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Spatially-resolved millimeter-wavelength maps of Neptune

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ABSTRACT

We present maps of Neptune in and near the CO (2–1) rotation line at 230.538 GHz. These data, taken with the Combined Array for Research in Millimeter-wave Astronomy (CARMA) represent the first published spatially-resolved maps in the millimeter. At large (~5 GHz) offsets from the CO line center, the majority of the emission originates from depths of 1.1–4.7 bar. We observe a latitudinal gradient in the brightness temperature at these frequencies, increasing by 2–3 K from 40°N to the south pole. This corresponds to a decrease in the gas opacity of about 30% near the south pole at altitudes below 1 bar, or a decrease of order a factor of 50 in the gas opacity at pressures greater than 4 bar. We look at three potential causes of the observed gradient: variations in the tropospheric methane abundance, variations in the H_2S abundance, and deviations from equilibrium in the *ortho/para* ratio of hydrogen. At smaller offsets (0–213 MHz) from the center of the CO line, lower atmospheric pressures are probed, with contributions from mbar levels down to several bars. We find evidence of latitudinal variations at the 2–3% level in the CO line, which are consistent with the variations in zonal-mean temperature near the tropopause found by Conrath et al. (Conrath, B.J., Gierasch, P.J., Ustinov, E.A. [1998]. Icarus 135, 501–517) and Orton et al. (Orton, G.S., Encrenaz, T., Leyrat, C., Puetter, R., Friedson, A.J. [2007]. Astron. Astrophys. 473, L5–L8).

1. Introduction

Neptune's millimeter continuum originates in the troposphere, from pressures of 1–5 bar. While collision-induced absorption of H_2 with hydrogen, helium and methane dominates the opacity at these wavelengths, several trace species also contribute, particularly H_2S, PH_3 and NH_3. The abundances of these trace species have yet to be uniquely determined, though good fits to centimeter-wavelength disk-integrated spectra, which probe depths of several bars down to tens of bars, are obtained using an H_2S abundance that represents a 30–50 times enrichment above the protosolar S/H value (de Pater et al., 1991; DeBoer and Steffes, 1996) and a protosolar abundance or less of nitrogen in NH_3 (Romani et al., 1989; de Pater et al., 1991).

Another trace atmospheric species, carbon monoxide (CO), produces strong rotational lines at (sub)millimeter wavelengths. CO is present in Neptune's upper atmosphere at a level several orders of magnitude greater than expected under thermochemical equilibrium conditions (Marten et al., 1991). Two major pathways have been identified for enriching Neptune's atmosphere in CO, and these pathways result in different vertical CO abundance profiles. The first of these is upward mixing of CO from warm, deep layers of the atmosphere where CO is thermochemically stable (Lodders and Fegley, 1994); CO supplied in this fashion will be well-mixed throughout the upper atmosphere and therefore will exhibit a uniform vertical profile. Alternatively, CO may be produced in the stratosphere of the planet as a result of the infall of oxygen-bearing material; in this case, downward transport will act as a sink and the CO abundance will fall below observable levels in the troposphere, where the diffusion rate increases dramatically (Moses, 1992).

To differentiate between these scenarios, models of Neptune's disk-integrated vertical CO profile have been produced using observations of the CO (1–0) (Luszcz-Cook and de Pater, 2013), (2–1) (Lellouch et al., 2005; Luszcz-Cook and de Pater, 2013) and (3–2) (Hesman et al., 2007) rotation lines at high spectral resolution (1.25–4 MHz) over a wide (8–20 GHz) frequency range. As illustrated in Fig. 1 for the CO (2–1) line at 230.538 GHz, such observations are necessary to characterize the full vertical CO profile, detecting emission from pressures below 0.1 mbar at line center, up to several bars in the far wings. From their respective studies, Lellouch et al. (2005) and Hesman et al. (2007) find substantial tropospheric CO abundances of 0.5 ± 0.1 and 0.6 ± 0.4 parts per million (ppm). The analysis of Luszcz-Cook and de Pater (2013), which favors a warmer temperature profile than Lellouch et al. (2005) and Hesman et al. (2007), produces a lower best-fit

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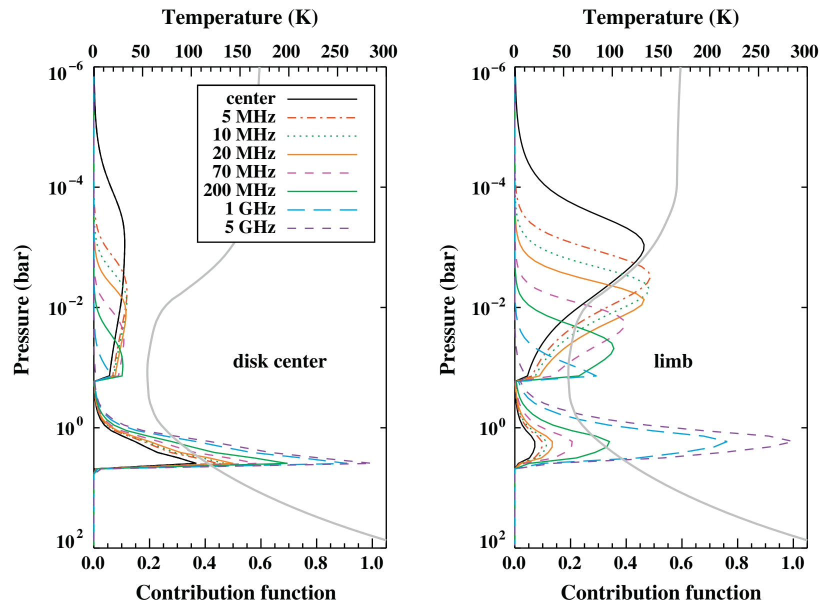

Fig. 1. Contribution functions for the CO (2–1) line, illustrating the altitudes contributing to the observed intensity for a selection of offsets from 0 to 5 GHz from line center. Contribution functions have been produced from the radiative transfer model, for disk center (selected to be where the viewing angle μ (the cosine of the emission angle) is greater than 0.9, shown left), and near the limb (μ < 0.45, right). The model was produced assuming a CO profile with 1.1 ppm CO in the stratosphere (at pressures less than 0.16 bar) and no CO in the troposphere. CO opacity is greatest near line center; and emission at this frequency comes from the highest altitudes in the atmosphere (black line). The cutoff in the CO abundance is responsible for the sharp decrease in the contribution functions near the tropopause. Neptune's thermal profile has been plotted for reference (gray, see Section 3 for more information).

tropospheric CO abundance of $0.1^{+0.2}_{-0.1}$ ppm. As first described by Prinn and Barshay (1977), the observed tropospheric CO mole fraction represents the equilibrium abundance at the CO 'quench level', which is defined as the depth at which the timescale for vertical mixing is equal to the timescale for chemical conversion of CO into CH_4. The equilibrium CO mole fraction is directly proportional to the equilibrium abundance of H_2O, and under the conditions of Neptune's deep atmosphere, nearly all the gas phase oxygen is contained in water. Therefore, the CO abundance of tropospheric CO acts as a probe of Neptune's global oxygen abundance. Luszcz-Cook and de Pater (2013) find that a tropospheric CO mole fraction of 0.1 ppm implies a global oxygen enrichment of at least 400, and likely more than 650 times the protosolar O/H value. Note, though, that the Luszcz-Cook and de Pater (2013) data are also consistent with 0.0 ppm of CO in the troposphere, in which case they do not constrain the global oxygen abundance. In addition to the CO abundance measured in the troposphere, Lellouch et al. (2005), Hesman et al. (2007), and Luszcz-Cook and de Pater (2013) all find that the CO line shape is best fit by a CO abundance profile that increases in the stratosphere, which suggests that infall must also contribute to Neptune's observed CO abundance. Based on the atmospheric CO/H_2O ratio, Lellouch et al. (2005) proposed that a recent large cometary impact could be responsible for Neptune's observed stratospheric CO abundance; however, comets of the necessary size are expected to be exceedingly uncommon. Luszcz-Cook and de Pater (2013) find that a constant influx of (sub)kilometer-sized comets could supply the observed stratospheric abundance of CO.

Spatially resolved maps of Neptune at centimeter wavelengths have been obtained by several authors (de Pater et al., 1991; Martin et al., 2006, 2008; Hofstadter et al., 2008). Martin et al. (2006, 2008) and Hofstadter et al. (2008) find a substantial (tens of K) increase in the 1.3–2 cm brightness temperature near the south pole. Such a temperature enhancement would result if dry air subsides at this location, which would cause a decrease in the atmospheric gas opacity so that warmer, deeper layers of the planet are probed. This observation is therefore consistent with a global circulation pattern in which air rises at mid- southern and northern latitudes and subsides near the equator and south pole. Recently, Butler et al. (2012) presented maps at 1 cm obtained with the upgraded VLA, with a resolution of better than 0.1″: they observe that Neptune's bright polar cap extends from the pole to 70°S. They also see evidence for equatorial brightening, which would be consistent with the circulation pattern outlined above.

In this paper, we present the first spatially-resolved measurements of Neptune at millimeter wavelengths, originally reported by Luszcz-Cook et al. (2010). Our dataset spans a range of frequencies, from the center of the CO (2–1) line at 230.538 GHz (1.3 mm) to a maximum offset of 6 GHz from line center, where continuum emission is detected. The motivation behind these observations was to look for latitudinal variations in the CO abundance, which would provide additional information about the pattern of CO infall/production. This was observed in the case of Jupiter after the impact of Comet Shoemaker–Levy 9 (SL9); Moreno et al. (2003) estimated that for SL9, latitudinal variations in the CO abundance would persist for roughly a decade. Furthermore, the CO abundance at a given latitude depends on the rate of vertical and meridional mixing, and could therefore act as a tracer of the large-scale circulation. The spectrum in the CO line is also affected by the temperature profile; therefore maps in the CO line will be affected by horizontal variations in temperature. In the 1.3 mm continuum, the intensity depends on the gas opacity at depths of 1.1–4.7 bar which may vary with latitude due to the large-scale circulation pattern.

2. Observations

We observed Neptune with the Combined Array for Research in Millimeter-wave Astronomy (CARMA), located in the Inyo Mountains of eastern California.[1] CARMA consists of eight 3.5-m

[1] CARMA is located at Cedar Flat, CA, at elevation 2200 m; latitude 37.3; longitude −118.1.