NH$_3$, H$_2$S, AND THE RADIO BRIGHTNESS TEMPERATURE SPECTRA OF THE GIANT PLANETS

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Recent radio interferometer observations of Neptune enable comparisons of the radio brightness temperature (T$_B$) spectra of all four giant planets. This comparison reveals evidence for fundamental differences in the compositions of Uranus' and Neptune's upper tropospheres, particularly in their ammonia (NH$_3$) and hydrogen sulfide (H$_2$S) mixing ratios, despite those planets' outward similarities. The tropospheric abundances of these constituents yield information about their deep abundances, and ultimately about the formation of the planets from the presolar nebula (Atreya *et al.*, 1995).

Figures 1, 2, 3, and 4 show the T$_B$ spectra of Jupiter, Saturn, Uranus, and Neptune, respectively, from 0.1 to tens of cm wavelength. The data shown are collected from many observers. Data for Jupiter, Saturn, and Uranus are those cataloged by de Pater and Massie (1985), plus the Saturn Very Large Array (VLA) data by Grossman *et al.* (1989). Figure 3, Uranus, shows only data acquired since 1973. Before 1973 Uranus' T$_B$ increased steadily as its pole moved into view, causing significant scatter in those data. Neptune data at >1 cm, all taken at the VLA, are collected from de Pater and Richmond (1989), de Pater *et al.* (1991), and Hofstadter (1993). For a variety of reasons, such as susceptibility to source confusion, single-dish data at those wavelengths are much noisier than the more reliable VLA data and have been ignored. Single-dish data by Griffin and Orton (1993) shortward of 0.4 cm are shown, along with the Owens Valley Radio Observatory (interferometer) datum at 0.266 cm by Muhleman and Berge (1991).

Spectra of Jupiter, Saturn, and Neptune share certain gross characteristics. In each spectrum, T$_B$ at 1.3 cm is ~120-140 K, less than ~30 K different from that at 0.1 cm. All three spectra show a break in slope at or near 1.3 cm, with T$_B$ increasing fairly rapidly with wavelength longward of 1.3 cm. Visible and IR spectroscopy show that NH$_3$, whose strong inversion spectrum peaks at ~1.3 cm, is an important tropospheric species at Jupiter and Saturn. Its signature on the Jovian radio spectrum is obvious, causing the prominent "hole" at 1.3 cm. At Saturn it is more subdued but is the source of that spectrum's change in slope at 1.3 cm. Radiative transfer models of Jupiter and Saturn with near-solar deep NH$_3$ abundances agree well with the data (*e.g.*, de Pater, 1990).

Uranus' T$_B$ spectrum does not fit this pattern. T$_B$ is ~175 K at 1.3 cm, ~80 K warmer than at 0.1 cm and much warmer than the other three planets. The data indicate a nearly linear increase in T$_B$ with log(λ) over the entire range shown in figure 3, requiring no break in slope near 1.3 cm. Notably, there is a distinct difference between Uranus' and Neptune's spectra: at ~20 cm, and also at 0.1-0.4 cm, Uranus' T$_B$ are quite similar to Neptune's, but in the intervening 1-10 cm range Uranus averages 30-55 K warmer than Neptune. Gulkis *et al.* (1978) first showed that Uranus radiative transfer models with near-solar NH$_3$ deep abundances predict T$_B$ at cm wavelengths that are much too cold. Their model using an NH$_3$ abundance about 1% of solar fit the data better, though far
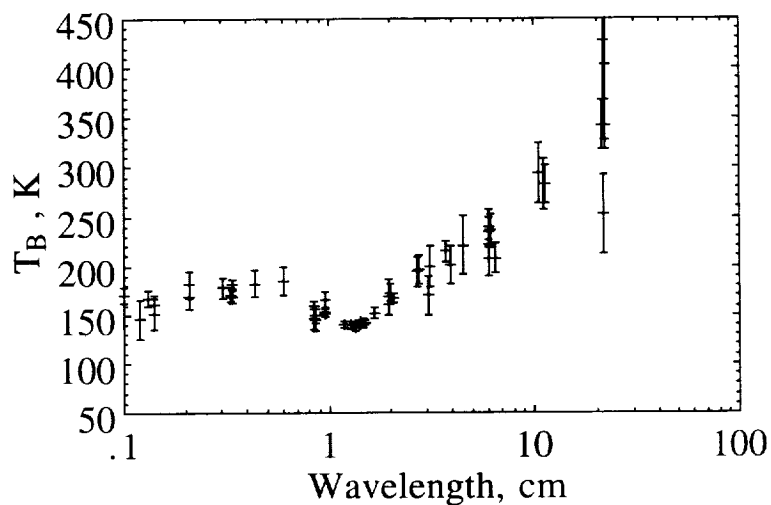
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Figure 1. Jupiter's radio brightness temperature spectrum

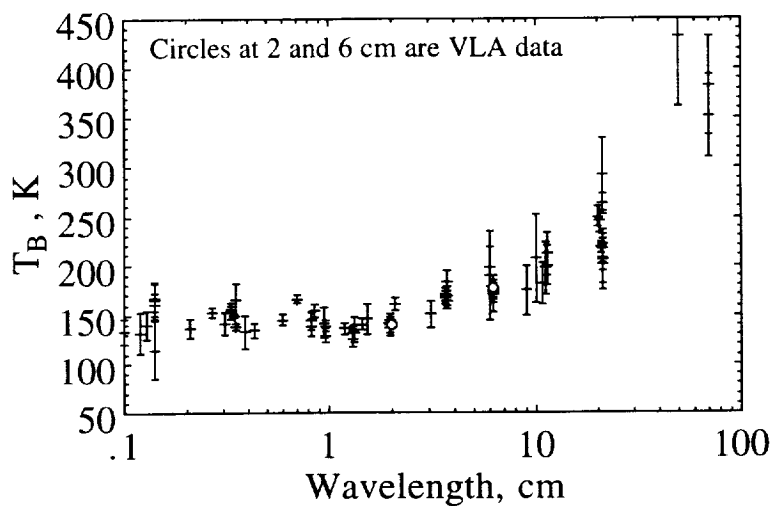*Figure 2.* Saturn's radio brightness temperature spectrum

from perfectly. They offered one possible cause for the apparent NH_3 depletion: a superabundance of H_2S could react out most of the NH_3, forming NH_4SH as first discussed by Wildt (1937). At the time most researchers assumed that essentially all nitrogen in giant planet tropospheres is in the highly reduced form. In that case the solar
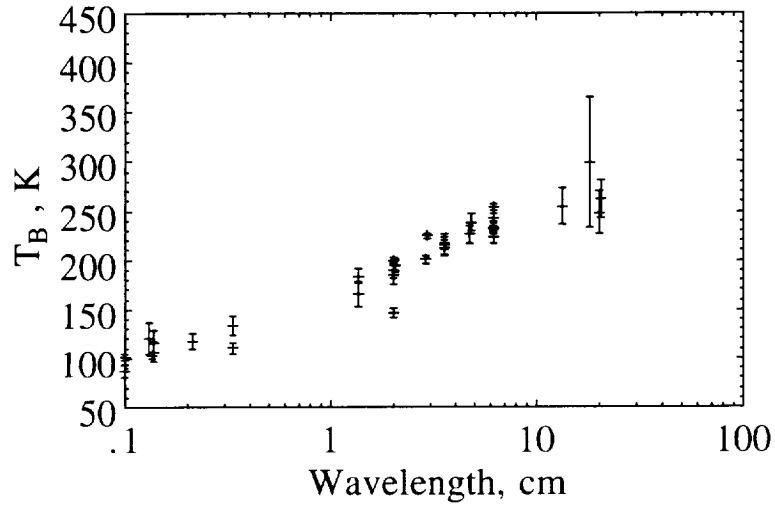
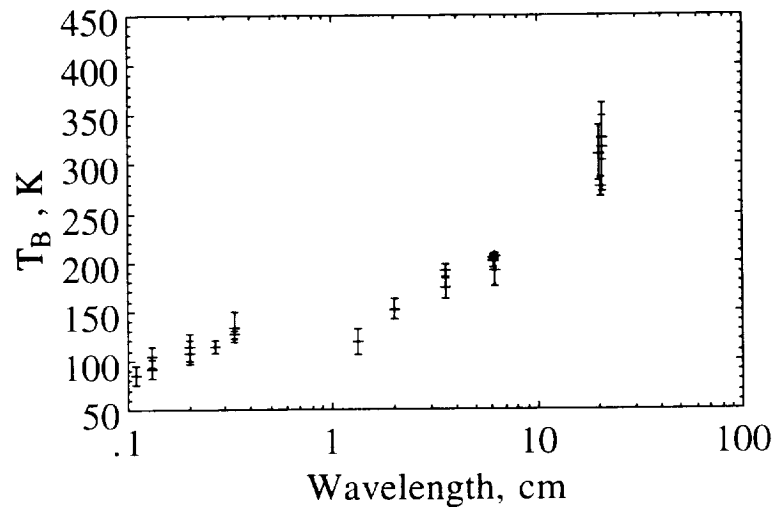*Figure 3.* Uranus' radio brightness temperature spectrum

Figure 4. Neptune's radio brightness temperature spectrum

abundance of sulfur made H_2S seem the most likely candidate to deplete NH_3, despite the lack of direct observational evidence of H_2S at Uranus or any of the other giant planets. This nondetection is expected even if sulfur abundances are approximately solar, since models predict the NH_4SH-forming reaction would restrict H_2S to depths inaccessible to visible or IR spectroscopy (Atreya and Romani, 1985).
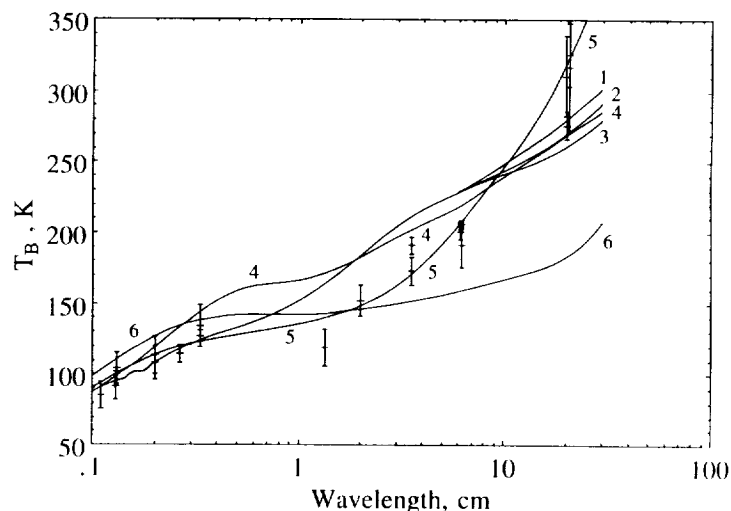
Figure 5. Neptune's radio brightness temperature spectrum, with predictions of various models superposed. See text for model descriptions.

Some researchers suggest a large H_2S superabundance at Neptune also. Problems fitting radiative transfer models to cm data prompted de Pater *et al.* (1991) to invoke NH_3-depleting H_2S at Neptune, and to suggest that H_2S might contribute significantly to the total opacity. Recently DeBoer and Steffes (1994) (hereafter "DBS") made laboratory measurements of cm H_2S opacities and found them a factor of two larger than Van Vleck-Weisskopf predictions. Based on this they suggest H_2S may be the major source of cm opacity in Neptune's upper troposphere, and reinterpret Lindal's (1992) Voyager 2 radio occultation data. Lindal assumed all opacity at the 6.3 bar level, the deepest probed, was due to NH_3 and derived a volume mixing ratio of 5×10^{-7}. DBS assume all opacity there is due to H_2S and derive a mixing ratio of 1.7×10^{-4}. Based on that result, they use radiative transfer models with H_2S above the NH_4SH cloud to generate predicted spectra they compare to the Neptune T_B data (both single-dish and VLA). Agreement between the predicted spectra and the superior VLA data is rather poor.

Figure 5 duplicates Figure 4 except it includes results from various radiative transfer models. Models 1-4 are after DBS, with 30 times solar H_2O and CH_4; NH_3 and H_2S abundances, respectively, are 0.5 solar and 15 times solar for model 1, solar and 18 times solar for model 2, twice solar and 25 times solar for model 3, and solar and 6 times solar for model 4. Models 1-3, whose spectral results are identical shortward of 6 cm, yield 1.7×10^{-4} H_2S above the NH_4SH cloud, while model 4 yields Lindal's 5×10^{-7} NH_3. Model 5 is after de Pater and Richmond (1989), using an ~2% solar NH_3 mixing ratio (3 $\times 10^{-6}$) throughout the atmosphere, limited by saturation, and no H_2S. Model 6, by the author, uses approximately solar NH_3 (2×10^{-4}) and no H_2S to demonstrate that Neptune models with uniformly near-solar tropospheric NH_3 mixing ratios are not consistent with the observed spectrum, so some form of NH_3 depletion (not necessarily H_2S) is needed.

Only the models with NH_3 above the NH_4SH cloud reproduce Neptune's T_B dip at cm wavelengths. Model 5, with more NH_3 than model 4, provides the best fit; slightly

more NH_3 would provide a better fit, further decreasing T_B longward of 1 cm. This does not conflict with Lindal's result, since he states NH_3 is probably still saturated at the deepest datum. Due to the H_2S spectrum's simple f^2 dependency longward of 0.4 cm, models dominated by H_2S above the NH_4SH cloud (DBS models 1-3) deviate <10 K from a straight line on the plot, quite unlike the data. Reproducing the T_B dip with such an absorber requires a relatively thin tropospheric layer near the 120-130 K level (~5 bar pressure level) with a much larger absorber mixing ratio than adjacent layers, a situation more appropriate to the upper stratosphere than the troposphere. Without a mechanism to maintain such a tropospheric layer, it is unlikely that the observed cm opacity in Neptune's upper troposphere is primarily due to H_2S. Neptune's radio spectrum appears to require NH_3, or another species with an opacity peak near 1-2 cm, in the upper troposphere.

Applying the DBS models 1-3 to Uranus leads to a different conclusion for that planet. Upper tropospheric T-P (temperature-pressure) relations for Uranus and Neptune are very similar: at equal pressures, their temperatures differ by ~5K at most from well above their
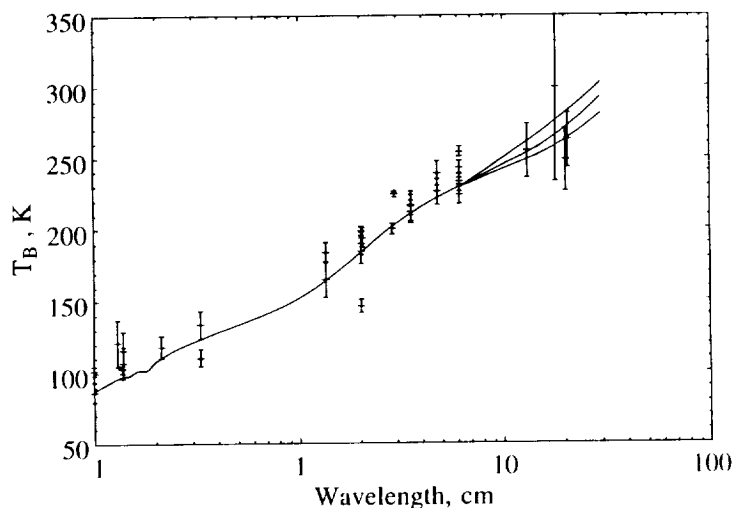

Figure 6. Uranus' radio brightness temperature spectrum, with predictions of H_2S-dominated models of Neptune by DBS (solid lines). See previous page for model descriptions.

tropospheres to the deepest level probed by radio occultation (Lindal et al., 1987; Lindal, 1992). Also, recent work by Killen and Flasar (1995) show that the cm spectra of the giant planets are largely insensitive to T-P profiles, but instead depend most strongly on the relative humidities of condensible absorbers. Given a fixed set of constituent abundance profiles, a model using Neptune's T-P profile will yield a T_B spectrum quite similar to one produced using Uranus' T-P profile. The dissimilarity of the two planets' observed radio spectra makes it highly unlikely they have similar constituent profiles. Figure 6 shows the result of using DBS' H_2S-dominated models of Neptune as first approximations to such models for Uranus. The models fit Uranus' observed spectrum much better than Neptune's, suggesting that tropospheric constituents whose cm opacities have f^2 dependencies, such as H_2S, could produce Uranus' observed radio T_B spectrum.

This does not rule out the presence of NH$_3$, but it points to other possibilities. Thus, while Neptune seems to need a small (relative to solar) but nontrivial amount of NH$_3$ in its upper troposphere, Uranus does not.

Recent work by Atreya *et al.* (1995) suggests that a significant fraction of Uranus' and Neptune's nitrogen could be in the form of N$_2$ instead of NH$_3$. Thus a range of nitrogen and sulfur abundances, both not greatly different from solar, could yield the observed depletion of NH$_3$. Further radiative transfer modeling can better define the limits of such abundances, which currently are poorly constrained. Insufficient data are available at this time to state with certainty the precise mechanisms for NH$_3$ depletions at Uranus and Neptune. Whatever the mechanisms, comparing the two planets' radio T$_B$ spectra shows that the resulting absorber mixing ratio profiles in their upper tropospheres are quite different.

Acknowledgement

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