidths for broadening by foreign gases H_2, He and N_2, with the dependence on the J, K quantum numbers and temperature. The interpretation of the H_2O distribution will be performed in the framework of photochemical models for the various planets.

2.5 Estimation of HIFI time (preliminary)

Synthetic calculations for the Outer Planets are underway. Table 1 indicates preliminary estimates of line contrasts in Giant Planets (in T_{RJ}, accounting for filling factors). **These numbers are preliminary because the effect of rotational smearing is only roughly estimated**. We assume at this point that three or four H_2O lines will be observed for each planet, both for redundancy and to search for line of different intensities. The estimated integration times in chopping mode are indicated in Table 3.

Table 2: Estimates of H_2O line T_{RJ} contrasts (K) (preliminary)

GHz	Jupiter	Saturn	Uranus	Neptune
556.9	4	0.8	0.05	0.05
1097.4	7	3	0.1	0.13
1669.9	15	2	0.25	0.3
1716.8	15	2	0.25	0.3

Table 3: Estimates of needed observing times (s) (preliminary)

GHz	T_{sys}	Jupiter (S/N = 100)	Saturn (S/N = 50)	Uranus (S/N=10)	Neptune (S/N=10)
556.9	223 K	124 s	777 s	2.2 h	2.2 h
1097.4	439 K	157 s	214 s	2.14 h	1.3 h
1669.9	1600 K	910 s	3.55 h	9.1 h	6.3 h
1716.8	1600 K	910 s	3.55 h	9.1 h	6.3 h

A S/N of 10 is not really sufficient but line smoothing (e.g. to 4 MHz) will be possible in the case of Uranus and Neptune.

Estimates for Titan have not been performed yet, but required integration times are expected to be roughly similar to what they are at Uranus, i.e. about 2 hours per line at 557 and 1097 GHz and 9 hours in band 6.

A possible observation plan is the following:

Jupiter:

a) Observe the four lines of Table 2 and 3: time = 0.58 hour
b) Map the 1717 GHz line (9 points on the disk): time = 9x910 sec = 2.3 hour
c) Repeat a) and b) four times (once a year)
Total = 11.53 hour

Saturn:

a) Observe three of the four lines of Table 2 and 3 (eliminate the 1669 or the 1717 GHz line) : time = 3.83 hour
c) Repeat a) and b) four times (once a year)
Total = 15.30 hour

Uranus:

a) Observe the 557 and 1097 GHz line of Table 2 and 3: time = 4.34 hour
b) Observe once the 1717 GHz or 1669 GHz line: time = 9.1 hour
c) Repeat a) but not b) four times (once a year)
Total = 26.46 hour

Neptune:

a) Observe the 557 and 1097 GHz line of Table 2 and 3: time = 3.5 hour
b) Observe once the 1717 GHz or 1669 GHz line: time = 6.3 hour
c) Repeat a) but not b) four times (once a year)
Total = 20.3 hour

Titan:

a) Observe the 557 and 1097 GHz line of Table 2 and 3: time = 4 hour
b) Observe once the 1717 GHz or 1669 GHz line: time = 9 hour
c) Repeat a) but not b) four times (once a year)
Total = 25 hour

The total HIFI time for this part of the program is 98.6 hour.

3 WATER AND CHEMISTRY IN THE MARTIAN ATMOSPHERE

3.1 Summary

We propose to monitor the water vapor abundance and vertical profile on Mars and to determine accurately its isotopic ratios (D/H, $^{16}O^{18}O$, $^{17}O/^{16}O$). A number of specific species, notably O_2, O_3, OH and H_2O_2, will be searched for. In addition, we propose to serendipitously explore the spectrum of Mars in HIFI bands 4 and 5. Follow-up observations of species possibly detected by PACS and SPIRE may also be considered.

3.2 Scientific background

There are still many unsolved questions related to the past climate of Mars and, in particular, the history of the H_2O and CO_2 reservoirs. In order to address these problems, we first need to better understand the present aeronomy of Mars and, more precisely, the water cycle with its various sources and sinks. The composition of the martian atmosphere is largely governed by the photochemistry of carbon dioxide and water. Understanding martian photochemistry in detail is important in a comparative planetology context (for example on the role of couplings between chemistry and dynamics), but it is also a pre-requisite to address the history of Mars with a firm grasp on key phenomena such as atmospheric escape. As regards the martian atmospheric composition, few gaseous molecular species have been spectroscopically identified so far: CO_2, CO, H_2O, O_2, O_3 and recently H_2, H_2O_2 and may be CH_4. Upper limits have been obtained, in particular, on sulfur species (SO_2, H_2S, OCS), hydrocarbons, HCl, and nitrous species. No information presently exists on other halides on Mars, nor on ClO (Encrenaz et al., 1995). Yet, photochemical models do predict the presence of a number of additional compounds, such as OH, O_2, NO, etc... (Nair et al. 1994, Fig. 3). A number of minor species in the martian atmosphere are intimately related to water and are expected to vary in correlation (e.g. H_2O_2, HO_2, OH) or anti-correlation (O_3) with it.

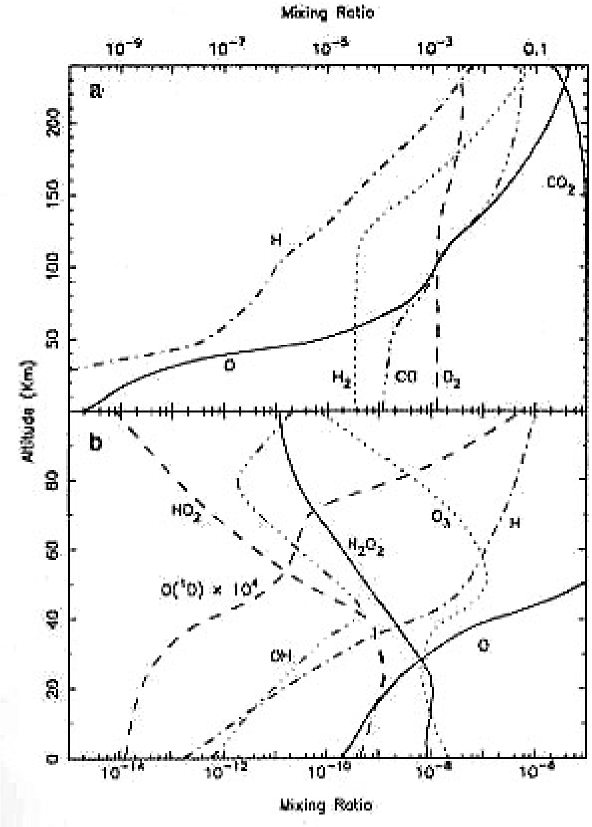

Fig. 3. Photochemical model predictions of the composition of Mars' atmosphere (Nair et al. 1994).

The current martian climate is governed by three main and inter-dependent cycles, namely the cycles of carbon dioxide, water, and dust. The water cycle (i.e. the variations of the water abundance and vertical distribution as a function of season and latitude/longitude) is a key aspect of the martian atmosphere/surface system. Temporal and spatial variations of the column-integrated amount of water has been (and continues to be) characterized by space missions such as Viking (Jakosky and Farmer 1982), MGS (Smith 2002), and since recently Mars Express. It can be reasonably well reproduced by General Circulation models (e.g. Richardson and Wilson 2002) in which the main source of water is injection from the north polar cap during its spring sublimation, although the detailed role in reservoirs such as water ice clouds and the surface regolith remain poorly understood. However, extremely limited information is available on the *vertical* profile of water. This parameter is not accessible to infrared and UV observations, and only ground-based heterodyne observations using the weak H_2O 22 GHz and HDO 226 GHz lines (Encrenaz et al. 1991, Clancy et al. 1996) have provided results. The most significant finding was that while water vapor is present up to relatively high altitudes ($\sim$ 50 km) at perihelion, it is confined to the bottom 10 km of the atmosphere at aphelion (due to lower temperatures). This is called the "variable hygropause level". If confirmed, this asymmetry is expected to drive a powerful transport mechanism from the North to the South and strongly influence the water cycle. Due to its potential importance, a better observational characterization of this phenomena is needed.

Isotope ratios carry information on the history of the martian atmosphere. This is particularly true of the D/H ratio, enriched by a factor of 5 ± 2 compared to the Earth value, probably as an effect of massive photolysis and escape of hydrogen from an early denser atmosphere (Owen et al. 1988). About oxygen, slightly non-terrestrial values have been reported for $^{18}O/^{16}O$ and $^{17}O/^{16}O$, respectively 10 % and 5 % lower than their telluric counterpart (Bjoraker et al. 1989). This surprising result (obtained on CO_2) needs confirmation by measuring both the CO_2 and the H_2O isotopes.

Remote sensing spectroscopy in the millimeter/submillimeter range is an important tool for studying the chemical composition of the Martian atmosphere. Molecular lines formed in the Martian atmosphere are narrow (20-500 MHz in general, though strong H_2O lines can cover up to 2 GHz), due to the small pressure broadening. Heterodyne spectroscopy provides the capability of measuring individual line shapes and is thus especially suited for vertical profiling. As compared to the IR, it has the advantage of being insensitive to the atmospheric dust loading and to offer better sensitivity for specific species, e.g. HDO and H_2O_2. Ground-based millimeter heterodyne spectroscopy has been used for over two decades for determining the thermal atmospheric profile from the CO transitions, for measuring the water abundance, and for measuring the mesospheric winds. Observations of the H_2O 557 GHz line by SWAS (Gurwell et al. 2000), although limited in S/N and in spectral bandwidth, have demonstrated that vertical information can be retrieved from the submillimeter lines of H_2O. Improved observations - with a bandpass of 4 GHz - have been recently obtained by ODIN (Biver et al., in preparation).

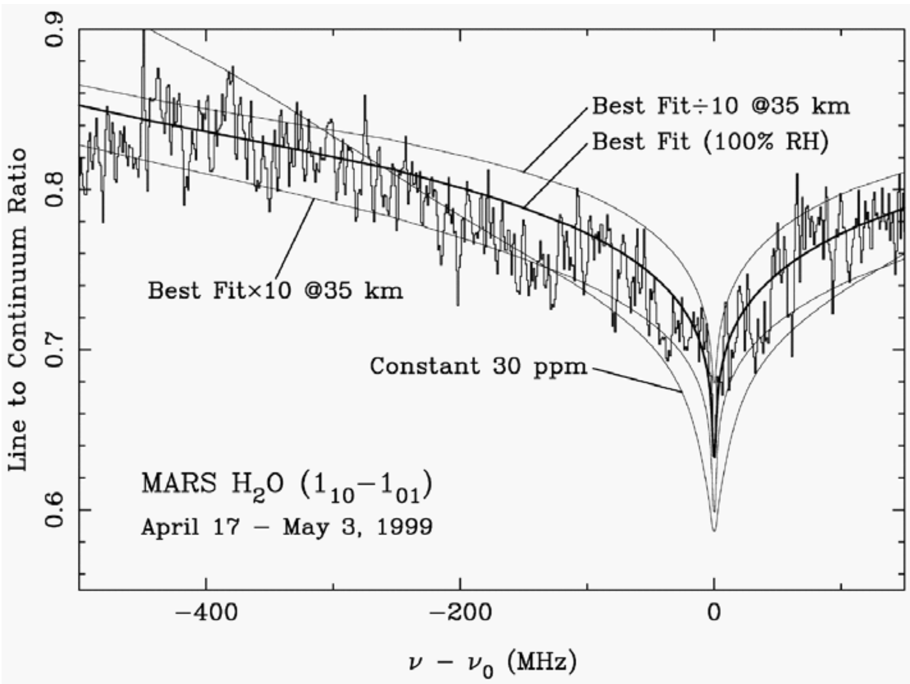

Fig. 4. The detection of the H_2O 556.935 GHz by SWAS on Mars, compared model with various water distributions (Gurwell et al. 2000).

3.3 HIFI observations

3.3.1 Goals

The main goals of this program are the following:

(1) obtain a detailed characterization of H_2O in the martian atmosphere, at all opportunities provided by the observability windows of Mars with Herschel (see below). This will include an accurate measurement of the disk-averaged abundance and vertical profile. The larger dish and broader bandwidth will clearly allow to improve upon the SWAS results. This will also include a measurement of the isotope ratios in water, using HDO, $H_2^{18}O$, and $H_2^{17}O$. Given the strong increase in HDO line strength from the millimeter to the submillimeter (e.g. factor 240 from 225.9 GHz to 1217.2 GHz), a much better estimate of D/H than currently available is expected.

(2) characterize and explore the global composition of Mars' atmosphere. This will include:

(i) measuring other species known to be present:

- CO, O_2, O_3, again at all possible opportunities, searching for variations correlated with those of water. In particular, molecular oxygen is very difficult to measure in the martian atmosphere by other means, and the question of its temporal variability is unresolved. In contrast, large spatial and temporal variations of O_3 are present, and expected to be anti-correlated with the water variations. $^{18}O/^{16}O$ and $^{17}O/^{16}O$ isotope ratios will also be measured on CO.

- H_2O_2. Hydrogen peroxide is a long-searched molecule in the martian atmosphere and deserves special consideration. It is both a key chemical intermediate (being the precursor for the key HO_x radicals which control the regulation of CO_2, H_2 and O_2), and the suspected elusive oxidant in the martian soil explaining the lack of organics on this planet. Very recently, H_2O_2 has been finally detected, both from submillimetre heterodyne spectroscopy at 362 GHz (Clancy et al. 2004), and from IR observations near 10 μm (Encrenaz et al., 2004b), with a mixing ratio of 15-50 ppb. H_2O_2 appears to vary seasonally and spatially. The seasonal variation could be related to the seasonal variation of the hygropause. Repeated observations of H_2O_2 and determination of its vertical profile in conjunction to that of H_2O would provide unique information on this issue.

(ii) search for new atmospheric species, including in particular OH, HO_2 Once again, OH and HO_2 seasonal variations are expected.

3.3.2 Observability windows, strategy and target lines

The current observability windows for Mars with Herschel are the following:

Table 4: Approximate observability windows of Mars

Number	Dates(yr/mo/day)	Solar long.	SubEarth lat.	Size	Comments
1	2007/06/01 - 2007/11/01	250-340	-24° – 6°	6”–12”	Perihelion; H_2O Southern max.
2	2008/02/15 - 2008/06/01	32-80	-2° – 18°	10”–5”	Beginning of Northern max.
3	2009/08/10 - 2009/12/05	319-20	-1° – 19°	5”–10”	Weak H_2O
4	2010/03/21 - 2010/07/07	67-115	13° – 25°	10”–5”	Aphelion; H_2O Northern max.

Based on theory and earlier searches, period 1 could be the most favorable for observing H_2O_2; period 4 could result in the largest OH abundances, while period 3 corresponds to an O_3 maximum.

The strategy will consist of a combination of high-S/N targetted observations with a complete exploration of the entire HIFI range at moderate depth. A 1-MHz resolution is sufficient.

1. *High S/N targetted observations:*

(1) For each of the observability windows:

- Observe a few (typically three) strong transitions of H_2O
- Observe one O_2 line (1120.725 GHz)
- Observe one O_3 line (e.g. 1180.3 GHz, TBC)
- Observe one H_2O_2 line (1047.4 or 1159.4 GHz)
- Observe CO and ^{13}CO for temperature profiling

(2) At time of water maximum (period 1 or 4)

- Measure the three isotopes of H_2O (HDO, $H_2^{18}O$, and $H_2^{17}O$)

- Make a deep dedicated search for OH and HO_2 (lines TBC)

(3) In one of the observability windows (TBD), perform additional dedicated observations:

- Observe one $C^{18}O$ and $C^{17}O$ line
- Search for a few other compounds (e.g. HCl, H_2CO, NH3, H_2S, NO), possibly depending on PACS results. For the first three of them, the increase of linestrengths compared to the millimeter transitions allows increased sensitivity.

2. *Spectral survey in some HIFI bands, at moderate depth.* The goal is to take advantage of the unique capability of HIFI to scan a large spectral interval at high spectral resolution to detect additional lines/species.

Table 5: Mars: Possible target lines for HIFI

molecule	GHz	band
H_2O	556.9	1
H_2O	1097.3	4
H_2O	1162.9	4
H_2O	1716.9	6
HDO	1217.3	5
HDO	1625.4	6
$H_2^{17}O$	1149.0	4
$H_2^{18}O$	1136.7	4
CO	1036.9	4
^{13}CO	991.3	4
$C^{18}O$	987.6	4
$C^{17}O$	1010.7	4
O_2	1120.7	4
O_3	1180.3	5
OH	~1834	6
H_2O_2	1047.4	4
NO	1152.9	4
HCl	1251.4	5
HCl	1876.2	6
H_2CO	1185.0	5
H_2S	1072.8	4
HO_2	TBD	TBD
NH_3	1214.9	5

3.4 Related work

3.4.1 Other observations

Full range spectra by PACS and will be useful in two respects. First they will provide information on the emissivity of Mars's surface as a function of wavelength. Besides its scientific interest, this will help the modelling of the HIFI data. Second, such low-resolution observations may drive additional follow-up line searches with HIFI. The total PACS time needed perform a complete spectral survey of Mars at a S/N of 100 is 2.2 hours, and we anticipate it will be provided by the PACS consortium. Complementary and concommitant observations of CO and ^{13}CO will be performed from the ground to monitor thermal profile variability.

3.4.2 Related laboratory and theoretical work

Spectroscopic parameters for the target lines are well known with the exception of the collisional linewidths for CO_2 broadening. For a given species, such linewidths vary with lines and detailed information for each of the target lines is desirable.

3.5 Estimation of HIFI time

Although complete synthetic calculations of Mars submillimeter spectrum have notbeen performed yet, Encrenaz et al. (2004c) have assessed the detectability of a number of compounds. Table 6 gives an idea of the time required to measure the Mars continuum with a S/N of 500. This is a reasonable ballpark number. Typically, the strong lines (H_2O) will thus be observed with a S/N larger than 100, while the expected weak lines (1 %) will be detected with a S/N of 5. Table 6 assumes a Mars' apparent diameter of 7.5" and a brightness continuum temperature of 200 K.

Table 6: Typical observation times for a S/N = 500 measurement on a Mars 200 K continuum level.

Frequency (GHz)	T_{rj}	Time
557	4 K	6145 sec
1000	12 K	2231 sec
1250	18 K	1580 sec
1800	32.5 K	10.8 hours

The 1000-1250 GHz range is clearly the more favorable, as providing the best compromise between the filling factor and system temperature. Based on this, we provisionnally allocate 1/2 hour for each targetted line observation (except for O_3, see below). The number of targetted observations will be:

- For each of the four windows: 3 H_2O lines, 1 O_2, 1 H_2O_2, 1 CO and 1 ^{13}CO lines. Total: 28 observations.

- For only one of the windows: 2 lines for HDO, H_2O^{18}, and H_2O^{17}, and OH. 1 line for HO_2, CO^{18}, CO^{17}, and three other species (e.g. HCl, NH_3, H_2CO). Total: 14 observations

- O_3 is more difficult to detect (best lines are at 1180 and 1214 GHz), and may require up to 4 hours (Encrenaz et al., 2004c). We will attempt to detect it twice in the mission, and thus dedicate 8 hours for its observation.

In total, the targetted line observations require 29 hours.

For a spectral survey, the necessary time was estimated with a goal of achieving a S/N of 100 on the continuum. The time per spectral position (i.e., per 4 GHz interval), again assuming a 7.5" target, is plotted in Fig. 5 for the entire range covered by HIFI. Fig. 5 clearly confirms that bands 4 and 5 are the most favorable, while band 6 is prohibitory expensive. Restricting a spectral survey to bands 4 and 5 seems to be an optimum strategy, as it seems unlikely to "miss" molecules that would have favorable lines exclusively outside the 960-1250 GHz range. For this domain, adding the elementary times of and division by a factor 2 (DSB observations) gives a total needed time of 0.7 hour.

The total time for this part of the program is 29.7 hours.

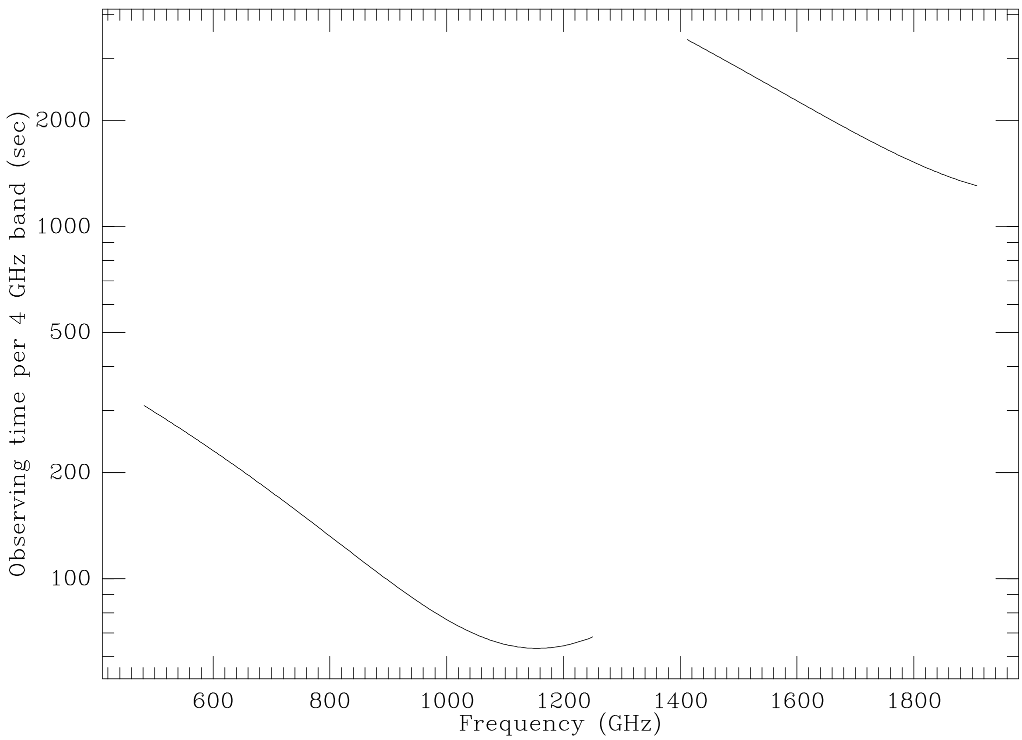

Fig. 5. Necessary time to measure the Mars' continuum with a S/N of 100 as a function of frequency.

4 FOLLOW-UP STUDIES

While the above two sections describe well-identified programs, it is felt necessary to already allocate time for follow-up studies. Indeed, initial results from the first two programs and/or from independent observations may warrant immediate additional HIFI observations. Example of such observations are:
(i) additional H_2O line observations in Giant Planets and Titan, particularly weaker and/or isotopic ($H_2^{18}O$) lines.
(ii) deeper targetted observations of some Martian lines based on HIFI/PACS spectral survey.
(iii) additional specific observations of Titan.

While the first two aspects are obvious to understand given the description of the previous sections, it is worth elaborating a bit of the third point.

Titan's dense atmosphere is a place for elaborate chemistry. This is attested by the presence of numerous hydrocarbons and nitriles resulting from the coupled photochemistry of methane and nitrogen. Atmospheric chemistry furthers appears to be coupled to dynamics (e.g. Lebonnois et al. 2001) and to ionospheric chemistry (Banaszkiewicz et al. 2000). It is important to detect as many chemical species as possible to assess the degree of complexity of Titan's organic chemistry. Titan will be one of the main targets of the Cassini-Huygens mission in 2004-2008. In particular, the Huygens descent probe will carry a gas chromatograph and mass spectrometer, while Cassini far-infrared instrument CIRS will measure the 7–1000 μm spectrum with a 0.3 cm^{-1} resolution (i.e. R = 300 at 100 μm). Model predictions (Coustenis et al. 1993) indicate that at least HCN, $H^{13}CN$, CO, H_2O, CH_4 should be detected by Cassini/CIRS in the 50–1000 μm range. Other, unexpected, species may be discovered in this and other spectral ranges. Large ground-based telescopes have allowed the detection of CO, HCN, HC_3N,

CH_3CN and a number of their isotopes (see e.g. Marten et al. 2002). However, because Titan is a small target, HIFI in general cannot compete with ground-based telescopes for species observable from the ground, and a blind exploration of its spectrum with HIFI is not feasible. With the exception of H_2O discussed previously, it seems more reasonable to wait for the first Titan observations of Cassini/CIRS (and possible even for those of Herschel PACS and SPIRE) to define and conduct dedicated molecular searches. Nonetheless, these follow-up observations are very important. For example, except in the case of optically thick lines, neither CIRS not SPIRE and PACS will have the means to infer vertical information on possible new minor species, justifying the subsequent use of HIFI. In addition, cross-comparison with CIRS/Cassini observations will provide additional indications on the HIFI calibration.

It is rather difficult to evaluate precisely at this stage how much follow-up observation time will be needed, but a ballpark 22 hours are required here. Justification for this number is as follows. Working at an optimum $\sim$ 1000 GHz frequency, Titan's continuum (a brightness continuum temperature of $\sim$ 76 K) can be measured at a 1 MHz resolution with a S/N of 10 in about 18 hours. This is adequate to observe an emission line superimposed onto the Titan continuum. For Mars, similar to what is dedicated for O_3, four hours are appropriate for a follow-up study of a weak martian line. In case where follow-up compositional studies do not turn out to be useful at Mars and Titan, the 22 hours would be used for additional water line searches in the Giant Planets, with no extra time provision requested here.

The grand total HIFI time for this proposal is 98.6 + 29.7 + 22 = 150.3 hours

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