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Ground-based measurements of the 1.3 to 0.3 millimeter spectrum of Jupiter and Saturn, and their detailed calibration

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Abstract

One of the legacies of the now retired Caltech Submillimeter Observatory (CSO) is presented in this paper. We measured for the first time the emission of the giant planets Jupiter and Saturn across the 0.3 to 1.3 mm wavelength range using a Fourier Transform Spectrometer mounted on the 10.4-meter dish of the CSO at Mauna Kea, Hawaii, 4100 meters above sea level. A careful calibration, including the evaluation of the antenna performance over such a wide wavelength range and the removal of the Earth's atmosphere effects, has allowed the detection of broad absorption lines on those planets' atmospheres. The calibrated data allowed us to verify the predictions of standard models for both planets in this spectral region, and to confirm the absolute radiometry in the case of Jupiter. Besides their physical interest, the results are also important as both planets are calibration references in the current era of operating ground-based and space-borne submillimeter instruments.

Keywords

Planets: Jupiter and Saturn; Radio Continuum and Lines: planetary atmospheres; Calibration: millimeter and submillimeter wavelengths

1 Introduction

The importance of Solar System planets as possible calibration references at submillimeter wavelengths is obvious due to the rarity of sufficiently strong and well characterized sources

in this region of the electromagnetic spectrum. However, up to date the brightness of the Solar System planets at submillimeter wavelengths has only been measured at a few frequencies with different telescopes either in very narrow bands (typically less than 1 GHz wide) but with high spectral resolution, or in wider bands (several tens of GHz) but without any spectral resolution. For narrow-band observations, accurate absolute calibration is quite often problematic.

In order to get large spectral coverage across the millimeter/submillimeter range and enough resolution to reveal spectral features of interest in the atmospheres of the Solar System Giant Planets, Weisstein and Serabyn (1996) used a ground-based Fourier Transform Spectrometer (FTS) mounted on the 10.4m dish of the Caltech Submillimeter Observatory. Their work revealed the submillimeter lines of phosphine in the atmospheres of Jupiter and Saturn. Technical details of their original 1996 experiment limited the observations to separate atmospheric windows so that the overall shape of the spectrum across the theoretically accessible 250-980 GHz range could not be obtained. The acquisition of a 1.1 THz low-pass filter for this FTS experiment (see Pardo et al. 2001, 2005) later allowed the simultaneous observation at all frequencies within this range. It is expected that the overall spectrum of Jupiter and Saturn at long wavelengths is dominated by the planets' thermal continuum emission and by H₂ collision induced continuum-like mechanisms. Superimposed on this smooth component, and seen in absorption, are three broad rotational lines of phosphine (mentioned above) and one rotational line of ammonia. The line center of the latter is so close to the strong atmospheric $1_{1,0}-1_{0,1}$ line of ortho-H₂O, centered at 557 GHz, that it cannot be seen from the ground. However, the wings of this line extend across sufficiently transparent atmospheric windows. Frequency resolutions of the order of 1 to 5 GHz, which are ideal to explore these broad planetary spectral features, are easy to obtain with differential paths $\sim 1\text{--}2\text{--}10$ cm in the FTS configuration described in Weisstein and Serabyn (1996). The drawback of the experiment is that the calibration is very challenging over such a large frequency band. The convolution of the telescope's beamshape with the source, the atmospheric transmission curve, and the losses due to imperfections in the telescope's primary dish surface, all change significantly over the target frequency range and, therefore, a quite complex frequency-dependent correction factor needs to be derived and applied.

One of the first systematic attempts to measure the broadband mm/submm spectrum of the Giant Planets was made by Goldin et al. (1997) with a 1.4-m balloon-borne telescope equipped with a multi-band bolometric radiometer operating in four bands centered at 172, 286, 495, and 675 GHz, with bandwidths ranging from 40 to 70 GHz. Unfortunately, the discontinuity of these bands, and the lack of spectral resolution within them, limited the scientific output of the experiment. Nevertheless, their results can be taken as an starting point. Several other observations have been carried out from space, with interesting results despite the small size of the telescope, such as the detection of 557 GHz water emission in the upper atmosphere (maximum pressures around 5 mbar) of both planets (Bergin et al. 2000). Disk-average brightness temperatures at 489 and 553 GHz resulted from these observations which are in disagreement with those of Goldin et al. (1997), thus illustrating how difficult it is to draw conclusions from data at a few frequencies provided by very different experiments (see also Hildebrand et al. 1985, Griffin et al. 1986). An additional

problem for Saturn is the changing temperature due to the effect of the rings, which makes the different data sets incompatible with a single model.

An additional problem to the mentioned calibration issues arises due to the large angular size of Jupiter. In fact, even with a relatively large telescope compared to the experiments mentioned above (10.4 m), the diffraction from the individual panels that make up the telescope's dish affects the planetary measurements (specially for Jupiter) at the highest frequencies (beyond 550 GHz). This is far more problematic than the other effects, but its correction is possible if measurements are obtained for different apparent sizes of the targets, as we will see in this paper.

The goal of this study is twofold. On one hand, the submillimeter observations of the planets are interesting in themselves, because the targetted spectral resolution will allow us to compare the physical and compositional conditions of the atmospheres of Jupiter and Saturn. On the other hand, the results will help in establishing calibration references in the submillimeter range, potentially interesting in the next era' of ground-based and space-borne submillimeter instruments. The observations and data reduction are described in detail in sections 2 and 3, which are the core of this paper since the reduction is particularly complicated due to a combination of atmospheric and instrumental effects. Reference radiative transfer models for Jupiter and Saturn are presented in section 4. The results are discussed in section 5 and, finally, the summary of this work is given in section 6.

2 Observations

Data from several FTS observing runs spanning 1998 to 2001 have been used in this work. They are summarized in Table 1. Observing the planets over several years has a great advantage, as their apparent sizes change and hence their convolution to the antenna main beam and side lobes. This allows for better determination of the additional calibration effects due to the side lobes. Some observations were carried out alongside other measurements with different science goals. For example, both Jupiter and Saturn were observed on July 1st 1999 under dry conditions atmospheric conditions (~0.6 mm of zenith water vapor column, see Pardo et al., 2001). The same night we followed a Lunar eclipse with the FTS (see Pardo et al. 2005).

The basic instrumental setup of the Fourier Transform Spectrometer was described in Serabyn & Weissstein (1996). For the planetary studies presented here, and due to the dry weather conditions that we had in general (see Table 1), we used a high frequency configuration of the FTS consisting of a 20" Winston Cone (light concentrator) and a 1.1 THz low-pass filter installed at the entrance of the bolometer. This configuration allowed us to scan the 300-1100 GHz frequency range.

Saturn and Jupiter data at different epochs listed in Table 1 have been first corrected individually, and then combined together to obtain a single disk-averaged equivalent blackbody temperature curve of each source (as defined in section 3) with uncertainties, the main goal of this study. The total integration time in all cases is a few hours. Depending on that integration time and the sky opacity (determined by the average zenith water column

measured with the same FTS) we determine the relative weight of a given observing session on the final averaged result. The relative weights are listed in the fifth column of Table 1.

3 Broadband calibration and data reduction

Jupiter and Saturn are the targets of this study. Mars has been used as a reference to evaluate the width of the telescope's primary beam at a reference frequency and the rms of the telescope's dish surface. To do this, observations at different apparent sizes were needed and carried out. Other issues, such as the effect of the Earth atmosphere, the ring angle of Saturn, etc..., have to be evaluated and/or corrected. This section is devoted to a detailed description of all calibration and data reduction steps.

3.1 Temperature calibration

For the calibration of the planetary observations, we take reference scans on the Earth's atmosphere (*sky*) at the same elevation of the planet (*sou*), and on an ambient temperature absorber (*hot*). The latter has a temperature T_{hot} . The optical-electrical gain factors are eliminated by taking the following ratio of the Fourier-transformed interferograms S (in Volts/GHz):

$$\mathcal{M}(\nu) = \frac{S_{sou}(\nu) - S_{sky}(\nu)}{S_{hot}(\nu) - S_{sky}(\nu)} \quad (1)$$

Following the explanation in our previous paper (Pardo et al. 2005), the uncorrected antenna temperature of the source is easily obtained from $\mathcal{M}(\nu)$ as:

$$T_a^*(\nu) = \mathcal{M}(\nu) T_{hot} \frac{h\nu / KT_{hot}}{\exp(h\nu / KT_{hot}) - 1} \quad (2)$$

From here, in the case of Jupiter and Saturn, three corrections are needed.

3.2 Atmospheric correction

This correction, already explained in Pardo et al. (2005), is made possible thanks to several atmospheric scans at an off position taken during the planetary observations (every ~20 min). The correction is represented by the function $g(\nu)$ (the antenna temperature definitions are as in Pardo et al. 2005):

$$T_A^*(\nu) = T_a^*(\nu) \cdot g(\nu) \quad g(\nu) = 1 - \Delta t(\nu) e^{\tau_t(\nu)} \quad (3)$$

where $\Delta t(\nu)$ (always a negative number) is the second order correction to the atmospheric transmission derived in Serabyn et al. (1998) for the atmospheric measurements with the same FTS, and τ_t is the total atmospheric opacity at the elevation of the source. This correction is thus straightforward thanks to the reference atmospheric scans obtained shortly after the planetary observations.

3.3 Main-beam and telescope efficiency correction

The second correction is related to the convolution or coupling of the telescope's beamshape to the source (η) divided by the dish efficiency function, because $T_A^*(\nu)$ is related to the disk averaged equivalent blackbody temperature of the source, $T_{EBB,sou}(\nu)$, as follows (Pardo et al., 2005):

$$\left[\exp \left(h\nu / K T_{EBB,sou}(\nu) \right) - 1 \right]^{-1} = \frac{\eta_{sky}(\nu)}{\eta_{sou}(\nu)} \frac{k T_A^*(\nu)}{h\nu} \quad (4)$$

In the lunar measurements presented in Pardo et al. (2005), the ratio $\eta_{sky}(\nu)/\eta_{sou}(\nu)$ could be assumed equal to unity, due to the large apparent size of the Moon, but this is not the case for Mars, Jupiter and Saturn due to their sizes being much smaller, and comparable to the beam. The correction to be applied can change significantly across the wide range of frequencies explored (there is a change of a factor of ~ 4 from the lowest to the highest frequency end). Under the assumption that the CSO telescope has a Gaussian beam with a given Half Power Beam Width at frequency ν_0 $HPBW_{CSO}(\nu_0)$ and that the losses are due to random deviations of the dish surface with respect to the perfect paraboloid shape characterized by an rms $\sigma_{CSOdish}$, we can try to fit a model to a set of measurements towards a reference body to get the values of these two parameters. Note therefore that the results on Jupiter and Saturn will depend on the selected reference and the model used to reproduce its disk-average emission. For this work we use Mars as the reference, and its emission model described in Rudy et al. (1987). Figure 1 shows four different FTS measurements of Mars in terms of $T_A^*(\nu)$ (atmosphere corrected only), with the planet at significantly different apparent diameters (4.63'' and 4.73'' on Nov/3/1998 and Dec/11/2000, 11.46'' on Jul/1/1999, and 18.45'' on May/26/2001), and the best η_{Mars} model fit for all of them simultaneously in the $[HPBW_{CSO}(230 \text{ GHz}), \sigma_{CSOdish}]$ space. The model takes into account the disk-averaged brightness temperature of Mars for each date and considers that the portion of the beam that does not couple with the planet ($1 - \eta_{Mars}$) receives the Cosmic Background Radiation at 2.73 K. It can be seen in Figure 1 that this is critical to correctly reproduce the observations when Mars is very small. The fact that we have very similar data from two different epochs where the apparent size of the planet was around 4.7'' proves the consistency of the observational procedures and their analysis. The best-fit $HPBW_{CSO}(230 \text{ GHz})$ of 32'' is in good agreement with the expected beam size for a 10.4 meter telescope, and the best-fit $\sigma_{CSOdish}$ of 35 μm is only slightly worse than the holography measurements of the dish surface cited by Leong et al. (2006). The latter measurements are limited to a frequency range of 230-460 GHz whereas ours extend up to 950 GHz, so this might be the reason for the discrepancy.

3.4 Effect of the error beam

3.4.1 The model—Jupiter typically presents an apparent size that is larger than the main beam of the CSO telescope at its operating frequencies. In addition, it becomes evident that the error beam starts to noticeably couple with the planet at frequencies above 550 GHz. The simplest way to evaluate this effect, and so far the only one used in our analysis, is to consider that the telescope beam consists of two Gaussians, a narrow one for the main beam

(*MB*) and a wider one that arises from diffraction from the individual panels that make up the segmented mirror, that we will call error beam (*EB*). The addition of the error beam to the main lobe means that the latter has to be multiplied by a factor <1 in order to retrieve the same coupling that fitted the results found for planets smaller or comparable to the main beam (the case of Mars presented above). Therefore, the coupling (η) to a large planet (*LP*), such as Jupiter, will be:

$$\eta_{LP}(\theta, \nu) = A \cdot \mathcal{G}[\theta, \theta_{MB}(\nu)] + \mathcal{G}[\theta, \theta_{EB}(\nu)] \quad (5)$$

where $\mathcal{G}$ are normalized Gaussian beams, both of them a function of θ (the angle from the disk centre), with half power widths $\theta_{MB}(\nu)$ and $\theta_{EB}(\nu)$ respectively. The parameter A depends on θ_{EB} as we will see. In fact, it is obvious that if $\theta_{EB} \rightarrow \infty$ then $A \rightarrow 1$ or, in other words, when the error beam does not affect the analysis (the case of Mars seen above) the coupling is well described by a single Gaussian with the HPBW derived using Mars ($\theta_{MB} = 32''$ at 230 GHz, see above). However, for a given $\mathcal{G}[\theta, \theta_{EB}(\nu)]$, the following condition has to be verified for a small planet of apparent size θ_{SP} :

$$\int_{-\theta_{SP}/2}^{+\theta_{SP}/2} [A \cdot \mathcal{G}(\theta, \theta_{MB}) + \mathcal{G}(\theta, \theta_{EB})] \partial\theta = \quad (6)$$

$$= \int_{-\theta_{SP}/2}^{+\theta_{SP}/2} \mathcal{G}(\theta, \theta_{MB}) \partial\theta \quad (7)$$

from which we can get a value for A as a function of θ_{EB} . As a consequence, the only unknown to determine the function $\eta_{LP}(\nu)$ is therefore $\theta_{EB}(\nu_{ref})$ but this is impossible to determine using as a reference a planet that is too small. But even if the planet is large enough (typically the apparent size of the reference planet should exceed $2\theta_{MB}$ across a significant part of the frequency range), the value of $\theta_{EB}(\nu_{ref})$ can be constrained only if we have measurements at different apparent sizes as we will explain below.

3.4.2 Strategy to get θ_{EB} —Since we have measurements of Jupiter at different sizes ranging from $37''.7$ to $48''.3$ we can establish the value of θ_{EB} at a reference frequency by minimizing the error bars on $T_{EBB, Jupiter}(\nu)$ after an analysis that consists of the following steps:

1. We smooth the raw data to 2 GHz resolution.
2. We apply individually for each observation date the atmospheric, error beam and source coupling corrections, using the corresponding atmospheric transmission spectrum (measured) and planet size (assuming a given $\theta_{EB}(\nu_{ref})$). This way, we obtain a set of $T_{EBB}(\nu)$ spectra for the different dates (or apparent sizes). If the assumed $\theta_{EB}(\nu_{ref})$ is correct, and we exclude other sources of error, the resulting $T_{EBB}(\nu)$ for the different dates should be constant for a planet that does not display any temporal variability at the scanned frequencies. If $\theta_{EB}(\nu_{ref})$ is not

correct, there would be some dispersion in the results and this dispersion will be larger as $\theta_{EB}(\nu_{ref})$ departs more and more from the true value.

3. We average the θ_{EB} corrected data using the weights listed in Table 1 for each observing date in order to obtain a time-averaged $T_{EBB}(\nu)$ spectrum. Then we calculate a weighted σ for each frequency point from the dispersion of the corrected data at the different dates. This weighted σ should reach a minimum when $\theta_{EB}(\nu_{ref})$ is the correct one, as follows from 2.
4. Therefore, the coupling of a large planet to the error beam will be solved by minimizing the weighted σ resulting from the proposed analysis. There is just one consideration to make: The problem of the secondary lobes affects the CSO Jupiter data only above 550 GHz. Therefore the range of $\theta_{EB}(\nu_{ref})$ to explore should not affect the analysis below that frequency. Too small values of $\theta_{EB}(\nu_{ref})$ will result in shapes of the spectrum below 550 GHz that are obviously incorrect.

This scheme is expected to eliminate inconsistencies in the overall shape of the spectrum across the entire ~200-950 GHz range. However an absolute calibration is extremely difficult given the number and complexity of the corrections that have to be applied to the raw data. For this reason, we only first aimed at presenting the results in terms of flux ratio with respect to a reference frequency that is chosen to be below 550 GHz (not affected by the error beam problem) and just in between the lowest two PH₃ lines, so that the impact of those lines on the flux is minimal. However, the comparison in absolute terms turns out to be quite good for Jupiter.

Also note that the disk-average Saturn's $T_{EBB}(\nu)$ changes significantly with ring angle in absolute terms whereas the impact is less important in terms of flux ratio. Let's consider that the ring is edge-on and that there is a line that absorbs 10% of the continuum (C_{disk}) at the line center. Now let's consider that the ring obscures 10% of the disk and that the continuum flux from the ring is only 10% of that of the disk. For the line considered we would have this continuum Level:

$$0.9 \cdot C_{disk} + 0.1 \cdot (0.1 \cdot C_{disk}) = 0.91 \cdot C_{disk} \quad (8)$$

and, at the center of the line:

$$0.9 \cdot (0.9 \cdot C_{disk}) + 0.1 \cdot (0.1 \cdot C_{disk}) = 0.82 \cdot C_{disk} \quad (9)$$

Therefore, when we have the rings edge-on the line-to-continuum ratio at the center of the line is 0.9, whereas in the second case the ratio is: $0.82/0.91=0.9011$. The difference in the ratio is very small even if the difference in flux from the disk and rings is large. This result changes only very slightly if we consider the emission from the fraction of the rings that appears outside the disk. If we look only at flux ratios we can use the same calibration for Saturn as for Jupiter. In other words, a comparison of our data to a Saturn model that neglects the rings is possible in relative terms.

4 Reference models

4.1 Radiative transfer

The submillimeter continuum of Jupiter and Saturn probes the upper troposphere, at regions around the 1 bar level. Superimposed on this continuum, molecular signatures of NH_3 and PH_3 are observed as broad tropospheric absorption lines. In fact, the opacity of the submillimeter continuum is dominated by NH_3 and PH_3 lines and their far wings, but the collision-induced absorption terms of hydrogen with the main atmospheric compounds (H_2 - H_2 , H_2 -He, and H_2 - CH_4) are also significant at high frequencies.

We have modeled the submillimeter spectrum of Jupiter and Saturn using a line-by-line radiative transfer code (Moreno et al., 2001), assuming a spherical geometry. The JPL molecular database (Pickett et al., 1998) was used for the spectroscopic data. The collision-induced absorption of H_2 - H_2 , H_2 -He and H_2 - CH_4 , were computed using the codes developed by Borysow and Frommhold (1986) and Birnbaum et al. (1996). For the ammonia line, we have used a Van-Vleck and Weisskopf (1945) lineshape. This lineshape is better suited to model the continuum-like absorption in the mm/submm domain than the Ben-Reuven formalism (de Pater and Massie 1985).

4.1.1 Jupiter modeling—The thermal profile used for the troposphere is the one retrieved by Lindal et al. (1981), and for the stratosphere it is that derived by Kunde et al. (1982). The mole fractions adopted for H_2 , He and CH_4 are 0.8622, 0.136 and 0.0018, respectively (Niemann et al., 1998). The vertical distribution of ammonia retrieved by Kunde et al. (1982) was used for pressures lower than 1 bar. Solar abundance for NH_3 was considered at higher pressure levels, but it does not influence the mm/submm continuum-like absorption. The vertical distribution of PH_3 is the one retrieved by Weisstein and Serabyn (1996).

4.1.2 Saturn modeling—The thermal profile used for the troposphere is the one retrieved by Lindal et al. (1985), and for the stratosphere it is that derived by Courtin et al. (1984). The vertical distributions of NH_3 and PH_3 are those retrieved by Courtin et al. (1984) and by Orton and Serabyn (2001), respectively. We note that a slightly different PH_3 vertical distribution - for example, that retrieved with Cassini/CIRS instrument (Fletcher et al. 2007) could probably also fit the observed spectrum within the error bars.

The rings were not taken into account to compute the synthetic spectrum. The impact of the rings on the brightness temperature (lowering it) should be more evident with increasing frequency (i.e. decreasing the telescope's beam size), and increasing ring inclination angle. In our case, when the HPBW is larger than the planet angular diameter (i.e. at $\nu < 400$ GHz), we estimated a possible overestimation of 5% of the modeled brightness temperature but the comparison with the data has been done in relative terms because the impact of the rings is greatly reduced as explained in section 3.4.2.

5 Results and discussion

Figures 2 and 3 show the different data reduction steps for our Jupiter and Saturn FTS measurements, following all the calibration steps explained above. The resulting value of θ_{EB} (225 GHz) (the same for both planets, obviously) is $240''$. The obvious interpretation is that this value corresponds to the error beam, introduced earlier, due to the diffraction limit of the individual panels that make up the segmented mirror. Since those panels have a diameter ~ 9 times less than that of the primary dish, the value found for θ_{EB} seems to be perfectly reasonable. We have calculated the rms of the final reduced Jupiter spectrum (curve 4 in figure 2, at 1 GHz resolution) to quantify the quality of the data: 3.8 K at $\nu < 550$ GHz, 1.2 K at $550 \text{ GHz} < \nu < 750$ GHz, and 1.4 K at $750 \text{ GHz} < \nu < 950$ GHz.

The final reduction is compared to model results obtained as described in sections 4.1.1 and 4.1.2. The effect of the error beam for Jupiter and Saturn follows the expected behavior, i.e., for Jupiter it is much larger and starts at smaller frequencies than for Saturn due to Jupiter's larger apparent size. The dispersion is larger in Saturn, also as expected, due to the variability introduced by the rings in the absolute measurements. To provide a reference, the model gives a disk average $T_{EBB, Saturn}(400 \text{ GHz}) = 130.06$ K, without rings. The phosphine lines that were first presented by Weisstein and Serabyn (1996) are also detected here, with the advantage that now the shape can be followed over a much wider frequency range. In the case of Jupiter it appears that the wings of the NH_3 line are now detected (its line center cannot be seen due to very strong atmospheric absorption of atmospheric water vapor). The comparison to the model seems particularly good for Jupiter, with a nice coincidence even in absolute terms.

6 Summary

The first 0.3-1.3 mm spectra of Jupiter and Saturn have been obtained with a consistent calibration across the entire wavelength range. The results reveal the combined contributions of the main mechanisms that play a role in the radiative transfer through these atmospheres at those wavelengths: the lowest rotational transitions of phosphine and ammonia as well as the $\text{H}_2\text{-H}_2$, $\text{H}_2\text{-He}$, and $\text{H}_2\text{-CH}_4$ collision-induced absorption mechanisms. Most of the paper describes the extensive calibration process but the final spectra are very valuable as a complement to the FIR data obtained from space with smaller telescopes, and provide a well-calibrated brightness temperature spectrum against which models and further measurements can be compared.

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Figure 1.

Atmosphere corrected FTS scans on Mars at four different epochs, and best fit model in the $[\text{HPBW}_{\text{CSO}}(230 \text{ GHz}), \sigma_{\text{CSOdish}}]$ space using the Rudy et al. (1987) emission model as reference.

Figure 2.

Jupiter data reduction steps: 1 (histogram): calibrated, atmosphere corrected and averaged spectrum corresponding to all Jupiter measurements listed on Table 1; 2 (histogram): Main beam and dish rms correction on 1; 3 (dark histogram+gray area): Error beam correction on 2, with uncertainties; 4 (dashed curve): Model described in section 4.1.1 plotted for comparison. All curves 1-4 have their vertical scale on the left. The dotted curve (5, vertical scale on the right) represents the average atmospheric transmission of the Jupiter measurements of Table 1.

Figure 3.

Saturn data reduction steps: 1 (histogram): calibrated, atmosphere corrected and averaged spectrum corresponding to all Saturn measurements listed on Table 1; 2 (histogram): Main beam and dish rms correction on 1; 3 (dark histogram+gray area): Error beam correction on 2, with uncertainties; 4 (dashed curve): Model described in section 4.1.2 plotted for comparison. For curves 1-4 (vertical scale on the left) only a relative flux comparison is possible due to the presence of the rings and their changing inclination through the different observation dates. The dotted curve (5, vertical scale on the right) represents the average atmospheric transmission of the Saturn measurements of Table 1.

Table 1

Description of the data sets used in this work. The zenith water vapor columns have been determined by fitting atmospheric transmission FTS scans as described in Pardo et al. (2001, 2005).

Source	(Epoch) UT date	Apparent size (")	Atm. zenith water column	Weight (%) in final spectrum	Ring angle (for Saturn only)
Jupiter	(1) Nov 3, 1998	45.96	0.86 mm	12.89	
Jupiter	(2) July 1, 1999	37.7	0.60 mm	33.76	
Jupiter	(3) Dec 11, 2000	48.27	0.52 mm	25.77	
Jupiter	(4) Nov 29-30, 2001	45.98	0.49 mm	27.58	
Saturn	(1) Nov 2-3, 1998	20.00	0.86 mm	19.20	-15.0 °
Saturn	(2) July 1, 1999	17.01	0.60 mm	49.33	-20.4 °
Saturn	(3) Dec 11, 2000	20.24	0.52 mm	16.00	-23.3 °
Saturn	(4) Nov 29-30, 2001	20.56	0.49 mm	15.47	-25.9 °
Mars	(1) Nov 3, 1998	4.63	0.86 mm		
Mars	(2) Jun 29-Jul 2, 1999	11.51	0.60 mm		
Mars	(3) Dec 11, 2000	4.73	0.52 mm		
Mars	(5) May 24-27, 2001	18.32	2.25 mm		