

NEPTUNE'S DEEP ATMOSPHERE REVEALED

Paul N. Romani

Science Systems and Applications, Inc.

Imke de Pater

Astronomy Department, University of California, Berkeley

Sushil K. Atreya

Department of Atmospheric, Oceanic and Space Sciences, The University of Michigan

Abstract. The brightness temperature of Uranus at 20 cm is $260 \pm 10\text{K}$, while for Neptune it is $318 \pm 16\text{K}$. Since NH_3 is the dominant absorber at this wavelength we have modeled the microwave spectra of Neptune based upon an assumed deep gaseous mixing ratio of NH_3 and subsequent loss into clouds. The difference between the two brightness temperatures implies that the NH_3 mixing ratio below the level of cloud formation on Neptune compared to Uranus is lower by nearly 2 orders of magnitude. An alternative explanation is that the 20 cm radiation from Neptune is a combination of thermal plus synchrotron emission as proposed by de Pater and Goertz [1989].

Introduction

Since Neptune and Uranus both formed in the outer part of the solar nebula and are of similar masses, it is plausible to assume that they formed out of the same bulk material and underwent similar evolutions. There are observations that support this hypothesis. Analysis of the infrared spectrum of both planets yield similar CH_4 mixing ratios of approximately 2% below the CH_4 ice cloud (at $\approx 80\text{K}$ and 1.3 bars) and approximately the same temperature pressure structure in the 1 bar region [Orton *et al.*, 1987]. Observations at radio wavelengths probe deeper into the atmospheres than the IR (up to 50-100 bars) with most of the opacity at centimeter wavelengths due to ammonia gas. At 3-6 cm ($P \lesssim 20\text{ bar}$) both planets show a depletion of ammonia gas [de Pater and Massie, 1985]. Recently, the thermal radio spectrum of Uranus has been shown to be consistent with NH_3 enriched by $> 1-10$ times above solar and H_2S enriched by a few hundred times above solar at $P \gtrsim 50-100$ bars; the NH_3 -gas mixing ratio is reduced at lower pressures in the atmosphere first by solution into a water cloud then by the formation of an NH_4SH cloud [de Pater *et al.*, 1989].

There are, however, differences between the two planets. Neptune has an internal heat source in excess of 100% of the absorbed solar energy, while the internal heat source on Uranus is less than 13% of the absorbed solar [Conrath *et al.*, 1988]. In the stratosphere of Neptune methane is supersaturated relative to the cold trap

(tropopause) mixing ratio but on Uranus methane in the stratosphere is cold trap limited [Orton *et al.*, 1987]. Uranus' radio spectrum is relatively flat at $\sim 260\text{K}$ between 6 and 20 cm but Neptune's brightness temperature increases from $\sim 200\text{K}$ at 6 cm to $\sim 318\text{K}$ at 20 cm [de Pater *et al.*, 1989; de Pater and Richmond, 1989].

In this paper we apply to Neptune's radio spectrum the models we developed to study Uranus's [de Pater *et al.*, 1989]. This work is the first attempt ever to use a cloud model to produce an NH_3 distribution in Neptune's atmosphere, compute the resultant synthetic radio spectrum, and compare it to observations. Recently de Pater and Goertz [1989] proposed that the higher brightness temperature at 20 cm on Neptune compared to Uranus was due to synchrotron emission on Neptune adding to a thermal flux that was the same for Uranus. The primary question we address here is: Can we model the radio spectrum of Neptune with an NH_3 mixing ratio in the deep atmosphere which is equal to or larger than the solar value, such that we match the 20 cm brightness temperature as well as the temperature at shorter wavelengths, i.e. an NH_3 distribution similar to Uranus.

Models

Atmospheric Model

The cloud model used in this study is a simple lifting parcel model that has been described extensively before [de Pater *et al.*, 1989]. The calculations start deep in the atmosphere below the formation of suspected clouds: aqueous ammonia solution, water ice, ammonia ice, hydrogen sulfide ice, ammonium hydrosulfide solid, methane ice, and argon ice, with a specified composition, temperature, and pressure. The model steps up in altitude and the new temperature is calculated from the dry adiabatic lapse rate and the new pressure by assuming hydrostatic equilibrium. The partial pressures of all constituents are calculated assuming the atmosphere to be an ideal gas. From the new temperature and empirical formulas the equilibrium saturation vapor pressures of all possible condensates are calculated. If the partial pressure of a condensate in the atmosphere exceeds its respective saturation vapor pressure, then a cloud forms and the atmospheric partial pressure of the condensing species is set equal to its equilibrium saturation pressure. Since the NH_4SH cloud forms as a result of a reaction between NH_3 and H_2S , the test for cloud formation is that the equilib-

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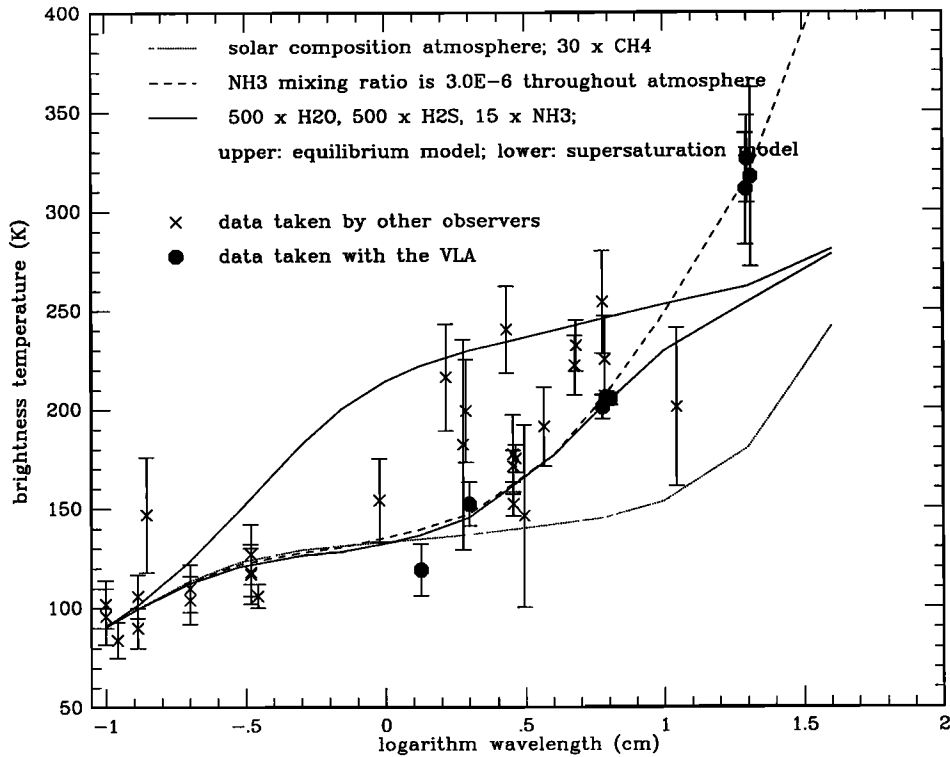


Fig. 1. Neptune's radio spectrum (from de Pater and Richmond) with superimposed model atmosphere calculations for assumed base level enrichments of H_2O , NH_3 , and H_2S relative to solar, as indicated on the figure. See text for further explanations.

rium constant is exceeded. And if the NH_4SH cloud forms the NH_3 and H_2S mixing ratios are reduced in equal molar quantities so the product of their atmospheric pressures now equals the equilibrium constant. If the aqueous ammonia cloud forms H_2S is dissolved into it. The model then steps up in altitude again using now either the dry or the appropriate wet adiabat. As the trace gases are removed from the atmosphere by condensation, "dry" air (an H_2 -He mixture) is entrained into the parcel to ensure the volume mixing ratios sum to one. This cycle is repeated until the tropopause temperature is reached.

The base level composition is for one mole of gas for which the He/H_2 ratio is 0.18 by number, and the other trace gases H_2O , CH_4 , NH_3 , H_2S , and Ar are present in selected enrichments relative to solar. The He/H_2 ratio is in conformity with our previous Uranus studies and is based on the Voyager 2 IRIS determination for Uranus [Conrath et al., 1987]. It is also within error bounds of the solar He/H_2 ratio. From all studies CH_4 was held at 30 times solar to reproduce approximately the observed 2% mixing ratio in the upper troposphere before the CH_4 ice cloud begins to form. Studies in the IR indicate that Neptune and Uranus have similar temperatures at the 1 bar level [Orton et al., 1987], so we have chosen the temperature and pressure of the base level to reproduce the observed 101K at 2.3 bars on Uranus by the Voyager RSS [Lindal et al., 1987].

Radio Spectrum Model

We used the radiative transfer code developed by de Pater and Massie [1985] to calculate the microwave

brightness temperatures from the atmospheric model. The opacity in the millimeter part of Neptune's spectrum is influenced by both the collision-induced absorption of hydrogen as well as absorption of ammonia gas, while in the centimeter part of the spectrum it is controlled by ammonia gas, water vapor, and droplets.

Data

Recently de Pater and Richmond [1989] presented VLA observations of Neptune at 1.3, 2, 6, and 20 cm. Along with their observations they updated previously reported measurements to the same flux density scale and then converted the flux densities to brightness temperatures using the best known size for Neptune. The data are shown in Figure 1, with the VLA data points being solid circles and other observations shown as X's.

In our attempts to fit the observations we will concentrate on matching the VLA results, as recommended by de Pater and Richmond (1989). These data points have a higher accuracy than the other data. This may be due, in part, to confusion problems in single dish observations of a weak source. The VLA measurements also form a self consistent data set. Also note that the strong cluster of non VLA data points at 3 cm, as well as the interferometric observations by Webster et al. (1972) agree with our values.

Fitting Attempts

Along with the radio data in Figure 1, we present several attempts to fit the model spectrum. As shown before

(e.g. de Pater and Massie, 1985) the spectrum for a solar composition atmosphere is too cold; this is indicated by the dotted line. The spectrum can be represented well with a constant low (3×10^{-6}) NH_3 mixing ratio throughout the atmosphere [de Pater and Richmond, 1989]; this curve is indicated by the dashed line. Note that this NH_3 mixing ratio is ~ 60 times below the solar value. The solid lines in Figure 1 are spectra for Neptune if it were to have a composition like we suggested for Uranus (de Pater *et al.*, 1989): $500 \times \text{H}_2\text{O}$, $500 \times \text{H}_2\text{S}$, and $15 \times \text{NH}_3$. The upper solid line is a calculation for an atmosphere in thermochemical equilibrium; the lower solid line for an atmosphere with the same composition, but in which the NH_3 mixing ratio is held constant once it reaches 3.0×10^{-6} ($T \lesssim 245\text{K}$, $P \lesssim 35\text{bars}$), i.e. NH_4SH is supersaturated. In a chemical equilibrium model, the formation of the NH_4SH cloud will completely remove NH_3 from the atmosphere if there is excess H_2S relative to NH_3 , since this reaction is equal molar in H_2S and NH_3 . This results in no NH_3 in the upper atmosphere and brightness temperatures too high to match the data. The spectrum of radio data (2-20 cm) for Neptune can only be matched with a constant low NH_3 mixing ratio of 3.0×10^{-6} over the pressure region probed at these wavelengths (10 to 80 bars). So in all of our cloud model fits, once the NH_3 mixing ratio was decreased to 3.0×10^{-6} , it was held constant at this value. This implies either supersaturation in the NH_4SH cloud (no NH_4SH forms even though the equilibrium constant is exceeded), or rapid vertical transport that mixes NH_3 rich gas below the NH_4SH cloud with NH_3 poor gas above. This requirement also occurred in modelling the Uranus spectrum but with NH_3 at about 7×10^{-7} for a global model [de Pater *et al.*, 1989].

As mentioned above the $500 \times \text{H}_2\text{O}$, $500 \times \text{H}_2\text{S}$, and $15 \times \text{NH}_3$ supersaturation model is typical of models that gave a good fit to the Uranus spectrum. However, the calculated brightness temperature at 20 cm falls well below the observed value of $318 \pm 16\text{K}$. A decrease in the NH_3 mixing ratio in the deep atmosphere to the solar value does not change the spectrum shortward of 6 cm and increases the 20 cm temperature only by 8K, still below the lower error bar.

While the NH_3 mixing ratio is decreased considerably from that specified in Neptune's deep atmosphere by solution of NH_3 into an aqueous ammonia cloud (up to 65% of the initial NH_3 mixing ratio for H_2O enrichments greater than about $100 \times$ solar), the aqueous ammonia cloud alone can not remove enough NH_3 for even large water mixing ratios. In cases in which H_2O is 500 times solar, the NH_3 mixing ratio is 5×10^{-4} at $\sim 300\text{K}$. Since in our model NH_3 is at 100% relative humidity, it can be interpreted that the cloud model would match the radio data if the relative humidity is on the order of 1%. While in small areas this is possible, the radio data are global averages implying an unrealistically globally dry Neptune. Increasing the water enrichment to $1000 \times$ solar would only allow the global relative humidity to rise to 10%.

Increasing the H_2S and/or NH_3 mixing ratio will push the formation of the NH_4SH cloud to deeper levels, thus decreasing the NH_3 mixing ratio at higher temperatures and pressures, and increasing the brightness temperature of the planet at longer wavelengths. An increase in the H_2S mixing ratio from 500 to $2000 \times$ solar results in the 20 cm brightness temperature barely touching the lower error bounds, regardless of the ammonia mixing ratio (0.1, 1 or $15 \times$ solar). A similar result can be obtained with

H_2S at $500 \times$ solar, and NH_3 at 0.1 times solar. Hence, the lower error bounds at 20 cm can be matched if either the H_2S mixing ratio in the deep atmosphere is increased to $2000 \times$ solar, or the NH_3 is decreased to $0.1 \times$ solar. At no time did the resultant curves go through the 20 cm data points, unless the NH_3 mixing ratio was at least a factor of ~ 60 below the solar value.

The formation of NH_4SH is incapable of reducing the NH_3 to a mixing ratio of 3×10^{-6} at $\sim 300\text{K}$ for the following reason. The equilibrium constant, K_p , for the formation of NH_4SH is:

$$\text{Log}_{10}(K_p) = 14.83 - \frac{4715}{T}$$

at equilibrium this is equal to:

$$K_p = P^2 \cdot \text{NH}_3 \cdot \text{H}_2\text{S}$$

where P is the atmospheric pressure in atmospheres and NH_3 and H_2S are the volume mixing ratios of ammonia and hydrogen sulfide respectively. In our model atmospheres $\sim 300\text{K}$ occurs at ~ 80 bars (the precise value depends upon the enrichment and whether or not a dry or wet adiabatic lapse rate was used). If at this level ammonia has been reduced to 3×10^{-6} by NH_4SH formation, then by using Equations 1 and 2 the H_2S mixing ratio must be 7: impossible. (We discuss the possibility of a non-adiabatic atmosphere in the next section).

Thus we are forced to assume that NH_3 is subsolar throughout Neptune's atmosphere, unlike Uranus where a subsolar NH_3 provided a poor fit and an above solar NH_3 mixing ratio coupled with removal into clouds gave the best fits to the data. Our calculation show that the mixing ratio on Neptune should be $\sim 1/60 \times$ solar value.

Discussion

Sub solar N

One possible explanation is that Neptune is depleted in NH_3 relative to Uranus. While a best fit to the Uranus microwave data at 20 cm requires a minimum mixing ratio of $10 \times$ solar NH_3 , a poor fit is possible with solar NH_3 . However the Neptune spectrum can only be matched at 20 cm by an NH_3 mixing ratio $\sim 1/60$ times solar. This requires nearly a 100 fold gradient in N content in the primitive solar nebula from Uranus to Neptune. Since at present there is no compelling theory on the origin of these planets that supports this, we do not favor this explanation. We also note that the spectrum of Neptune can be fit at the other wavelengths by a composition similar to Uranus with only the 20 cm brightness temperature being a problem.

Another possibility is that N is present on both planets in the same mixing ratios but in the form of N_2 on Neptune and NH_3 on Uranus. While the dominant form of N in the outer solar system was probably N_2 , this was likely converted back to NH_3 in the formation of the giant planets [Prinn and Fegley, 1981]. To photolyze NH_3 back to N_2 requires a warmer Neptune in the past enabling NH_3 to get to the one bar level and above so it can absorb the solar UV before Rayleigh scattering blocks the penetration of solar UV. Also the interior of Neptune must be cold (a non-adiabatic atmosphere) and H_2 poor so N_2 is

not converted back to NH_3 by the Haber process. Scaling the NH_3 photolysis loss rate from Jupiter (4.0×10^{-12} grams cm^{-2} sec^{-1} , (Atreya, et al., 1977) to Neptune gives a loss rate of 1.2×10^{-13} grams cm^{-2} sec^{-1} . Assuming Neptune's atmosphere to be at least 1 Earth mass, photolysis can convert only 0.2 of a solar mixing ratio of NH_3 on Neptune over the age of the solar system. So we consider this unlikely. If N turns out to be in the form of N_2 on Neptune then Voyager 2 will be able to detect it; N_2 will not freeze out at Neptune's tropopause (saturation mixing ratio $\sim 6.7 \times 10^{-2}$) and the Voyager 2 Ultraviolet Spectrometer can detect N_2 as low as 10 ppb at the microbar level.

Non-adiabatic atmosphere

In all our calculations we assumed that the thermal structure was adiabatic. This was important in showing that NH_4SH formation is incapable of reducing the NH_3 mixing ratio to 3×10^{-6} at 300K. But we can ask the question: what is the pressure for a given temperature (300K), H_2S mixing ratio (10^{-2} , ≈ 500 x solar) and NH_3 mixing ratio (3×10^{-6}). From Equations 1 and 2, the pressure must be 2000 bars. In an adiabatic atmosphere, the temperature at this pressure level is 600K, twice 300K. Thus Neptune's atmosphere would have to be more isothermal than an adiabatic one with a lapse rate nearly half the adiabatic. However, Neptune emits more energy than it receives from the Sun, and it is likely that in the deep atmosphere the heat transport is done by convection. This implies an adiabatic thermal structure, so we consider this alternate thermal structure unlikely.

Synchrotron radiation

De Pater and Goertz [1989] have proposed that Uranus and Neptune do have similar compositions and that the difference between the two 20 cm brightness temperatures is that Neptune's is a combination of thermal and synchrotron emission while Uranus' is thermal alone. This seems to be the likeliest explanation. The electron population and magnetic field required for this interpretation will be directly verifiable by Voyager 2 experiments.

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- Atreya, Sushil K., Department of Atmospheric, Oceanic and Space Sciences, The University of Michigan, Ann Arbor, MI 48109-2143.
- de Pater, Imke, Astronomy Department, Campbell Hall 601, University of California, Berkeley, CA 94720.
- Romani, Paul N., Code 693.2, NASA/Goddard Space Flight Center, Greenbelt MD 20771.

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