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First detection of the 56-μm rotational line of HD in Saturn's atmosphere*

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Abstract. The R(1) rotational line of HD at 56.23 μm has been detected for the first time on Saturn using the Long Wavelength Spectrometer (LWS) on board the Infrared Space Observatory (ISO). The measurements were made using the LWS in Fabry-Perot mode in January 1996 during the ISO performance verification phase. The measured spectrum has been compared with atmospheric models to determine the HD/H_2 abundance ratio. The best model fit to the measured spectrum was obtained with a D/H ratio in hydrogen of 2.3×10^{-5}; D/H values between 1.5×10^{-5} and 3.5×10^{-5} are however also compatible with the data. This result is intermediate between the saturnian value derived from ground-based observations of methane and its deuterated isotope, and the preliminary determination of the jovian D/H ratio measured by the mass spectrometer in the Galileo probe. The initial Saturn measurements reported here will be repeated to improve the signal-to-noise ratio, and LWS observations of HD on Jupiter, Uranus and Neptune will also be made.

Key words: planets and satellites: individual: Saturn – infrared: solar system

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1. Introduction

The accurate determination of the D/H ratio in the giant planets has profound cosmogonical implications. The current best estimate of the D/H ratio in the present-day interstellar medium (ISM) is (1.47 - 1.72)$\times10^{-5}$ (Linsky et al. 1993). The value at the time of formation of the solar system, 4.5 billion years ago, should have been greater than this because deuterium is destroyed in stars. In each planet, the main reservoir of deuterium is molecular hydrogen, and for Jupiter and Saturn, the D/H ratio in H_2 should be representative of the value in the primitive solar nebula because no substantial contribution from ices enriched in deuterium is expected (Hubbard & McFarlane 1980). Measuring D/H in these planets can thus provide an estimate of the value in the ISM when the solar system formed, more precise than that derived from ^{3}He/^{4}He measurements in the solar wind (Geiss 1993). During planetary formation, the hydrogen envelopes of Uranus and Neptune are thought to have been been mixed with volatiles originating from ices which made up the cores of these objects, or from infalling planetesimals. As a result, the HD reservoir would have been strongly enriched in deuterium compared to the protosolar value. Currently available observations are not very precise but suggest that this enrichment did occur (Gautier & Owen 1989). Accurate measurements of the D/H ratio in hydrogen in Uranus and Neptune would permit us to infer, through interior models, the value in ices embedded in the outer part of the solar nebula (Lecluse et al. 1996).

Detection of the quadrupole HD lines at visible wavelengths from ground-based observations is very difficult: they have been measured only in Jupiter, with a poor signal-to-noise ratio (Smith et al. 1989). The deuterium abundance in hydrogen in the giant planets has therefore been inferred from measurements of D/H in methane through the relationships

$$\text{D/H in H}_2 = \frac{1}{2}\,\frac{\text{HD}}{\text{H}_2}\,,$$

$$\text{D/H in CH}_4 = \frac{1}{4}\,\frac{\text{CH}_3\text{D}}{\text{CH}_4}\,,$$

$$\text{D/H in H}_2 = \frac{1}{f}\,\text{D/H in CH}_4\,,$$

where f is the fractionation factor between HD and CH_3D. The CH_3D/CH_4 ratio is however uncertain (Gautier & Owen 1989), and in addition the fractionation factor f depends on rather inaccurate kinetics of isotopic reactions and on the poorly known dynamics of the atmosphere (Lecluse et al. 1996). The recent in situ measurement of the jovian D/H ratio in hydrogen by the mass spectrometer on board the Galileo probe produced a surprisingly high value of $(5\pm2)\times10^{-5}$ (Niemann et al. 1996), in conflict with previous estimates for Jupiter: $(2.0\pm0.8)\times10^{-5}$ (Gautier & Owen 1989); $(1.0 - 2.9)\times10^{-5}$ (Smith et al. 1989).

As initially proposed by Gautier & Bezard (1984) and Bezard et al. (1986), ISO offers a unique opportunity to detect the far-infrared, pure-rotational lines of HD on the four giant planets and thus to determine more directly the HD/H_2 abundance ratios in their atmospheres. A key objective of the LWS observing programme is therefore to search for the R(0) and R(1) lines centred at 112 and 56 μm respectively. At the time of writing, most of these observations have yet to be made. In this work however we present the first detection of the R(1) line on Saturn made in LWS test observations during the performance verification (PV) phase of the ISO mission (Kessler et al., 1996).

2. Observations

The observations were made on January 4 1996, during ISO's 47th orbit. Although these PV phase observations were not made using a conventional Astronomical Observation Template (AOT), the measurement procedure was roughly equivalent to AOT L03 (Clegg et al. 1996). The short-wavelength Fabry-Perot of the LWS was scanned over the range 56.05 to 56.46 μm in steps of 0.00256 μm. The Fabry-Perot was order-sorted by the LWS grating, which has a roughly Gaussian response profile with a FWHM of 0.29 μm. The data were corrected for the grating response profile which was measured separately by observing an unresolved 57-μm line of N III in the planetary nebula NGC7027. The Fabry-Perot response profile, measured before launch on an unresolved far-infrared laser line (Davis et al. 1995), is an Airy function with a resolving power of 8500 (FWHM at 56.23 μm = 0.0066 μm). The spectral sampling interval thus corresponded to 2.6 samples per Fabry-Perot resolution element.

Ionising particle hits on the LWS detectors result in glitches which must be removed from the data stream (Swinyard et al. 1996). To facilitate de-glitching, the observations were taken in fast-scanning mode, whereby one 0.4-second integration was made at each Fabry-Perot position before moving to the next position. Ten independent scans were made in this way, and were de-glitched and averaged. The total integration time per point was thus four seconds. Points for which more than half of the ten individual measurements were discarded by the de-glitching algorithm were rejected as unreliable. After de-glitching, the average usable integration time per point was 2.6 seconds. The data were also corrected for detector dark current and small responsivity drifts, which were monitored by means of the LWS on-board infrared illuminators.

3. Modelling

The HD observations were analysed using a radiative transfer model in which the HD/H_2 mixing ratio was a free parameter. The atmospheric thermal profile of Saturn was taken from Voyager radio-occultation measurements (Lindal 1992). Since the angular diameter of Saturn (16″) was much less than the beam of the LWS (80″), the transfer equation was integrated over the entire planetary disk. At the time of the observations, the inclination angle of the rings was 1.8°, and we have assumed that the contribution of the rings to the emission or absorption was negligible. Saturn's oblateness was also neglected. Continuum opacities in the atmospheric model are due to the absorption induced by H_2–H_2 and H_2–He collisions (Borysow et al. 1985), and to the far-wing opacity contribution of NH_3 rotational lines. Possible additional opacity due to clouds was not considered in this preliminary model. The spectroscopic parameters (line positions, dipole moment, collisional broadening) of the HD R(1) line were taken from Drakopoulos & Tabisz (1987a, 1987b) and Ulivi et al. (1991). The monochromatic model spectrum was convolved with the Fabry-Perot response function (§2).

4. Results and discussion

Since these LWS data are not yet absolutely calibrated, the observations were analysed in terms of the line:continuum ratio. The data are shown in Fig. 1, together with four synthetic spectra corresponding to D/H ratios of 7.5×10^{-6}, 1.5×10^{-5}, 2.5×10^{-5} and 5.0×10^{-5} ; the data and models have all been normalised to a continuum level of 1. The FWHM spectral resolution is indicated at the top of the figure. The R(1) line is clearly detected in absorption. The gaps in the plot correspond to data points which were discarded by the de-glitching procedure. The overall signal-to-noise ratio is not sufficient to confirm the reality of the apparent emmission feature in the centre of the line.

As is clear from the models shown in Fig. 1, both the depth and width of the HD line are sensitive to the HD mixing ratio. We have carried out a chi-squared analysis to determine the D/H ratio which gives the best fit to the data. We adopted a uniform fractional uncertainty of 0.027, derived by calculating

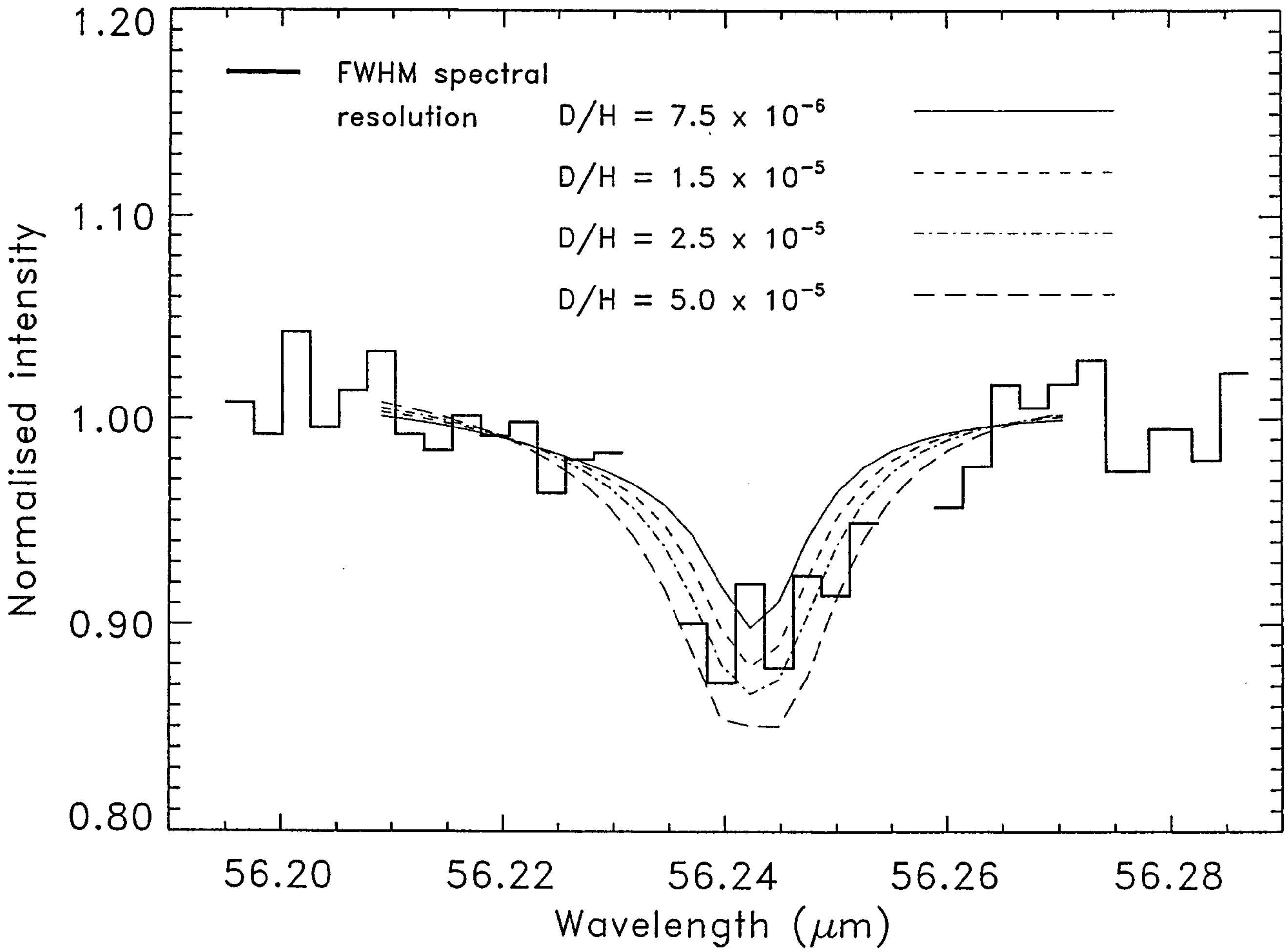

Fig. 1. The Saturn spectrum around 56 μm, measured with the ISO LWS in Fabry-Perot mode. Superimposed are models with different D/H ratios as indicated.

the standard deviation of the continuum data points on each side of the line. The best fit corresponds to a D/H ratio of 2.3×10^{-5}, for which chi-squared is 11.0 with 20 degrees of freedom. We do not regard the quality of these preliminary data as sufficiently high to establish formal statistical errors on the derived D/H ratio; however, from the diagram, values between 1.5×10^{-5} and 3.5×10^{-5} are also compatible with the data. The lower end of this range is compatible with the value in the present-day ISM (Linsky et al. 1993): we therefore cannot decide at this stage whether the Saturn value is definitely higher than the current ISM value.

Our measurement agrees with the ground-based observations of CH_3D on Saturn by Noll & Larson (1990), who derived a D/H ratio in methane equal to 2.1×10^{-5} with an upper limit of 3.45×10^{-5}. Adopting a fractionation factor f of 1.38, as calculated by Lecluse et al. (1996), this corresponds to a D/H value in hydrogen of $(1.5 \pm 1) \times 10^{-5}$, which is consistent with our value.

It is also important to compare our measurement with the recent Galileo probe result on Jupiter. Both Jupiter and Saturn are expected to have a D/H ratio close to the protosolar value (e.g. Hubbard 1974). The relatively higher abundance of ices in Saturn could slightly enhance the D/H ratio with respect to the jovian value, and could certainly not lower it (Hubbard & McFarlane 1980). The jovian D/H value of $(5 \pm 2) \times 10^{-5}$ derived by Niemann et al. (1996) from the Galileo mass spectrometer tends to be higher than our result for Saturn, although consistent within the uncertainties.

Compatibility between the Noll & Larson measurements and the Galileo D/H value would require a fractionation factor between HD and CH_3D no higher than 1.15. Such a low value would imply vertical velocities in the troposphere too high to be physically realistic. It might be that the actual CH_3D/CH_4 ratio is somewhat higher than measured by Noll & Larson (1990), or the lower limit of the Galileo D/H value may not be sufficiently conservative. Indeed, Niemann et al. (1996) propose another indirect estimate of the D/H ratio in Jupiter. The protosolar value derived by Geiss (1993) is proportional to the difference between the $^3He/^4He$ ratios in the solar wind and in meteorites (assuming the latter to represent the protosolar ratio) since deuterium is converted to ^3He in the sun. Niemann et al. consider the solar wind $^3He/^4He$ ratio as correctly measured; but they take the protosolar $^3He/^4He$ ratio to be the value which they measured in Jupiter with the Galileo mass spectrometer. They then obtain D/H = $(3\pm1)\times10^{-5}$ for the solar nebula. Assuming that the jovian D/H ratio is identical to the protosolar value, this is in better agreement with our result than their direct Galileo determination. Furthermore it is also more consistent with the preliminary ratio derived from the ISO SWS measurement of the R(2) HD line on Jupiter of about 2.2×10^{-5} (Encrenaz et al. 1996). However, this approach implicitly assumes that the calibration of the HD measurement by the Galileo mass spectrometer is subject to revision.

New LWS measurements of the HD R(1) line with greatly improved signal-to-noise ratio, and scheduled observations of the 112-μm R(0) line will permit us to improve the accuracy of the determination of the HD mixing ratio in the atmosphere of Saturn, and to derive this important parameter for the other giant planets.

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