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Letter to the Editor

Broad-band spectroscopic detection of the CO J=3–2 tropospheric absorption in the atmosphere of Neptune

D.A. Naylor[1], G.R. Davis[2], M.J. Griffin[3], T.A. Clark[4], D. Gautier[5], and A. Marten[5]

[1] Department of Physics, University of Lethbridge, Lethbridge, Alberta, Canada T1K 3M4
[2] Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 0W0
[3] Department of Physics, Queen Mary and Westfield College, Mile End Road, London E1 4NS, UK
[4] Department of Physics and Astronomy, University of Calgary, Alberta, Canada T2N 1N4
[5] Laboratoire d'Astronomie Infrarouge, Observatoire de Paris, Section de Meudon, F-92195 Meudon Principal Cedex, France

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Abstract. We report the first detection of the CO J=3→2 absorption feature in Neptune. The broad tropospheric absorption line was measured in May 1993 using a polarizing Fourier transform spectrometer on the James Clerk Maxwell Telescope. The measured width and depth are in general agreement with the model of Marten et al. (1993), supporting their suggestion that carbon monoxide is transported upward into the stratosphere from the deep Neptunian atmosphere.

Key words: Planet and satellites: Neptune – Radio continuum: solar system

1. Introduction

The recent and unexpected discovery of CO in the stratosphere of Neptune and its absence in Uranus (Rosenqvist et al., 1992; Marten et al., 1993) reinforce the differences between the atmospheres of these planets revealed by the Voyager observations. These authors estimated stratospheric CO mixing ratios of $(6.5\pm3.5)\times10^{-7}$ and $(1.2\pm0.5)\times10^{-6}$, respectively. These results have important implications for the source of CO in Neptune: if the CO abundance is much smaller in the troposphere than in the stratosphere, then the stratospheric CO is probably due to infalling material; if, however, the abundance is constant or decreasing with altitude, as Marten et al. suggest, then it must originate in the interior of the planet, perhaps reaching higher altitudes in Neptune by convection due to its stronger internal heat source. Thermochemical models of the deep atmosphere (e.g., Fegley et al. 1991) would have to be revised in this case since they predict a CO abundance several orders of magnitude smaller than observed.

The CO concentration in the Neptunian troposphere is poorly constrained by experimental measurements. The bandwidths of the Rosenqvist et al. (J=2→1, 230 GHz) and the Marten et al. (J=3→2, 345 GHz) heterodyne measurements were insufficient to confirm unambiguously a tropospheric absorption component, although both were consistent with the presence of absorption features. Assuming a uniform vertical distribution for CO, Marten et al. predicted observable pressure-broadened absorption lines from the tropospheric component. Recently, Guilloteau et al. (1993) used the IRAM radio interferometer and a hybrid heterodyne technique to detect several points across the J=1→0 tropospheric absorption feature in Neptune. They estimated a line-to-continuum ratio of ~5%, consistent with a mixing ratio of $(0.6–1.5)\times10^{-6}$. In contrast, the photometric measurements of Uranus and Neptune by Griffin and Orton (1993) imply that the J=2→1 and J=3→2 absorption features may not be as strong as predicted by the uniformly mixed CO model if the concentration is as high as 10^{-6}. If this is indeed the case, then an external origin for CO would be more credible.

This question can only be resolved by spectroscopic measurements over a sufficiently wide spectral range. Neither the broad-band relative photometry of Griffin and Orton nor the narrow-band heterodyne observations are well matched to the width of the strongly pressure-broadened absorption lines (~10 GHz). The lines are ideally suited, however, to observation with a Fourier transform spectrometer (FTS). In this paper we present the first broad-band spectroscopic observations of the CO J=3→2 tropospheric absorption in Neptune obtained using a polarizing FTS from the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii. The results are found to be in good agreement with the model of Marten et al.

2. Observations and Analysis

The data presented in this paper were obtained on 10 May 1993 using the University of Lethbridge polarizing FTS (Naylor et al. 1991, 1993, 1994) mounted at the left Nasmyth focus of the JCMT. The two input ports of the FTS, designated 1 and

Send offprint requests to: G.R. Davis

Table 1. Planetary data

	Uranus	Neptune
Angular diameter (")	3.7	2.3
Equatorial radius (km)	25563	24760
Ellipticity	0.024	0.021

2, were directed through the telescope onto the sky with an angular separation of 65". The spectrometer operated in rapid-scan mode with the JCMT common-user bolometer system UKT14 (Duncan et al. 1990) placed at one of the two output ports. The instrument can operate over any of the filter bands of UKT14 to a maximum spectral resolution of ~120 MHz (0.004 cm^{-1}).

The 850 μm filter of UKT14 was used for these observations, and the focal plane aperture of UKT14 was chosen to give a beam width of 14" FWHM, which is the JCMT diffraction limit at this wavelength. The angular diameters of the two planets for the date of observation are given in table 1. Since the Marten et al. model predicted a full width at half maximum of 10 GHz for the CO J=3→2 line, the resolution of the FTS was set at 1.8 GHz (0.06 cm^{-1}) to resolve the line adequately. At this resolution the scan time was ~15 s. It was clear from the first observations of Uranus that the interferogram was dominated by an imbalance signal between the two input beams. It is thought that this imbalance was due to differential spillover of the two beams on the JCMT secondary mirror. It was therefore decided to observe each planet in both ports and to remove the imbalance signal by differencing the spectra during post-processing. The close proximity of Uranus and Neptune (~1.5°) during the observations was crucial to the success of this technique since it allowed for rapid observations of both planets under essentially the same atmospheric conditions, minimising the influence of atmospheric transmission variations on the measured interferograms and their nonlinear effect on the resulting spectra. In order to obtain similar noise levels for the two planets, the spectra were acquired as follows: three spectra of Uranus in port 1 of the FTS and three in port 2, followed by ten spectra of Neptune in port 2 and ten in port 1. During a period of two hours, 60 spectra of Uranus and 200 spectra of Neptune were obtained, which form the basis for the results presented here. The telescope pointing was checked regularly during this time by performing five-point sequences on Uranus, and was found to be consistent to within 2" over the course of the observations.

The low signal strength from the two planets and the presence of harmonic noise required a modification to the standard spectral analysis procedure. The interferograms were heavily oversampled (20 times) and a digital filter was applied to the raw data to remove the $1/f$ and harmonic noise. The reduced noise in the interferogram allowed a more accurate determination of the phase error term. Since the optical elements in the spectrometer and detector produce negligible dispersion over the narrow spectral range of interest, a linear phase correction was determined by weighting phase values obtained from the Fourier transform of a short double-sided interferogram by the amplitude of the corresponding spectrum, and was applied to each interferogram individually before Fourier transformation. The spectra were then averaged in groups according to the port through which they were observed. The group averages for each planet were then differenced to remove the imbalance signal discussed above. The Neptune differences were then ratioed against the Uranus differences for each group. These group ratios were finally averaged over the complete run to yield the average ratio of Neptune to Uranus.

3. Results

Figure 1 shows the averages of 60 spectra of Uranus and 200 spectra of Neptune. Both have been normalised to unity

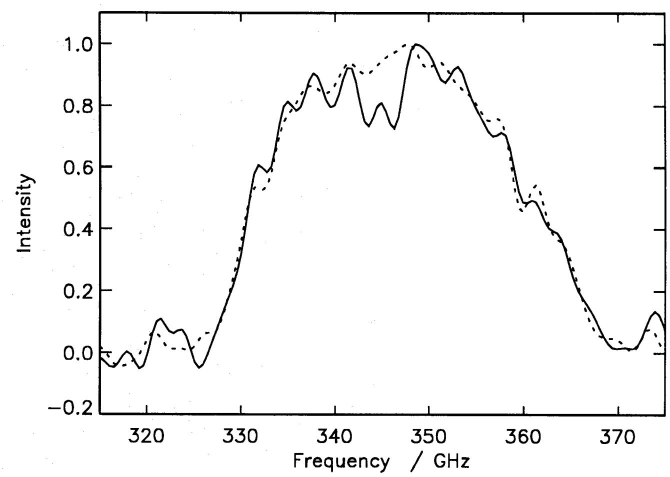

Fig. 1. Averaged spectra of Uranus (dotted line) and Neptune (solid line).

in order to illustrate the difference in the spectral shape. In the absence of any spectral structure in the source, the result in each case would be the combined transmission profiles of the atmosphere, the spectrometer and the detector system. There is an obvious dip in the Neptune spectrum that is not present in the Uranus spectrum, corresponding to an absorption feature at 345 GHz. It is also clear, however, that residual channel fringes exist and that they have different structure for the two planets. Channel fringes arise from parasitic Fabry-Perot effects caused by plane parallel surfaces in the optical train, and are difficult to eliminate at these wavelengths (Naylor et al. 1988). Moreover, since the channel fringe patterns were highly repeatable for each planet, they were not attributable to small pointing and tracking errors. The difference in the fringe structure between Uranus and Neptune is thought to be due to the different angular sizes of the two planets at the time of observation (table 1); aside from this difference in size, there was essentially no difference in the manner in which the two sources coupled to the interferometer.

The brightness temperature spectrum in Fig. 2 was calculated by multiplying the average ratio of Neptune to Uranus

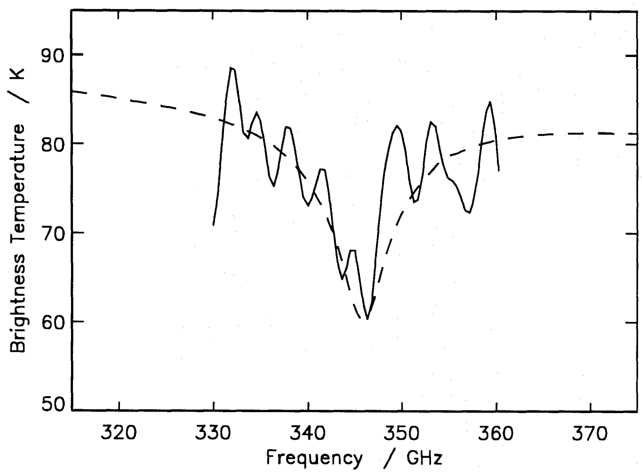

Fig. 2. Neptune brightness temperature spectra: raw data (solid) and prediction by Marten et al. (dashed).

determined above by the model Uranus continuum spectrum of Marten et al. (1993), taking into account the different solid angles of the two planets. The solid angles were calculated using the equatorial radii and ellipticities in table 1, and were corrected for polar inclination angles; the radii correspond to the 1 bar pressure level (Hildebrand et al. 1985). Figure 2 also shows the model Neptune spectrum of Marten et al., smoothed to the 1.8-GHz spectral resolution of the FTS and overlaid without any scaling. Although it is difficult to establish a baseline continuum level for the line profile because of the narrow width of the 850 μm atmospheric window, the detection of the absorption line is unambiguous. Given the magnitude of the residual channel fringes, the agreement between theory and observation is encouraging.

In deriving a CO mixing ratio from the observations, we have used the central depth of the absorption line rather than attempting to fit the line profile to avoid effects of the channel fringes. We estimate the observed temperature at the line centre to be 63±3 K, where the uncertainties correspond to the extremes of the channel fringe pattern near that point. We adopt a value of 85 K for the continuum level from the model spectrum of Marten et al. (1993), ascribing an error of ±5 K to this figure. Combining these results gives a value of 22±6 K for the difference between the centre of the absorption line and the continuum. For this line the central intensity is almost linearly proportional to the CO mixing ratio, implying a tropospheric CO mixing ratio in the range $(0.7\text{–}1.3)\times10^{-6}$. This result is therefore consistent with the model of Marten et al., and with the CO 1→0 measurement of Guilloteau et al. (1993).

Our observations illustrate the potential for broad-band intermediate resolution spectroscopy of planetary atmospheres at submillimetre wavelengths. Further FTS observations are planned to determine the CO J=3→2 line shape with greater accuracy and to extend the measurement to the CO J=2→1 line at 230 GHz. These observations will constrain more reliably the CO vertical profile.

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