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▶ To cite this version:

T. Cavalié, F. Billebaud, N. Biver, M. Dobrijevic, E. Lellouch, et al.. Observation of water vapor in the stratosphere of Jupiter with the Odin Space Telescope.. Planetary and Space Science, 2008, 56 (12), pp.1573-1584. 10.1016/j.pss.2008.04.013 . hal-00261908

HAL Id: hal-00261908 https://hal.science/hal-00261908

Submitted on 10 Mar 2008

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Observation of water vapor in the stratosphere of Jupiter with the Odin Space Telescope

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Abstract

The water vapor line at 557 GHz has been observed with the Odin space telescope with a high signal-to-noise ratio and a high spectral resolution on November 8, 2002. The analysis of this observation as well as a re-analysis of previously published observations obtained with the Submillimeter Wavelength Astronomy Satellite seem to favor a cometary origin (Shoemaker-Levy 9) for water in the stratosphere of Jupiter, in agreement with the ISO observation results. Our model predicts that the water line should become fainter and broader from 2007. The observation of such a temporal variablity would be contradictory with an IDP steady flux, thus

Preprint submitted to Elsevier

5 March 2008

supporting the SL9 source hypothesis.

Key words: Jupiter, atmosphere, water, spectroscopy, Odin space telescope

1 1 Introduction

The Infrared Space Observatory has detected water vapor in the stratospheres 2 of the giant planets (Feuchtgruber et al. 1997; Feuchtgruber et al. 1999; Lel-3 louch 1999). The large amount of water measured above the condensation 4 level of vapor (cold trap at the tropopause) implies the presence of an ex-5 ternal source of oxygenated compounds (Moses et al. 2000b; Lellouch et al. 6 2002). These compounds could be brought by interplanetary dust particles 7 (IDP), sputtering from the rings and/or satellites and large cometary im-8 pacts. Observations of Jupiter carried out by ISO tend to prove that most of 9 the stratospheric water is due to the Shoemaker-Levy 9 (SL9) comet impacts 10 in July 1994 (Lellouch et al. 2002), whereas Bergin et al. (2000) obtained sat-11 isfactory fits to the Submillimeter Wavelength Astronomy Satellite (SWAS) 12 data by considering IDP infall, with a constant flux of 2.0×10^6 cm⁻².s⁻¹. 13

The submillimeter satellite Odin was launched in 2001 and obtained a high resolution spectrum of Jupiter's water vapor line (1₁₀-1₀₁) at 557 GHz on November 8, 2002. This spectrum is presented in this work as well as a reanalysis of SWAS observations. Spectral analysis combined with the use of our photochemical model (Ollivier et al. 2000, adapted to Jupiter) provides new clues which help understanding the origin of water vapor in the stratosphere

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20 of Jupiter.

A description of the observations is given in Sect. 2. Our photochemical and radiative transfer models are described in Sect. 3. Our results are presented in Sect. 4 and the different sources of H_2O are discussed in Sect. 5.

$_{24}$ 2 Observations

The space telescopes SWAS and Odin observed the water vapor 557 GHz line on Jupiter in 1999, 2001 (SWAS) and 2002 (Odin). The resulting brightness temperature spectra have a signal-to-noise ratios of ~ 17 , 10 and 16 respectively for the 1999, 2001 and 2002 observations. The spectral resolution is about 1 km.s⁻¹ for the SWAS spectra and 0.6 km.s⁻¹ for the Odin spectrum.

The SWAS spectra are corrected for the Double Side Band (DSB) response of the instrument. Nevertheless, the SWAS spectra show broad features at 100 km.s⁻¹ and more, which cannot be reproduced in models. These wings, probably due to instrumental effects as mentionned in Bergin et al. (2000) and Lellouch et al. (2002), cause an uncertainty on the continuum level of the emission. More details on the SWAS 1999 and 2001 observations can be found in Bergin et al. (2000) and Lellouch et al. (2002).

The Odin observations were carried out with the Acousto-Optical Spectrometer (AOS) in a classical position switching mode (Olberg et al. 2003). The receivers are operated in a Single Side Band (SSB) mode. The spectral band is 1 GHz. As Jupiter has a strong continuum emission at this frequency, stationary waves are generated within the instrument, causing ripples on the spectrum (Fig. 1). The subtraction of the ripples is the source of an uncertainty of 10%



Fig. 1. Odin observations of Jupiter at the $H_2O(1_{10}-1_{01})$ line frequency on November 8, 2002. The observed antenna temperature is displayed as a function of velocity. The signal-to-noise ratio is 16.

43 on the line contrast and some uncertainty on the line wing shape.

As the beam size $(3.3' \times 4.5')$ for SWAS and 2.1' for Odin) is larger than the 44 planet size $(\sim 35-40^{\circ})$, all the observed features correspond to the emission of 45 the whole planet. The line width is dominated by the smearing effect because 46 of limb equatorial velocity $\sim 12.6 \text{ km}.\text{s}^{-1}$ of the planet (Bergin et al. 2000). As 47 no absolute calibration has been done for the Odin observations, all results are 48 discussed in terms of line-to-continuum ratios and the Odin/SWAS observed 49 continuum have been rescaled to the brightness temperature scale of our model 50 $(T_B = 128.6 \text{ K}).$ 51

52 **3** Modeling

⁵³ We describe, in this section, details of our data analysis procedure that can ⁵⁴ be summarized in the following way:

• A water vertical profile is simulated from a time-dependent 1D photochem-

ical model. The main parameters that affect this profile are the altitude
and the magnitude of water deposition (in the case of a sporadic cometary
origin), the magnitude of the water influx (in case of a steady interplanetary
dust particle flux) and the eddy diffusion coefficient in the stratosphere.

A radiative-transfer model computes a synthetic spectrum for each water
 vapor profile.

Comparison of observational data and synthetic spectra enables to constrain
 parameters of the photochemical model.

64 3.1 Photochemical modeling

We used a time-dependent photochemical model, derived from the model developed for Saturn by Ollivier et al. (2000) and which has been adapted to the case of the atmosphere of Jupiter. For each altitude and each chemical compound i, the code solves the continuity equation

69
$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = P_i - n_i L_i - \mathrm{div}\left(\phi_i\right) \tag{1}$$

where *n* is the concentration, *P* the chemical production, *L* the chemical loss and ϕ the vertical flux. This is a one-dimensional model since only the vertical transport is considered.

The model includes 46 oxygenated compounds and hydrocarbons and 593 reactions (photolysis processes and chemical reactions). Condensation near the tropopause is also considered. The eddy diffusion coefficient profile we took comes from Moses et al. (2005). We chose their nominal eddy profile called "model C" (see Sect. 5). The influx rates of oxygenated compounds (proportion of H₂O, CO₂ and CO) and H atoms were also taken from Moses ⁷⁹ et al. (2005).

Moses et al. (2000) showed that an IDP source is more likely than a ring/satellite 80 source since there is a difference of ~ 2 orders of magnitude in the estimated 81 fluxes. This is the reason why we chose to compare the results of two models: 82 an IDP source model and a low-IDP+SL9 source model. For the sake of sim-83 plicity, the latter model will be called the SL9 model hereafter. The lack of 84 spatial resolution of the observations allowed us to use disk-averaged mixing 85 ratio vertical profiles for water, even if the SL9 impacts were all located in the 86 southern hemisphere. The only input parameter we had to fix to test the IDP 87 source hypothesis is the external flux of infalling water $\Phi_{H_2O}^{IDP}$. In order to test 88 the SL9 source hypothesis, we have built vertical profiles at the time of the 89 impacts (July 1994) and let them evolve with the photochemical model until 90 the time of the observations (September 1999, January 2001 for the SWAS 91 data and November 2002 for the Odin data). The initial water vertical profiles 92 have been built on the base of a low stationnary external flux and a sporadic 93 input, due to the comet. The low stationnary input flux is modeled via an IDP 94 model with a flux $\Phi_{\rm H_2O}^{\rm IDP} = 4 \times 10^4 \text{ cm}^{-2} \text{.s}^{-1}$ (Lellouch et al. 2002). This value is 95 2 orders of magnitude lower than a pure IDP model (see Sect. 4). The spo-96 radic input of water due to the impacts was modeled via two parameters: the 97 deposition pressure p_0 and the initial mixing ratio q_0 above the p_0 level (see 98 Lellouch et al. 2002 for more details). For each computation, the value of q_0 99 was set to a constant value as a function of altitude (above the p_0 level). 100

Thus, we have two possibilities for the SL9 models. The first one consists of fixing the value of p_0 and adjusting the value of q_0 with the data. In the second case, we fix q_0 and adjust p_0 . Some constraints exist on both p_0 and q_0 . The most reliable constraint is probably the fact that the deposition level that was



Fig. 2. Example of SL9 source vertical profiles of water at the time of the SL9 impacts (07/1994) in solid line and at the time of the Odin observations (11/2002) in dashed lines. The evolution of water abundance is computed by the photochemical model. The water vapor mixing ratio is displayed as a function of atmospheric pressure. Profiles correspond to a fixed value of $p_0=0.2$ mbar, and an adjusted value of $q_0=1.9\times10^{-7}$.

observed for CO during the SL9 impacts is 0.2 ± 0.1 mbar (Moreno 1998). From 105 CO and CS post-impact observations, Lellouch et al. (1995), Lellouch et al. 106 (1997) and Moreno et al. (2001) derived p_0 levels of 0.3 mbar, 0.04-0.2 mbar 107 and 0.1 mbar (respectively). The other constraint lies on the observed column 108 density of water vapor. Lellouch et al. (2002) inferred that the H_2O/CO ratio 109 is equal to 0.07 in mass according to the entire ISO data set, thus fixing the 110 H_2O column density to $(2.0\pm0.5)\times10^{15}$ cm⁻². Such a value lead to the derival 111 of a mixing ratio of water vapor of 6×10^{-8} above the deposition level. An 112 example of a SL9 model profile at the time of the impacts and at the time of 113 the Odin observations is shown on Fig. 2. 114

We modeled the observed submillimeter radiation with a line-by-line non-116 scattering radiative transfer model. We computed synthetic spectra of the 117 H_2O 557 GHz line. The program represents the approximate spherical geome-118 try of the planet so that planetary disk and limb contributions are taken into 119 account. We assumed an uniform distribution of all other opacity sources and 120 we adopted a mean thermal profile (see Fig. 3) of the atmosphere of Jupiter 121 (Fouchet et al. 2000a) since our beam size is larger than the observed plan-122 etary disk. Continuum opacity is dominated by H₂-He-CH₄ collision-induced 123 absorption (Borysow et al. 1985, 1986 and 1988). Following Moreno (1998), 124 the opacity due to the far wings of ammonia and phosphine lines was also 125 included. We used the Fouchet et al. (2000b) ammonia and phosphine mixing 126 ratio vertical profiles (see Fig. 4). Spectroscopic parameters for NH₃, PH₃ and 127 H_2O were taken from Pickett et al. (1998). The line widths are determined by 128 the collisional line widths for H_2 and He broadening. The broadening γ and 129 temperature dependance exponent n values that we took for NH_3 , PH_3 and 130 H_2O are summarized in Table 1. All lines, except the NH_3 ones, were assumed 131 to be Voigt-shaped. Following Moreno (1998), we took a modified Van Vleck 132 and Weisskopf line profile for ammonia. 133

The rapid rotation of Jupiter (9.9 h) induces the smearing of the disk-averaged line on the spectrum, because of the Doppler shifts due to the gas rotation velocity (12.6 km.s⁻¹ at the eastern and western limbs). The way this effect is taken into account is described in Bergin et al. (2000).

¹³⁸ We briefly come back to the use of disk-averaged vertical profiles of mixing



Fig. 3. Disk-averaged thermal profile of the atmosphere of Jupiter. The tropopause temperature is 109 K. The profile is isothermal (T=165.4 K) between 1 mbar and 10^{-3} mbar. Reference: Fouchet et al. (2000a).



Fig. 4. Ammonia (solid line) and phosphine (long-dashed lines) mixing ratio vertical profiles as a function of pressure in Fouchet et al. (2000b).

ratio. The fact that the SL9 impacts were all located in the southern hemisphere is not a limitation to our hypothesis. All the impacts occured at the

γ	H_2	He	Jupiter
NH_3	0.069		0.069
PH ₃ (2-1)	0.1064	0.0606	0.1001
H_2O	0.0811	0.0228	0.0731
n	H_2	He	Jupiter
$ m NH_3$	0.67		0.67
PH_3	0.73	0.30	0.67
$\rm H_2O$	0.9	0.50	0.85

Table 1

Collisional line width γ [$cm^{-1}.atm^{-1}$] (at 300 K) and temperature dependance factor n for NH₃, PH₃ and H₂O with H₂ and He and for Jupiter (a blank space means that no data are available). References: Berge & Gulkis (1976) and Brown & Peterson (1994) for NH₃, Levy et al. (1993,1994) for PH₃ and Dutta et al. (1993) for H₂O.

latitude of 44°S. Longitudinal mixing proved to be efficient in the submillibar 141 region. Indeed, HCN was observed at such pressure levels a few months after 142 the comet impacts and the maps showed that it had already spread over sev-143 eral degrees in longitude (Bézard et al. 1997). So, the deposits quickly formed 144 a longitudinal belt after the impacts. Thus we have to take into account the 145 background amount of water present in the stratosphere of Jupiter, which is 146 due to the low IDP flux ($\Phi_{H_2O}^{IDP} = 4 \times 10^4 \text{ cm}^{-2} \cdot \text{s}^{-1}$), and the SL9 input located 147 at 44°S, which is modeled via the parameters p_0 and q_0 . By averaging those 148 two kinds of vertical profiles over the surface of the planet, we obtain the 149 kind of profile shown in Fig. 2 (see "hybrid model" in Lellouch et al. 2002), 150

where p_0 is determined by the SL9 input and where q_0 is multiplied by the ratio between the surface of the SL9 longitudinal belt and the total surface of the planet. Using this approach, the values of q_0 we derive from the observations are disk-averaged values. A disk-averaged water vertical profile is adapted since the beam size is greater than the planet size.

156 4 Results

The best-fit models have been determined with a χ^2 minimization process. All profiles and column density values are disk-averaged. One must note that an uncertainty of 5 K on the thermal profile would add an uncertainty of 0.4×10^{15} cm⁻² on the water vapor column density, 0.3×10^{-7} on q_0 (in the case of a SL9 origin) and 0.6×10^6 cm⁻².s⁻¹(in the case of an IDP origin).

162 4.1 SWAS data

The observed Rayleigh-Jeans temperature continuum of the 1999 and 2001 ob-163 servations are 126.4 K (Bergin et al. 2000) and 118.0 K (Lellouch et al. 2002) 164 at $-60 \text{ km}.\text{s}^{-1}$ respectively. After rescaling the continuum value to the bright-165 ness temperature continuum of our model, it appears that only the SL9 models 166 give satisfactory fits to both sets of data, either in the wings or in terms of line 167 contrast. If we fit the line center, the IDP model with $\Phi^{\rm IDP}_{\rm H_2O}{=}(3.4{\pm}0.5){\times}10^6$ 168 $cm^{-2}.s^{-1}$ results in spectra which have too broad wings (see Fig. 5). It is not 169 possible fit within the 1- σ error bars the line center and the wings at the same 170 time. The best-fit model for both SWAS datasets is obtained with a SL9 model 171 with $p_0=0.2$ mbar and $q_0=(1.8\pm0.5)\times10^{-7}$ (see Figs. 5 and 6), leading to an 172



Fig. 5. Best-fit model to the (a) SWAS 1999 and (b) 2001 data obtained with a SL9 model with the initial parameters $p_0=0.2$ mbar and $q_0=1.8\times10^{-7}$ (solid lines). The IDP models (long-dashed lines) correspond to infall fluxes of $\Phi_{\rm H_2O}^{\rm IDP}=3.4\times10^6$ cm⁻².s⁻¹ for 1999 and 2001 respectively.

initial (in July 1994) column density of $(3.5\pm1.0)\times10^{15}$ cm⁻².

Nevertheless, the value of the continuum of both observations is quite uncertain, mostly due to the broad spectral features. Shifting downward the value
of the continuum level within the error bar, it is possible to derive new values
of the IDP flux that permits us to obtain synthetic spectra that match the
SWAS data. For instance, if the continuum of the 1999 and 2001 observations are set to 125.4 K and 117.0 K (respectively) instead of 126.4 K and 118
K (respectively) and then rescaled to the brightness temperature continuum



Fig. 6. Water mixing ratio vertical profiles as a function of pressure for a SL9 model with $p_0=0.2$ mbar and $q_0=1.8\times10^{-7}$ at the time of the SWAS 1999 observations (solid line) and at the time of the SWAS 2001 observations (long-dashed lines) and for IDP models with a steady flux of water $\Phi_{H_2O}^{IDP}=3.4\times10^6$ cm⁻².s⁻¹ (short-dashed line). The column density of water is $n_{H_2O}=3.5\times10^{15}$ cm⁻² for the SL9 model at the time of the impacts and $n_{H_2O}=2.6\times10^{15}$ cm⁻² for the IDP model.

of our model (T_B =128.6 K), then the fits of IDP models are far better (Fig. 181 7). The flux we derive is $\Phi_{\text{H}_2\text{O}}^{\text{IDP}} = (3.7 \pm 0.5) \times 10^6 \text{ cm}^{-2} \text{.s}^{-1}$ and the correspond-182 ing column density is $(2.8\pm0.4)\times10^{15}$ cm⁻². The synthetic spectrum is within 183 the 1- σ error bars on the data over the [-80;+20] km.s⁻¹ range. Finally, the 184 IDP model cannot be ruled out at this stage, because of the uncertainty on 185 the continuum level of each observation, even if a χ^2 analysis shows that the 186 SL9 model gives a better match to the data than the IDP model. All the IDP 187 models that are considered for the SWAS data in what follows are models 188 with downward shifted continuum (to 125.4 K and 117.0 K, for 1999 and 2001 189 respectively). 190

The SL9 model where q_0 is fixed to 6×10^{-8} also gives a good fit for $p_0 = (0.45 \pm$ 191 0.09) mbar (see Fig. 8). Here, the error bar on the p_0 value is not due to the 192 $1-\sigma$ level of the spectrum. Indeed, the synthetic spectra with either $p_0=0.37$ 193 mbar or $p_0=0.54$ mbar are outside the 1- σ level of the spectrum. This error 194 bar is due to the fact that the integration step of the photochemical model 195 is 5 km. This results in 0.09 mbar steps in the 0.2-0.6 mbar region. Taking 196 $p_0=0.45$ mbar and $q_0=6\times10^{-8}$, the column density of water is $(2.6\pm0.6)\times10^{15}$ 197 cm^{-2} at the time of the impacts. 198

199 4.2 Odin data

After removing the ripple pattern, the line shows some asymmetry in the line 200 wings. This, as well as the noise level, is a limitation in the determination 201 of the best-fit model. Testing the IDP fluxes leads us to retrieve of a lower 202 flux than the flux retrieved from the SWAS data. Indeed, the χ^2 minimum is 203 obtained for a flux value of $\Phi_{\text{H}_2\text{O}}^{\text{IDP}} = (3.4 \pm 0.5) \times 10^6 \text{ cm}^{-2} \text{.s}^{-1}$ (see Fig. 9). This 204 result is compatible with the SWAS initial results (before shifting downward 205 the Rayleigh-Jeans temperature continuum). If we try to fit the line with an 206 averaged best-fit model to the SWAS/Odin data ($\Phi_{\rm H_2O}^{\rm IDP}$ =3.6×10⁶ cm⁻².s⁻¹), 207 then the line center is better reproduced (see Fig. 9). Nevertheless, such a 208 modeling results in broader wings, but they still are within the 1- σ error bars. 209

As for the SL9 model, restraining the bulk of water above an initial pressure level of 0.2 mbar, results in narrower lines than the IDP model. The line center as well as the wings are well reproduced with the synthetic spectra. When fixing p_0 to 0.2 mbar, the optimum water mixing ratio above this level is $q_0=2.0\times10^{-7}$. The uncertainty is 0.5×10^{-7} . When fixing q_0 to 6.0×10^{-8} (Lellouch et al. 2002), p_0 is found to be (0.54 ± 0.09) mbar (see Fig. 10). The latter model implies a column density of $(3.2\pm0.6)\times10^{15}$ cm⁻² at the time of the comet impacts.

218 5 Discussion

The best-fit model parameters for each observation, as derived from χ^2 minimization, are summarized in Table 2. From this set of parameters, we derived averaged values. For each model (IDP, SL9 with q_0 fixed and SL9 with p_0 fixed), the value obtained is affected a weight related to the signal-to-noise ratio of the observation. Doing this way, we obtained the averaged values used in Fig. 11.

First of all, when considering the SL9 source hypothesis and fixing the value 225 of q_0 at 6×10^{-8} , we derive a deposition pressure level p_0 in the range of 0.45-226 0.54 mbar. The column density we derived is consistent with the value of 227 Lellouch et al. (2002). However, even if our model does not provide a more 228 precise value of p_0 , the range of the values we derive is outside the ranges 229 derived by Lellouch et al. (1997) and Moreno (1998) from CO observations at 230 millimeter wavelengths at the time of the impacts, which are 0.04-0.2 mbar and 231 0.2 ± 0.1 mbar (respectively). Therefore, we regard this possibility as unlikely 232 with regard to both SWAS and Odin data. 233

So, the models we have to compare are the IDP model and the SL9 model with $p_0=0.2$ mbar. We derived an external flux of water, originating from an IDP source, of $\Phi_{H_2O}^{IDP}=(3.6\pm0.5)\times10^6$ cm⁻².s⁻¹. This value is greater than the one derived by Bergin et al. (2000) by a factor of less than 2. From their physical

model, which only included vertical transport (no chemical or photochemical 238 processes), the authors derived a deposition flux of 2.0×10^6 cm⁻².s⁻¹. To ob-239 tain a narrower line from their model and thus to obtain their best-fit model, 240 they increased the mixing ratio over pressure slope $(-d(\log q)/d(\log p))$ of their 241 physical profile from 0.8 to 1.3. Nevertheless, as noted by the authors, chang-242 ing the slope could not simulate precisely the effects of photolysis, chemical 243 reactions and the non-linearity of the interactions between these processes as 244 well as vertical transport and condensation. Taking photolysis and chemical 245 losses into account, they would probably have obtained a higher value for the 246 flux consistent with our result. 247

With a SL9 model, we obtain $q_0 = (1.9 \pm 0.5) \times 10^{-7}$ when fixing $p_0 = 0.2$ mbar. 248 Lellouch et al. (2002) derived a column density of $(2.0\pm0.5)\times10^{15}$ cm⁻² at the 249 time of the ISO observations. The column density we derived is $(3.7\pm1.0)\times10^{15}$ 250 $\rm cm^{-2}$ at the time of the impacts. This value is greater than the ISO value, 251 but by taking photolysis, chemical reactions, vertical transport and conden-252 sation, this value decreases down to $(3.1\pm0.8)\times10^{15}$ cm⁻² at the time of ISO 253 observations. This value is still above the Lellouch et al. (2002) value, but 254 there is a small overlap on the ranges of values. Moreover, considering an un-255 certainty of 5 K on the thermal profile ends up in an additional uncertainty 256 of 0.4×10^{15} cm⁻² on the column abundance. So, these values could well be 257 consistent and an intermediate value of column density should be compatible 258 with all inferred values. As the water vapor vertical profile of Lellouch et al. 259 (2002) was computed from a vertical transport model, the ISO data should be 260 re-analysed with a more complete photochemical model. This work still has 261 to be done and its results could be directly comparable to ours. 262

²⁶³ The SL9 model quoted above better reproduces the line contrast as well as the

SWAS 1999 and 2001				
Model	$\Phi^{\rm IDP}_{\rm H_2O}[\rm cm^{-2}.s^{-1}]$	$p_0 \; [\text{mbar}]$	q_0	
IDP	$(3.7\pm0.5)\times10^{6}$	-	-	
SL9 $(q_0 \text{ fixed})$	4.0×10^{4}	(0.45 ± 0.09)	6×10^{-8}	
SL9 (p_0 fixed)	4.0×10^{4}	0.2	$(1.8\pm0.5)\times10^{-7}$	
Odin 2002				
Model	$\Phi^{\rm IDP}_{\rm H_2O}[\rm cm^{-2}.s^{-1}]$	$p_0 \; [\text{mbar}]$	q_0	
IDP	$(3.4\pm0.5)\times10^{6}$	-	-	
SL9 (q_0 fixed)	4.0×10^{4}	(0.54 ± 0.09)	6×10^{-8}	
SL9 (p_0 fixed)	4.0×10^{4}	0.2	$(2.0\pm0.5)\times10^{-7}$	

Table 2

Best-fit model parameters for each set of data and each model, from which the averaged best-fit value are derived (see text).

line wings than the IDP model (see Fig. 11). A χ^2 analysis clearly indicates that the SL9 model gives better fits to the data. However, all the IDP synthetic spectra are within the 1- σ error bars on all observations. So, this model cannot be ruled out at this stage.

If the observed water would come from the SL9 comet, then the non-steady state created by the deposition of the cometary material above the p_0 level in our model should evolve towards a steady state where the only observable source of water would be the low IDP flux (4×10⁴ cm⁻².s⁻¹ in our model). From our computations, such a state is reached ~400 years after the im-

pacts. As a result, the downward diffusion of water as well as the photochem-273 ical/chemical losses effects would first desaturate the line. Thus, the line con-274 trast should first increase with time (see Fig. 12). Our photochemical model 275 predicts that the line center temperature of the line should increase by 0.76 K 276 from 1999 to 2007. Taking the noise level of the SWAS 1999 observations into 277 account, our model predicts that this effect could only be observed in 2007 by 278 reaching a signal-to-noise ratio of 50 with the Odin telescope. Afterwards, the 279 amount of water decreasing more and more with time at submillibar pressures, 280 the line should become fainter and broader and should tend towards the line 281 that would be due to the low IDP flux only (see Fig. 12). This change should 282 be observable with Herschel-HIFI. 283

One must not forget that the shape of the water vertical profile computed 284 with a photochemical model highly depends on the vertical eddy diffusion 285 coefficient profile K(z). Due to strong uncertainties in the chemical scheme, 286 each photochemical model derives, from comparison with observational data, 287 a new value of K(z) that can differ by about one order of magnitude at some 288 altitudes (see Dobrijevic & Parisot 1998, Dobrijevic et al. 2003 and Hébrard 289 et al. 2007 for a detailed discussion on this point). For instance, as shown on 290 Fig. 7 of Moses et al. (2005), many different K(z) profiles have been inferred 291 from past observations. At the submillibar pressure range, $K(z) \simeq 5 \times 10^4$ 292 $cm^{-2}.s^{-1}$ within a factor of 2 (Moreno et al. 2003). According to the Moses 293 et al. (2005) model C value used in this work, K(z) is equal to 7.8×10^4 294 $cm^{-2}.s^{-1}$. At pressures between 0.1 mbar and 100 mbar (tropopause level), 295 Gladstone et al. (1996) found values of K(z) higher by a factor of ~ 3 . So 296 we have to consider the fact that another choice in the K(z) profile could 297 change our results. In the lower stratosphere, our adopted K(z) profile gives 298

a lower limit to K(z) values (see Fig. 7 in Moses et al. 2005). By taking the 299 Gladstone et al. (1996) K(z) profile, we would obtain an eddy mixing in the 300 lower stratosphere more efficient than in our study and it would result in more 301 water above the condensation level. The direct impact on the spectra of such 302 a change in the K(z) profile would be a broadening of the wings. Thus, the 303 IDP origin synthetic spectra would be out of the 1- σ error bars of the SWAS 304 and Odin observations. Finally, taking Moses et al. (2005) model C as a K(z)305 profile is a conservative way of analysing the observed lines with regard to the 306 implications noted above. 307

308 6 Conclusion

In this paper, we have shown that the high signal-to-noise ratio observations 309 of water vapor in the stratosphere of Jupiter, carried out with SWAS and the 310 Odin telescope between 1999 and 2002, favor a SL9 origin for water. Indeed, 311 all observations are better fitted when the bulk of water is restricted to sub-312 millibar pressures. In our disk-averaged and simplified deposition model of 313 the SL9 water, we derived a water mixing ratio of 1.9×10^{-7} above an initial 314 pressure deposition level of 0.2 mbar. In this model, a low IDP flux of 4×10^4 315 $cm^{-2}.s^{-1}$ was also taken into account. This suggests a localised input of water, 316 in terms of altitude, which is contradictory with a steady state resulting from 317 an IDP permanent flux. Nevertheless, all synthetic spectra obtained from an 318 IDP flux of $\Phi_{\rm H_2O}^{\rm IDP} = (3.6 \pm 0.5) \times 10^6 \text{ cm}^{-2} \text{.s}^{-1}$ give fits that are within the 1- σ er-319 ror bars of the observations, but the χ^2 value is greater than the one computed 320 from the SL9 model. In view of these results, the ISO data of 1997 should be 321 re-analysed using the model developped in this work. 322

Further observations, reaching a higher signal-to-noise ratio are needed to 323 state on the origin of water vapor in the stratosphere of Jupiter, even if the 324 SL9 origin is favored by both SWAS and Odin observations. The analysis of 325 the latest Odin observations (August 2007) is underway. Moreover, Herschel 326 observations with the HIFI instrument (500 GHz - 2000 GHz) should allow ob-327 taining a signal-to-noise ratio with a comparable spectral resolution in reason-328 able times. Such a high signal-to-noise ratio would enable us to better resolve 329 the line wing shape in order to discriminate between both origins. Moreover, 330 a temporal variability of the line could be brought to light. Such a variability 331 should not be expected with an IDP origin. Indeed, Moses et al. (2000a) sug-332 gested that the production of the IDP is dominated by short-period comets. 333 Selsis et al. (2004) showed that 48 short-period ($\sim 5-10$ year periods) comets 334 approach Jupiter's orbit at less than the Roche lobe radius of the planet. So, 335 the IDP flux on Jupiter should be steady. Finally, using HIFI at the highest 336 frequencies would result in a sufficient spatial resolution to carry out maps of 337 Jupiter at water vapor frequencies. A latitudinal inhomogeneous distribution 338 of water, with an increase of its amount in the southern hemisphere would be 339 a strong signature of a SL9 impact origin and could provide information on 340 the horizontal diffusion at the submillibar level. 341

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Fig. 7. Brightness temperature spectra as observed by SWAS (a) in 1999 and (b) in 2001. Both spectrum continuum have been rescaled so as to obtain a better fit of the line wings with an IDP model. (c): water mixing ratio vertical profile as a function of pressure resulting from the observed flux of $\Phi_{\rm H_2O}^{\rm IDP}=3.7\times10^6$ cm⁻².s⁻¹.



Fig. 8. SL9 model results compared to the (a) SWAS 1999 and (b) SWAS 2001 observed spectra, when fixing $q_0=6.0\times10^{-8}$. The derived initial deposition pressure level p_0 is 0.45 mbar. (c): corresponding water mixing ratio vertical profiles at the time of the observations (solid line for 1999 and long-dashed lines for 2001).



Fig. 9. Odin 2002 data modeled with IDP models. The solid line corresponds to a flux of $\Phi_{\text{H}_2\text{O}}^{\text{IDP}}=3.4\times10^6 \text{ cm}^{-2}.\text{s}^{-1}$ (χ^2 minimum value). The long-dashed lines correspond to the overall (SWAS and Odin data) best-fit model ($\Phi_{\text{H}_2\text{O}}^{\text{IDP}}=3.6\times10^6 \text{ cm}^{-2}.\text{s}^{-1}$).



Fig. 10. Odin 2002 data modeled with SL9 models. When p_0 is fixed to 0.2 mbar, the derived q_0 value is 2.0×10^{-7} (solid line) whereas when fixing q_0 to 6.0×10^{-8} , the derived p_0 pressure level is 0.54 mbar (long-dashed lines).



Fig. 11. Overall best-fit models for the SWAS 1999 and 2001 and Odin 2002 observations. Solid lines: SL9 model with $p_0=0.2$ mbar (fixed) and $q_0=1.9\times10^{-7}$; long-dashed lines: SL9 model with $p_0=0.45$ mbar and $q_0=6\times10^{-8}$ (fixed); short-dashed lines: IDP model with a steady infall flux of water $\Phi_{\rm H_2O}^{\rm IDP}=3.6\times10^6$ cm⁻².s⁻¹. The overall best-fit parameter have been obtained from Table 2 and by taking the signal-to-noise ratio of each observation into account. Doing this way, the SWAS 1999 observations have a lower impact on the results than the SWAS 2001 and Odin 2002 observations.



Fig. 12. Evolution of the line shape with time, in the case of a SL9 origin. Vertical distribution of water has been computed with our photochemical model at various dates. Parameters p_0 and q_0 have been set to 0.2 mbar and 1.9×10^{-7} respectively. The spectrum is plotted at the time of SWAS 1999 observations (solid line), Odin 2002 observations (long-dashed lines), in 2007 as observed with the Odin telescope (short-dashed lines). Once all the water deposited by SL9 will be removed by photochemistry, transport and condensation, the remaining water will only be due to the low IDP flux ($\Phi_{H_2O}^{IDP}=4 \times 10^4 \text{cm}^{-2}.\text{s}^{-1}$). The dashed-dotted lines represent the line due to this flux, as it would be observed by Odin. The line resulting from an IDP model ($\Phi_{H_2O}^{IDP}=3.6 \times 10^6 \text{ cm}^{-2}.\text{s}^{-1}$) is plotted for comparison in dotted lines.