

SEASONAL CHANGE IN THE DEEP ATMOSPHERE OF URANUS

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ABSTRACT

We have observed changes in the deep atmosphere of Uranus, using the Very Large Array. Observations made in April of 1994, at wavelengths of 2 and 6 cm, show a structure significantly different from what was observed throughout the 1980's. A radio-bright region (probably due to a relatively low absorber abundance) which extended from the South Pole to -45° latitude between 1981 and 1989, in 1994 extended down to -35° . Furthermore, the pole to equator contrast grew substantially stronger at 2 cm, reflecting a change in the upper ~ 20 bars of the atmosphere.

INTRODUCTION

Unresolved, disk-averaged measurements of Uranus have been made since 1965, and show a trend of increasing brightness from the 1960's into the late 1980's [1]. This trend could either be due to seasonal change (each Uranian season lasting 21 Earth-years), or be due to a static, pole to equator brightness gradient and the changing viewing geometry from Earth (which sometimes looks down at a pole, such as in 1985, and other times at the equator, as we will in 2007). The first radio telescope able to clearly map Uranus was the Very Large Array, or VLA. Early observations found that there was a pole to equator brightness gradient on Uranus [2], [3], but that the gradient was not strong enough to explain the changing disk-averaged measurements. Later work [4], [5] quantified this, and found that latitudes between the South Pole and -45° were significantly brighter than regions between -45° and the equator, and that the brightness distribution had not changed between 1981 and 1989.

OBSERVATIONS

Since the older, disk-averaged observations suggested dramatic seasonal changes in radio brightness could occur as the Southern Hemisphere entered its fall or winter, in April of 1994 we again observed Uranus for 16 hours with the VLA. The 2 and 6 cm disk-averaged brightness temperatures of Uranus were 193 ± 10 K and 241 ± 12 K, respectively. These are comparable to other measurements made since the mid-1970's, but significantly higher than older measurements [6]. Mapping the 1994 data, however, reveals changes have occurred since the 1980's (Fig. 1). We find that the South Pole in 1994 was still unusually bright, but that the bright region had spread northward, down to about -35° latitude. We also find that the 2 cm pole-to-equator contrast (corrected for viewing angle effects) increased substantially between 1985 and 1994: from 30 K to 60 K. Interestingly, the 6 cm pole-to-equator contrast did not change significantly over the same period: from ~ 45 K (as measured in 1981 and 1989) to 49 K. While Fig. 1 also suggests change at northern latitudes, we view these as speculative given the large error bars on the older data. Work is underway to reanalyze these data which should allow a significant reduction in the uncertainty.

ANALYSIS

The VLA measurements indicate that, at the largest scales, the atmosphere of Uranus has two states. One appears bright at radio wavelengths, the other dark. Since the kinetic temperature and composition of the atmosphere as a function of pressure (equivalent to depth) determines the radio brightness of an atmosphere, these two parameters must be functions of latitude and time. We first fit the observed zonal structure with horizontal variations in composition, assuming the temperature profile was the same at all latitudes. We find that to simultaneously fit the 2 and 6 cm observations in 1994, the 5 to 20 bar region of the atmosphere must be ~ 5 times more absorbing between -40° and $+30^\circ$ latitude than from -40° to the South Pole, while deeper regions, down to 40 or 50 bars, are ~ 50 times more absorbing at the equator than the pole. At depth, the region of highest opacity appears slightly narrower in latitude than is seen higher up, extending from about -30° to $+30^\circ$ (Fig. 2). (Higher opacity means we cannot see to the deeper,

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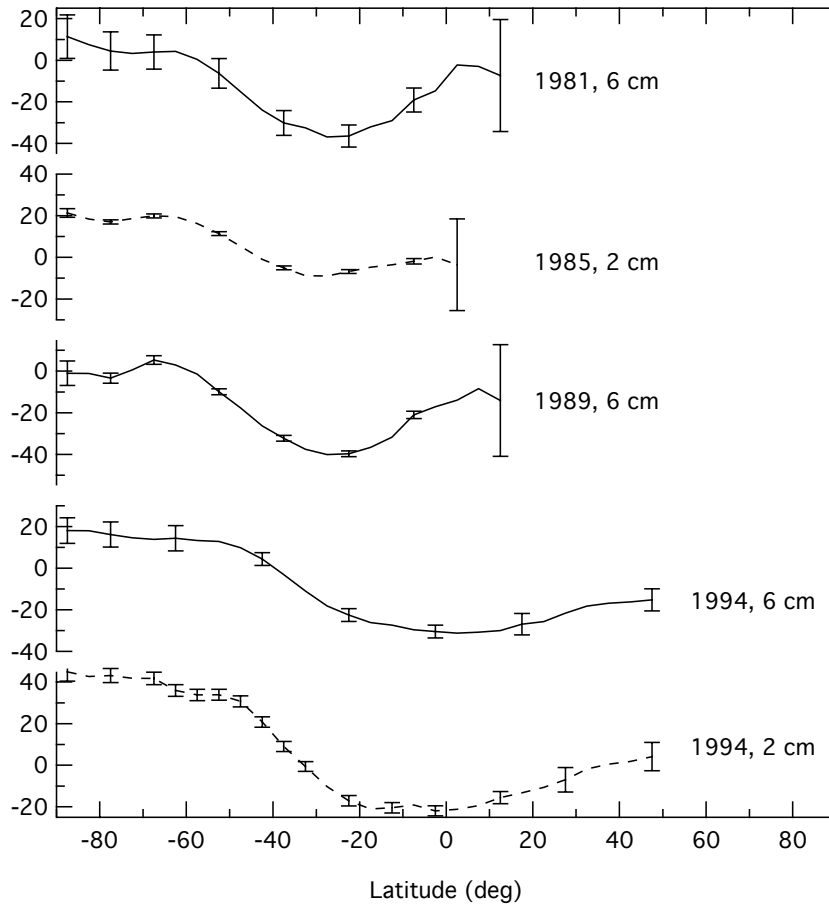


Fig. 1. Time history of the zonal brightness structure on Uranus. Each curve shows the brightness of the planet relative to a model with no horizontal variations. (Plotting relative brightness removes geometric effects, such as limb-darkening.) Temperatures are averaged into latitude bins 5° wide. Curves are ordered chronologically from top to bottom, with 6 cm wavelength data shown as solid lines, and 2 cm data indicated with dashed lines. Note the separate temperature scales, each spanning 70 K. The error bars indicate the uncertainty in the shape of each curve, and are spaced to approximate the beam positions across the central meridian of Uranus. Note that the zonal structure did not change throughout the 1980's, but between 1989 and 1994 the bright region around the South Pole grew wider and the brightness contrast at 2 cm increased significantly. The large error bars on the older Northern Hemisphere observations prevent us from drawing conclusions in that region, though a re-analysis of those data is underway.

hotter parts of the atmosphere, so the darker regions are interpreted as being more opaque.) These horizontal variations are quite large, but since the likely microwave absorbers (NH_3 and H_2O , [6] and [7]) are condensable, cloud formation can explain them [8]: a deep-seated atmospheric upwelling in (radio-dark) low latitudes carries absorber rich air parcels to altitudes where the absorber condenses out. These air parcels, now depleted of absorber, can then move poleward at high altitude and descend, maintaining clear polar regions. This circulation pattern is reminiscent of Earth's Hadley cell, whose ascending branch over the Equator brings water vapor into the upper troposphere and stratosphere, but whose descending branches at plus and minus 30° latitude are extremely dry, accounting for deserts such as the Sahara and Kalahari. Alternatively, variations in convective activity could explain the absorber distribution [2]. If sunlight, which is preferentially deposited at the poles, inhibits convection, the polar atmosphere could become stagnant. If there is also a mechanism that removes absorber from this region, it would become radio bright. Lower latitudes, however, which remain convective, would have their absorber abundance continually restored from below. This circulation also has an Earth analog: in winter, polar vortices form that isolate the polar stratosphere from lower latitudes, aiding in the formation of the infamous "ozone hole". In this scenario on Uranus, however, the absorber depletion mechanism over the pole is not clear: condensation might not be effective in the stagnant environment envisioned. When an

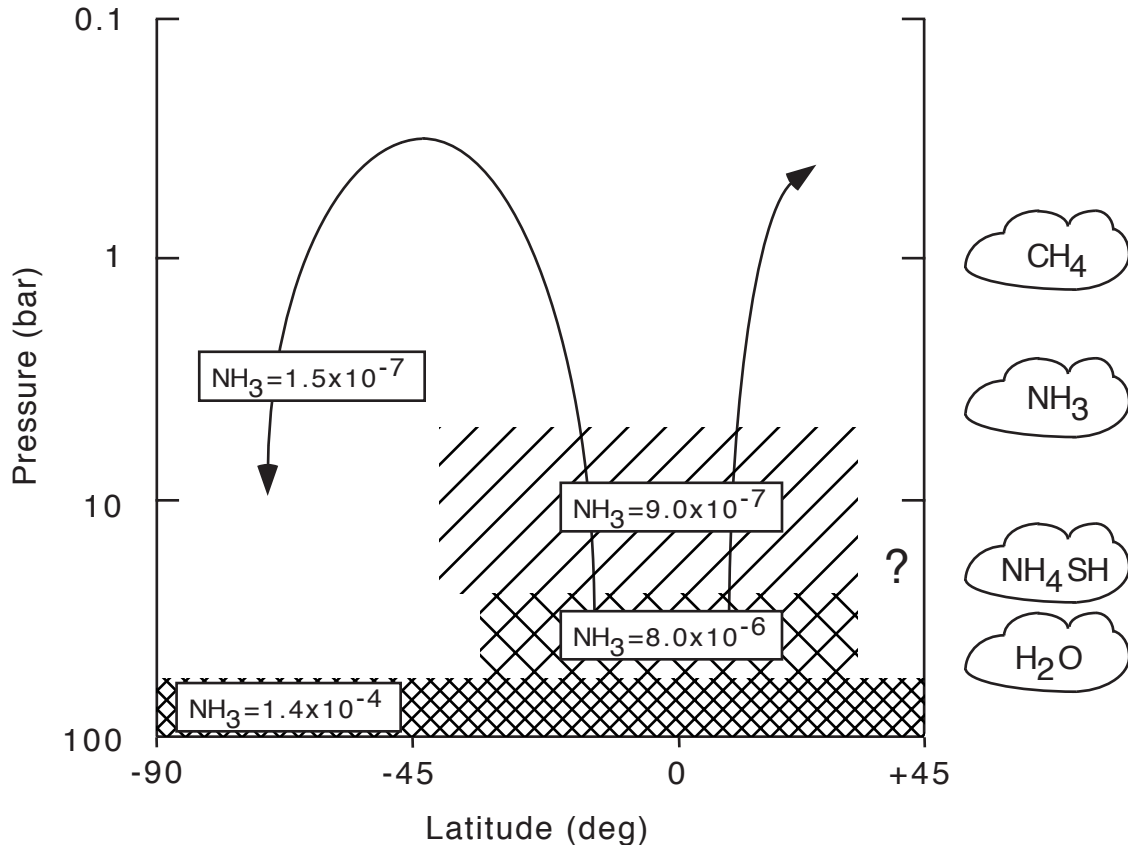


Fig. 2. The absorber distribution required to fit the 1994 observations, assuming an adiabatic temperature profile with no horizontal temperature gradients. The density of cross-hatching in a region indicates the absorber abundance there. Note the absorber rich deep atmosphere at all latitudes, the variation of absorber with height at low southern latitudes, and the relatively absorber-free higher latitudes. These elements are required to fit the observations. The NH₃ volume mixing ratios shown, the cloud layers, and the circulation pattern are more speculative, but demonstrate that there are plausible mechanisms to maintain the required gradients. The current data set is insensitive to conditions at high northern latitudes. (The cloud model used for these calculations is described in [8].)

atmospheric model was fit to the 1981, 1985, and 1989 data [5], [8], the results were that the enhanced opacity region was shifted in latitude, extending from the Equator to -45° . Horizontal variations in the upper troposphere were also found to be smaller than in 1994, with low southern latitudes only 2 or 3 times more absorbing than the South Pole. The region between ~ 20 and 50 bars, however, had its absorber abundance vary horizontally by a factor of ~ 300 , much stronger than is found in 1994.

The foregoing discussion assumed temperature variations on surfaces of constant pressure are small (less than 10 K). The observed zonal brightness structure has also been fit assuming that temperature and not composition varies. In this case, we find kinetic temperature gradients of > 60 K exist across 20° of latitude at pressures of tens of bars. There are also significantly sub-adiabatic regions in the atmosphere, which must change their temperature by ~ 40 K between 1989 and 1994. We believe temperature structures such as these are unlikely, but they cannot be excluded by the observations alone.

CONCLUSIONS

The pure temperature and pure compositional solutions just discussed are end-members of a range of models that fit the radio observations. The following properties are common to all solutions, however, and as such form our core conclusions:

- When viewed with a resolution of $\sim 5^\circ$ in latitude, the Southern Hemisphere of Uranus has two atmospheric states, one appearing bright at centimeter wavelengths, the other dark. The bright region has, in the upper ~ 50

bars of the atmosphere, either higher kinetic temperatures, a lower absorber abundance, or both, than the darker region.

- The south polar region is bright, and its size varies in time. The boundary between it and dark lower latitudes was at $-45^\circ \pm 5^\circ$ between 1981 and 1989, but it shifted to $-35^\circ \pm 5^\circ$ between 1989 and 1994.
- Throughout the 1980's, horizontal gradients were unchanging in the 5 to 50 bar region of the atmosphere. Between 1989 and 1994, however, horizontal contrast in the upper ~20 bars of the atmosphere grew stronger, while contrast near 50 bars decreased.

While the radio data by themselves cannot distinguish between temperature and compositional gradients, we believe compositional gradients are likely to play the dominant role in creating the observed structures. The reason for this is that condensation can easily cause the changes in absorber abundance required to explain the observations, but there is no obvious mechanism to produce the large and rapidly changing temperature gradients that would be required.

We hope the above discussion helps renew interest in modeling the dynamics of Uranus. In particular, the maintenance of strong horizontal gradients which change over relatively short time scales must be explained. Some models have predicted a bi-modal atmosphere [9], but place the transition zone between these states at lower latitudes than is seen in Fig. 1, and also call for more gradual changes than are observed. Refined dynamical models, coupled with new VLA observations through the Uranian equinox (2007) hold promise for revealing much about the deep interior of giant planets.

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