LWS MEASUREMENTS OF HD IN THE GIANT PLANETS

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ABSTRACT

The first two rotational lines of HD were measured in all four giant planets using LWS. For Uranus and Neptune, medium-resolution observations of the R(0) line of HD have been analysed using both Mars and Callisto as calibrators. The results for Callisto are promising, but those for Mars are inconsistent for reasons which have not yet been identified. For Jupiter and Saturn, analysis of the high-resolution observations reveals the presence of the R(0) and R(1) lines in both planets.

Key words: ISO – LWS – HD – Giant Planets

1. INTRODUCTION

The accurate determination of the D/H ratio in the atmospheres of the giant planets has profound cosmogonical implications. Deuterium was produced in the big bang, is destroyed by nuclear fusion processes in stellar interiors, and is not regenerated by any known mechanism. The universal D/H ratio should therefore decrease with time as the universe ages, and its value at the time of Solar System formation is a critical test of cosmological models. For Jupiter and Saturn, the present D/H ratio should be representative of the value in the primitive solar nebula since these planets have evolved little since they were formed; for Uranus and Neptune, on the other hand, the HD reservoir should be strongly enriched in deuterium because the hydrogen envelopes are thought to have been been mixed with volatiles originating from ices which made up the cores of these planets (Bézard et al. 1986).

Measurements of the D/H ratio prior to ISO (Kessler et al. 1996) confirm this overall picture, but the error bars are large because indirect methods, the analysis of which involves poorly-determined parameters, were used. The LWS (Clegg et al. 1996) offers the unique opportunity to measure the first two rotational lines of HD, an isotope of molecular hydrogen, in all four giant planets, from which the D/H ratios can be directly determined (Griffin et al. 1996).

2. LWS MEASUREMENTS OF THE HD LINES

The R(0) and R(1) lines of HD occur at 112.07 μm and 56.23 μm respectively. Using the high-resolution mode of the LWS, provided by two Fabry-Perot interferometers in series with a grating (Davis et al. 1995), both lines were measured in Jupiter and Saturn and the R(0) line was measured in Uranus and Neptune. An unconventional scanning procedure was adopted for these measurements: the grating was placed at a fixed position corresponding to the wavelength of the line to be observed, and the Fabry-Perot was then scanned over a large spectral range to fully map the grating response function. This procedure eliminated any uncertainties due to the known nonrepeatability of the grating positioning mechanism (Swinyard et al. 1998). These observations were carried out as Guaranteed Time COIFs and details are provided in Table 1.

In addition, the R(0) line in Uranus and Neptune was measured in the medium-resolution mode of the LWS using the grating alone. These Open Time observations were made using conventional AOTs.

3. URANUS AND NEPTUNE: ANALYSIS

The measured photocurrents for Uranus and Neptune are shown in Figure 1. Two results are immediately apparent: first, there appears to be a strong absorption feature in both planets at the position of the R(0) line; and second, the spectral structure is highly correlated between the two planets. This is to be expected since the photocurrent is a raw measurement from which the instrumental response function has not been removed.

The flux calibration algorithm in the LWS data analysis pipeline employs Uranus as the primary calibrator: it has a smooth, featureless spectrum and was measured frequently during the ISO mission. In the present case, however, it cannot be used for calibration because it contains an HD signature which we wish to measure. Given that a different calibration target was required, the algorithm for analysis of the medium-resolution data can be represented simplistically as follows:

$$F_{\rm source} = \left(\frac{I_{\rm source}}{I_{\rm calibrator}}\right) F_{\rm calibrator}, \qquad (1)$$

Table 1. Details of the LWS observations of the HD R(0) and R(1) lines in the giant planets. "Start" and "Stop" denote the spectral range of the scan, and "Sampling" represents the number of spectral points per resolution element.

	Jupiter R(0)	Jupiter R(1)	Saturn R(0)	Saturn R(1)
Start /μm	111.757	56.1070	111.757	56.1070
Stop /μm	112.405	56.3773	112.405	56.3928
Sampling	4	4	4	4
Resolution /μm	0.0140	0.00703	0.0140	0.00703
Int. Time /s	4.450	5.340	10.680	10.680

	Uranus R(0)	Neptune R(0)
Start /μm	109.363	109.362
Stop /μm	114.485	114.485
Sampling	4	4
Resolution /μm	0.6	0.6
Int. Time /s	42.275	36.935

in which F represents flux and I represents photocurrent. The choice of a suitable calibration target is critical for this procedure. The calibrator must meet three requirements: it must contain no HD, it must be spectrally smooth in the vicinity of the R(0) HD line, and it must be measured by LWS with high S/N. Three calibration objects have been examined: Mars, Callisto and Ceres.

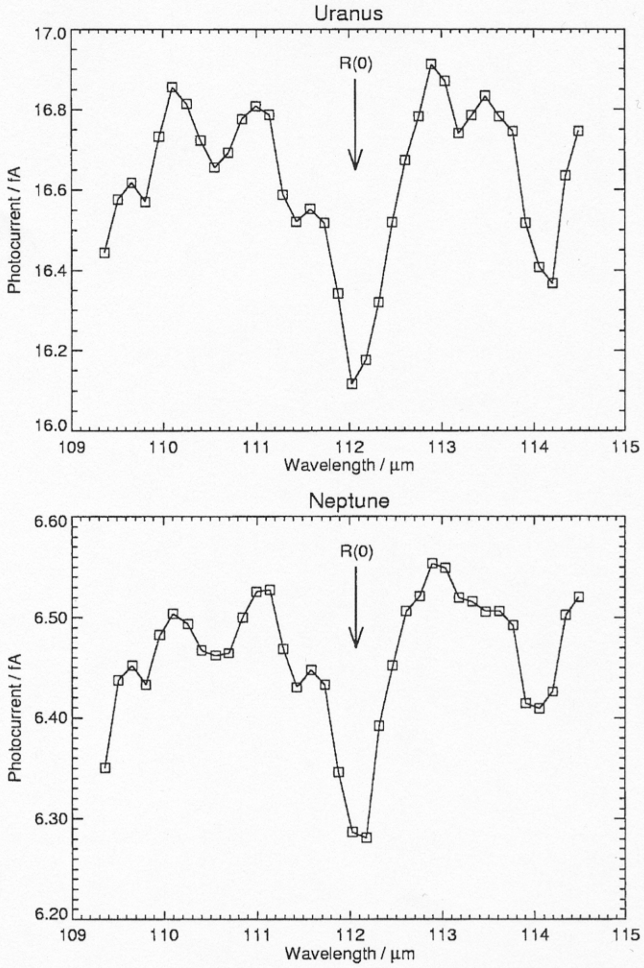

Figure 1. Measured photocurrents for Uranus and Neptune. The position of the R(0) line of HD at 112.07 µm is indicated.

4. URANUS AND NEPTUNE: RESULTS

Mars meets two of the three criteria listed above: it contains no HD and its spectrum was measured with high S/N with the LWS. The disadvantage of Mars is that its spectrum contains absorption features due to H_2O in the vicinity of the R(0) HD line. Since the H_2O profile in the martian atmosphere has been measured with ISO/SWS, however, these features can be accurately modelled (Burgdorf et al. 2000).

Three spectra are shown in Figure 2: a model of the Mars flux, the measured Uranus/Mars photocurrent ratio, and the product of the two (as in Eq. 1). The H_2O absorption lines are clearly evident in the model spectrum. The HD absorption feature seen in the measured Uranus photocurrent, however, vanishes in the ratio against Mars. This result is perplexing and, if confirmed, would have profound repercussions.

To test this result, the analysis was repeated using Callisto as a calibration target. Callisto has a featureless spectrum which makes it superior for this purpose, but the S/N is less than for Mars since the object is colder. The equivalent three spectra are shown in Figure 3. In the Uranus/Callisto photocurrent ratio, the HD absorption feature is apparently preserved, in direct contrast with the result obtained using Mars.

In order to distinguish between these apparently contradictory results, the analysis has been repeated using Ceres as a calibration target. The results are currently inconclusive, and further investigation is in progress.

5. JUPITER AND SATURN: ANALYSIS

Beginning with the measured photocurrents, the algorithm for analysis of the high-resolution data was as follows:

1. The dark current was subtracted. This is a fixed, known quantity for each LWS detector. The dark current is small (negligible) compared with the photocurrent levels for Jupiter and Saturn, which are both extremely bright objects.
2. The measured photocurrents were corrected for responsivity drifts during the observation using a standard routine in LWS Interactive Analysis (LIA) (Sidher et al. 1998).
3. The Jupiter and Saturn measurements were all contaminated by stray light. The stray light contribu-

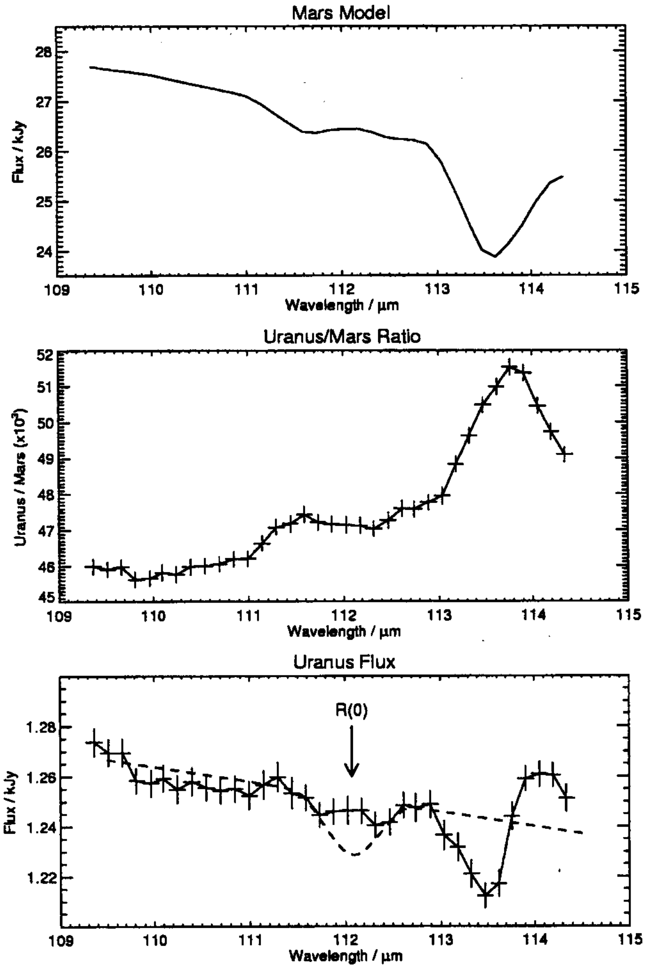

Figure 2. Uranus observations, calibrated against Mars. The Uranus flux was obtained by multiplying the measured photocurrent ratio by the Mars model. The absorption feature at 112.07 µm vanishes in this ratio.

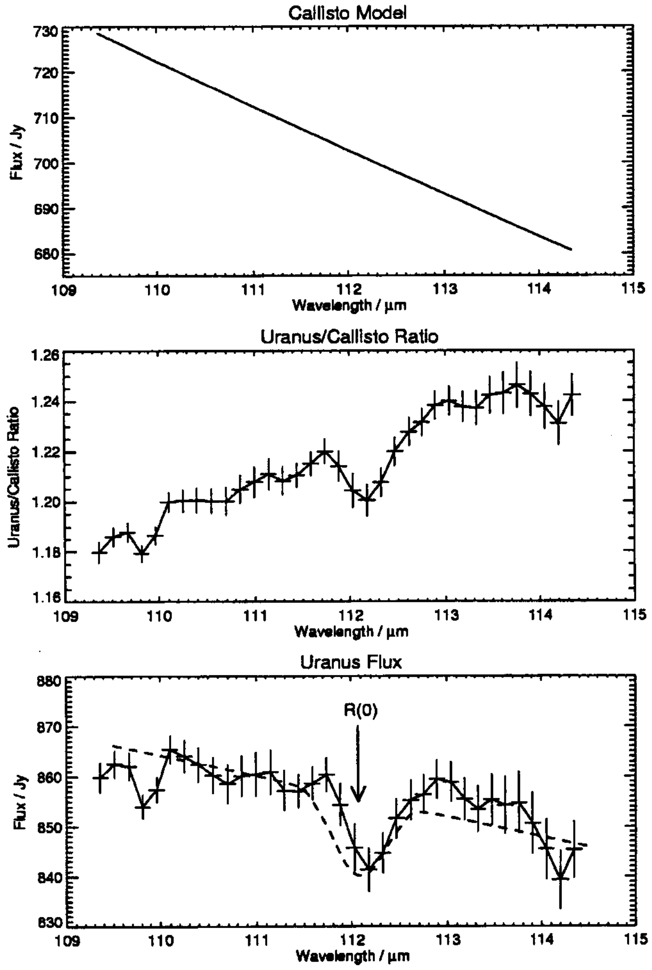

Figure 3. Uranus observations, calibrated against Callisto. The Uranus flux was obtained by multiplying the measured photocurrent ratio by the Callisto model. The absorption feature at 112.07 µm is preserved in this ratio.

tion was measured separately for each planet using a mixed-mode observation. The value so obtained was subtracted from the measured photocurrents.

4. The Jupiter data in particular suffer from a marked difference between forward and reverse scans of the Fabry-Perot. This is caused by the transient response of the detectors to a large, sudden flux change. An empirical algorithm has been developed to correct for this effect.
5. A polynomial was fitted to the photocurrent in order to characterise the grating response profile. This is especially necessary for this dataset to take account of the interferometer non-parallelism introduced by the non-standard scanning procedure.
6. Using the LWS on-board illuminators, the photocurrent was corrected for the absolute responsivity change with respect to the Uranus calibration observations. Only the flash following the observation from the illuminator directly facing the selected detector was used.
7. The nonrepeatability in the LWS grating mechanism necessitates an adjustment of the grating position used when removing its response function. This was done using an interactive procedure in LIA. The same routine performs all of the standard flux calibration operations to determine the measured flux.

Two further steps are required but have not yet been attempted: velocity correction of the wavelength, taking into account the radial velocity of the planet; and removal of high-frequency fringing.

6. JUPITER AND SATURN: RESULTS

The results of this analysis for Jupiter and Saturn are shown in Figures 4 and 5. Synthetic spectra, excluding HD, are also shown: these spectra were calculated for atmospheres composed of H_2, He, NH_3, PH_3 and CH_4.

All four lines have been unambiguously detected for the first time. The R(0) lines in both planets are clearly distorted, however: the origin of this distortion has not

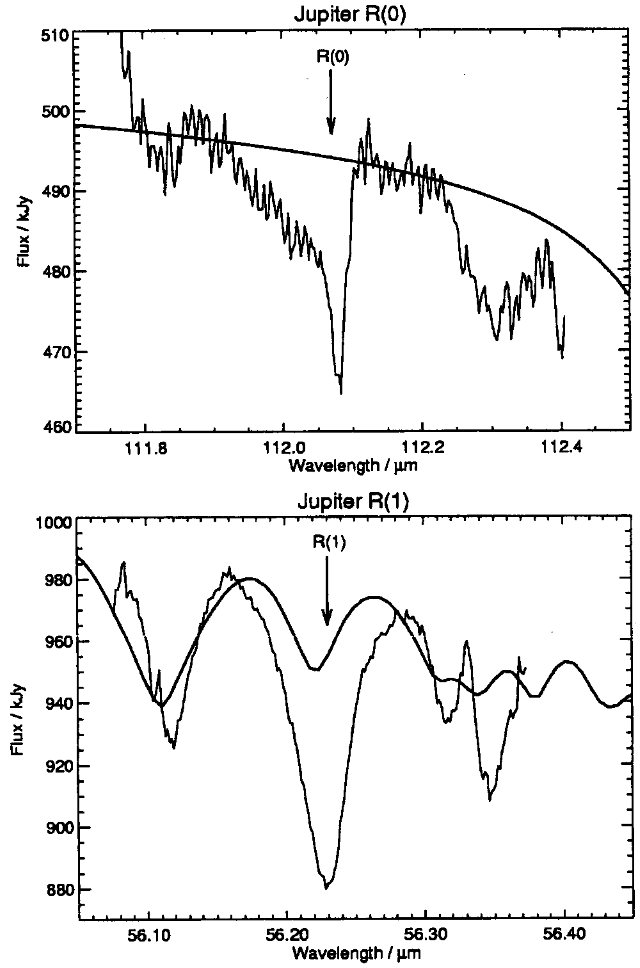

Figure 4. Measured R(0) and R(1) lines of HD in Jupiter. The synthetic spectra do not include HD.

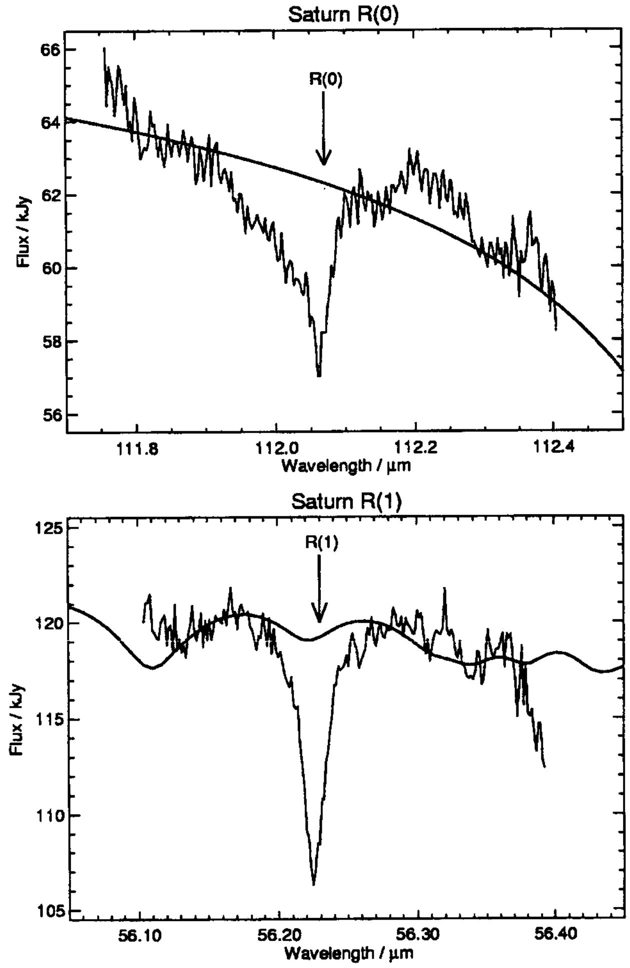

Figure 5. Measured R(0) and R(1) lines of HD in Saturn. The synthetic spectra do not include HD.

yet been identified, but is probably instrumental in origin. One possibility is that the interferometer meshes were not accurately parallel for these observations: PV-phase LWS observations revealed that this effect can introduce an asymmetric distortion into the spectrum. This is an unlikely explanation since there is no indication of non-parallelism in the housekeeping telemetry, but it is under investigation. Further interpretation of the R(0) lines awaits the resolution of this issue.

The R(1) lines are not distorted and, for Saturn in particular, appear to represent high-quality detections. The R(1) line for Jupiter is more difficult to interpret since it falls in the middle of a strong absorption manifold of NH3. Analysis of these results is ongoing.

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