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ISO LWS measurement of the far-infrared spectrum of Saturn*

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Abstract. The spectrum of Saturn from 43 to 197 μm was measured with the ISO Long Wavelength Spectrometer (LWS) during the performance verification phase of the mission. The measurements were made using the LWS in grating mode, with spectral resolutions of 0.29 μm from 43 to 90 μm and 0.6 μm from 90 to 197 μm. The spectrum was compared with an atmospheric radiative-transfer model and four results were obtained: first, the slope of the measured continuum within each detector passband is in good agreement with the model; second, absorption features due to ammonia and phosphine were unambiguously detected, and all detected features were attributed to these two molecules; third, the ammonia absorption features agree reasonably well with the nominal model (based on Voyager IRIS measurements); and fourth, the phosphine absorption features disagree with the nominal model. Superior agreement with the measured spectrum was obtained with a modified PH_3 profile in which the tropospheric mixing ratio was increased to 7×10^{-6} and the cutoff due to photodissociation was lowered to 300 mbar. These results are based on trial observations during performance verification of the LWS, and provide an indication of the results we expect to obtain when the spectrum of Saturn is measured comprehensively later in the mission.

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1. Introduction

The far infrared spectral region offers great promise for the study of planetary atmospheres: not only is it the region of maximum thermal emission, but it also contains rotational transitions due to many of the major and minor molecular constituents which serve as valuable probes of the physical and chemical atmospheric conditions. Observations at these wavelengths have historically been constrained, however, by the prohibitive opacity of the terrestrial atmosphere and by photon noise associated with the telescope and instrument optics. As a result, the far infrared has remained, until ISO, a relatively unexplored region of the electromagnetic spectrum.

We present an initial measurement of the spectrum of Saturn from 43 to 197 μm, made with the Long Wavelength Spectrometer (LWS) instrument (Clegg et al. 1996) on the Infrared Space Observatory (ISO) satellite (Kessler et al. 1996). A comprehensive set of Saturn measurements is scheduled for later in the ISO mission, including a high signal-to-noise spectrum at medium resolution ($\lambda/\Delta\lambda \simeq 200$) over the entire 43–197 μm range, and a number of spectra at high resolution ($\lambda/\Delta\lambda \simeq 8000$) over smaller ranges to investigate specific spectral features. The present analysis provides an early indication of the results which are likely to be obtained when this full set of Saturn spectra is acquired.

2. Observations and Data Analysis

The observations were made on 10 December 1995 during ISO's 27th orbit, and were amongst the first test measurements carried out with the LWS. The measurement procedure was similar to Astronomical Observation Template L01 (Clegg et al. 1996). The LWS grating was scanned from one end of its range to the other and then back again for a total of two scans. Each scan comprised 300 steps of the grating mechanism, the step size corresponding to a spectral sampling rate of 4 samples per resolution element. The integration time was set to 0.25 s per sample, of which 0.1 s were discarded during data processing as is standard with LWS data. The total integration time per point was thus 0.3 s. The two scans were averaged and corrected for detector dark current and small responsivity drifts, which were monitored by means of the LWS on-board illuminators.

Although these measurements were made with reduced detector bias because of the high flux from Saturn, there is nevertheless some evidence of nonlinearity in the spectra. We have therefore not attempted an absolute flux calibration at this stage. To remove the instrument response function, the Saturn data were divided by a grating-mode spectrum of Uranus measured by the LWS in March 1996, for which a model spectrum was assumed (Swinyard et al. 1996).

3. Modelling

The observations were analysed using a multilayer, radiative-transfer model of the saturnian atmosphere. The atmospheric thermal profile was taken from the Voyager 2 radio-occultation measurements (Tyler et al. 1982). Since the angular diameter of Saturn (16″) was much smaller than the LWS beam (80″), the transfer equation was integrated over the visible hemisphere. The oblateness of the planet was neglected. At the time of the observations, the inclination angle of the rings was 2.5°, and we have assumed that the contribution of the rings to the emission spectrum was negligible.

The primary sources of continuum opacity at these wavelengths are the H_2–H_2 and H_2–He collision-induced absorptions. The assumed mixing ratios for H_2 and He were 0.965 and 0.03 respectively (Conrath et al. 1984) and the opacities were calculated using the formulations of Borysow et al. (1985, 1988).

Ammonia and phosphine also contribute to the opacity through their rotational transitions. The ammonia mixing ratio was assumed to be 10^{-4} in the deep troposphere, and constrained by saturation above the 1.5 bar level. The phosphine mixing ratio was assumed to be 1.4×10^{-6} in the troposphere, with a cutoff at 5 mbar to represent photodissociation (Kaye & Strobel, 1983). Both of these distributions (Fig. 1) were derived by Courtin et al. (1984) from Voyager IRIS spectra. The line parameters for both molecules were taken from the 1992 GEISA compilation (Husson et al. 1994), and the lines were modelled using the Voigt line shape. These are the same input parameters used by Bézard et al. (1986) in their comprehensive study of the far-infrared spectra of Jupiter and Saturn, to which we refer herein as the “nominal model".

Finally, the calculated spectrum was convolved with a Gaussian distribution of width equal to the LWS grating-mode resolution to facilitate direct comparison with the measured spectrum.

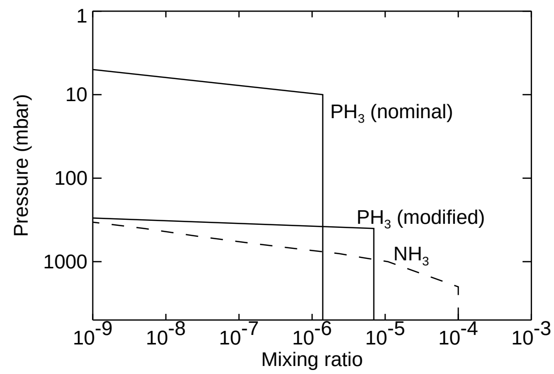

Fig. 1. Mixing ratio vertical profiles for NH_3 and PH_3. The NH_3 and nominal PH_3 profiles are from Courtin et al. 1984; the modified PH_3 profile provides a better fit to the detected PH_3 features

4. Results and Discussion

The nominal model spectrum of Saturn is shown in Fig. 2. The spectrum is characterised by a continuum due to the H_2 collision-induced opacity, punctuated by absorption features of ammonia and phosphine. Also shown in Fig. 2 are the measured spectra from the ten LWS detectors: each Saturn:Uranus ratio (§2) was scaled to match the synthetic spectrum at the centre of the corresponding passband, and offset from the model by an arbitrary amount (different for each detector) for clarity of presentation. We emphasise that the measured spectra have not been calibrated, that the ordinate scale applies only to the model spectrum, and that the mismatch between adjacent detectors is not real.

Three results are immediately apparent. First, the slope of the continuum within each passband is in reasonable agreement with the model, particularly at the shorter wavelengths ($<100\,\mu$m). The continuum slope at longer wavelengths is distorted by broad phosphine absorption features, as discussed below. Second, most of the predicted features due to ammonia and phosphine have been unambiguously detected, many for the first time, and the veracity of the detections is demonstrated by the simultaneous appearance of many features in more than one detector passband. Finally, all of the obvious features in the measured spectra can be attributed to these two molecules.

Two of the individual spectra have been selected for further study. The measured and modelled line-to-continuum ratios for detectors SW5 and LW5 are shown in Figs. 3 and 4 respectively. The nominal model line-to-continuum ratios (top curve in both figures) were obtained by ratioing the model spectrum (Fig. 2) against a theoretical continuum, determined by running the atmospheric model with no ammonia or phosphine included. The measured line-to-continuum ratios (bottom curve in both figures) were obtained by ratioing against the same theoretical continuum. Finally, the curves in Figs. 3 and 4 are offset by an arbitrary amount for clarity of presentation.

Ammonia. The two ammonia lines near 84 μm are reasonably well matched by the nominal model (Fig. 3). The fit is not equally good, however, for all of the ammonia features in

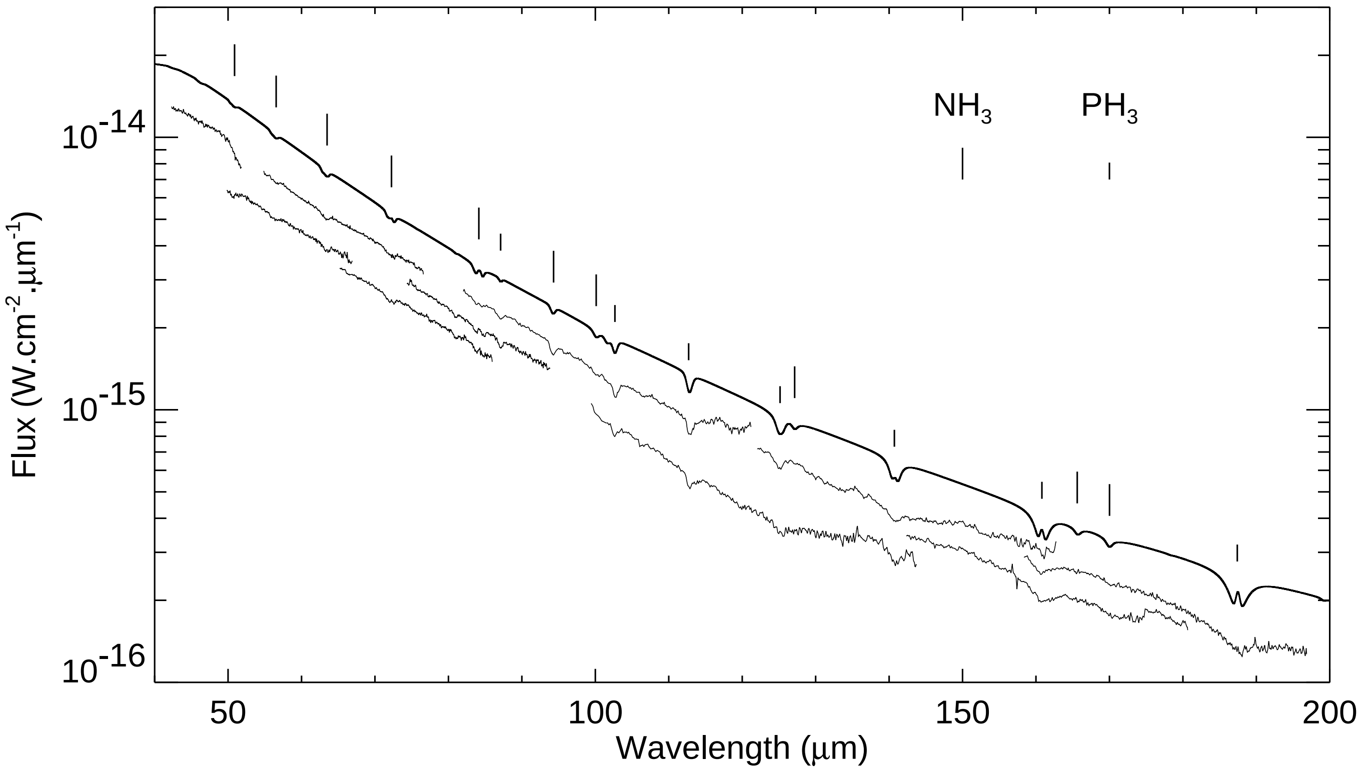

Fig. 2. Synthetic and measured spectra of Saturn. The synthetic spectrum, to which the ordinate scale applies, corresponds to the nominal model. The NH_3 and PH_3 features are indicated. The measured spectra are shown separately for each detector: they have been arbitrarily scaled and offset from the model spectrum to show the concident detection of NH_3 and PH_3 features in more than one detector

Fig. 2: the line at 94 μm, for example, is deeper than predicted, while the lines at 166 and 170 μm (Fig. 4) are only marginally detected. The acquisition of a complete Saturn spectrum later in the mission, with a much longer integration time and higher signal-to-noise, will provide an opportunity to resolve these discrepancies. The agreement between the ammonia features in the nominal model and in the measured spectrum is nevertheless encouraging.

Phosphine. In contrast, the phosphine features in the nominal model clearly do not agree with the measured spectrum. The model lines at 81 μm and 87 μm (Fig. 3) are too shallow, while those at 161 μm and 187 μm (Fig. 4) are too deep and feature prominent emission cores due to stratospheric PH_3. The absence of emission cores in our data indicates a depletion of phosphine in the saturnian stratosphere relative to the nominal model. Further, the lines at 161 μm and 187 μm are much broader than calculated, indicating an enhancement of tropospheric phosphine relative to the nominal model. Referring to Fig. 2, the features at 125 μm, 141 μm, 161 μm and 187 μm are all so broad that they distort the slope of the neighbouring continuum.

We therefore ran the atmospheric model for a second phosphine abundance profile meeting the above requirements: we used a tropospheric mixing ratio of 7×10^{-5} (5 times the nominal value), with a hard cutoff at 300 mbar instead of 5 mbar. We refer to this profile as the “modified model" hereafter. The abundance profile is shown in Fig. 1 and the calculated line-to-

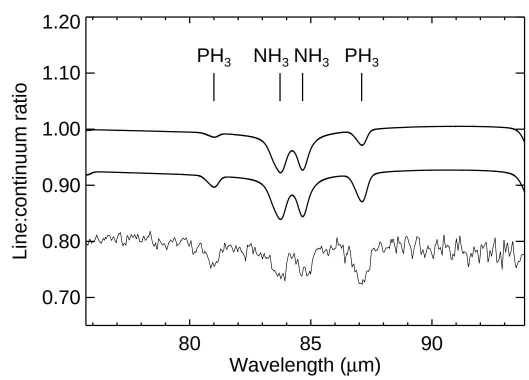

Fig. 3. Line:continuum ratios for detector SW5. The top curve is the nominal model, the middle curve is the modified model, and the bottom curve is the measured line:continuum ratio

continuum ratios for the modified profile are shown in Figs. 3 and 4 (middle curves). For all four PH_3 features in these figures, the fit is much improved by these two changes to the phosphine vertical distribution.

The discrepancy between this result and the nominal profile, obtained by Courtin et al. (1984) from analysis of Voyager IRIS spectra at 8.9 μm and 10 μm, is as yet unresolved. Courtin et al. required a cutoff at 5 mbar in order to match the Q-branch of the ν_4 fundamental of PH_3 at 10.1 μm, but the absence of

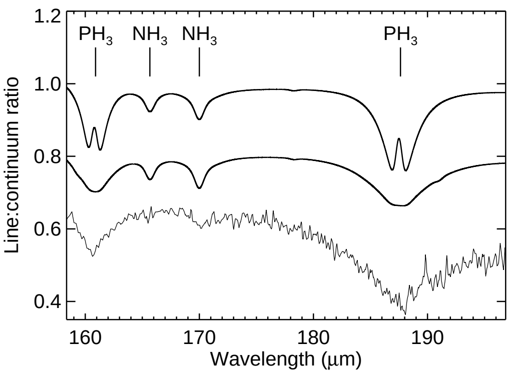

Fig. 4. Line:continuum ratios for detector LW5. The top curve is the nominal model, the middle curve is the modified model, and the bottom curve is the measured line:continuum ratio

emission cores in our spectrum is unambiguous within the error limits imposed by the measurement noise. Weisstein & Serabyn (1994) observed the PH_3 J=1–0 line at 266 GHz using a Fourier transform spectrometer on the Caltech Submillimeter Observatory. They also observed no emission core, and from comparison of their measured line profile against a radiative-transfer model they inferred a tropospheric mixing ratio of 3×10^{-6} and a cutoff between 13 and 140 mbar. This represents a deviation from the nominal model in the same sense as we have obtained with the LWS data.

Although the modified PH_3 profile produces a good fit to the PH_3 features in the measured spectrum, there are several potential sources of systematic error which remain to be considered. These include the effect of atmospheric aerosols on the continuum opacity and the sensitivity of the model spectrum to uncertainties in the assumed temperature profile, the PH_3 line widths, and the line width temperature coefficients. It is, however, beyond the scope of this preliminary analysis to consider these in detail.

5. Conclusions

We have measured the spectrum of Saturn from 43 to 197 μm. Several results were obtained on the basis of comparison against a theoretical radiative-transfer model of the saturnian atmosphere: first, the slope of the continuum within each detector passband is in good agreement with the model; second, absorption features due to ammonia and phosphine were unambiguously detected, and all detected features were attributed to these two molecules; third, the ammonia absorption features agree reasonably well with the nominal model based on Voyager IRIS measurements; and fourth, the phosphine absorption features disagree with the nominal model. Superior agreement with the LWS spectrum was obtained using a modified PH_3 profile in which the tropospheric mixing ratio was increased to 7×10^{-6} and the cutoff due to photodissociation was lowered to 300 mbar. These results are preliminary and we therefore regard the quantitative results as tentative, but they provide a good indication of the results we expect to obtain when the spectrum of Saturn is measured comprehensively later in the mission.

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