

Time Variability of the Uranian Atmosphere

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Primary Conclusion

Planetary-scale changes in composition and/or temperature are seen as deep as 50 bars. This is much deeper than current seasonal models predict.

Abstract

We have analyzed microwave maps of Uranus made with the VLA in 1981, 1985, 1989, 1994, and 2002. The observations, at wavelengths of 2 and 6 cm, are sensitive to atmospheric composition and temperature between 5 and 50 bars. Over this time Uranus moved from early southern summer to early fall. All maps show the planet to be strongly bi-modal: a region around the South Pole is consistently much brighter than all other latitudes, with the transition always centered near -45 degrees. The contrast between bright and dark regions, however, increased significantly between 1989 and 1994. The planet appeared stable both before and after this time. Disk-averaged measurements at a wavelength of 3.5 cm (M. Klein et al. 2002), also show a rapid change occurring around 1992. It is surprising that planetary-scale changes occur this deep and this rapidly.

The most likely explanation for brightness features on the planet is spatial variations in the abundance of absorbers such as NH_3 and H_2O . Bright regions are depleted in absorbers by more than an order of magnitude. Since these species are condensable, atmospheric circulation and cloud formation can create the observed spatial variations. The changes we see over time might therefore be related to seasonal variations in the deep circulation. The dynamical model of Friedson and Ingersoll (1987) does predict a bi-modal atmosphere, with some latitudes being convective and others stably stratified, but it does not predict meridional variability as deep as we have seen.

We will continue to observe Uranus throughout its equinox passage in 2007 in anticipation of further changes. We are coordinating our work with observers at visible and infrared wavelengths (see Hammel and Lockwood 2005) in hopes of developing a comprehensive picture of the troposphere, and are working with dynamicists to better constrain atmospheric models. We are also working with the Goldstone-Apple Valley Radio Telescope science education partnership (see Klein et al. 2002).

Microwave Images of Uranus from the Very Large Array (VLA)

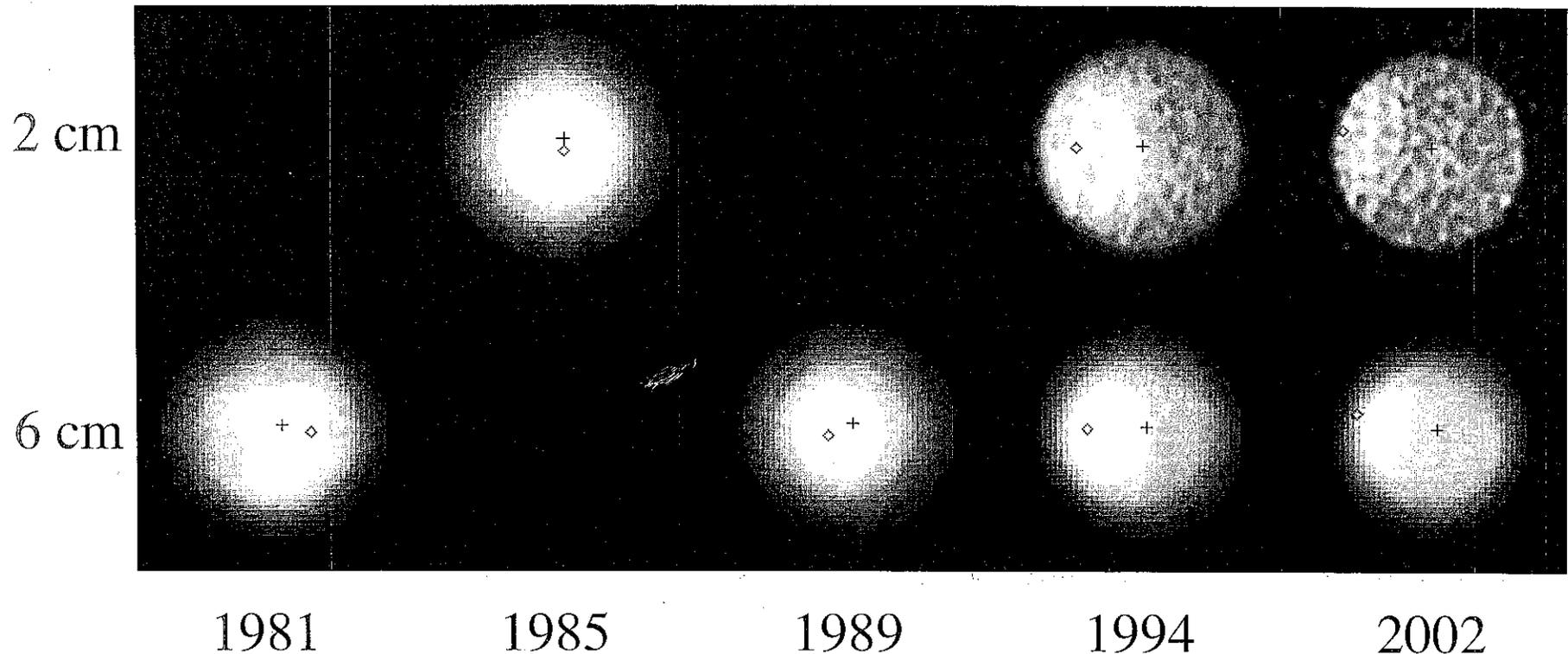


Figure 1: Maps of sky brightness. Each column is a different year, row indicates wavelength. The disk center is marked with a cross, the South Pole with a diamond. The main things to note are the changing viewing geometry, and that there is a bright region associated with the pole. False color scale is linear, spanning from 0 to 260 K at 2 cm, and from 0 to 300 K at 6 cm. The planet is approximately 3.7" in diameter: there are ~8 beams across the planet at 6 cm, and ~18 at 2 cm. Each map is made from ~7 hours of observations so the planet's 17 hour rotation period smears features in longitude. Southern solstice was in 1985, the next equinox is 2007.

Brightness as a Function of Latitude and Time

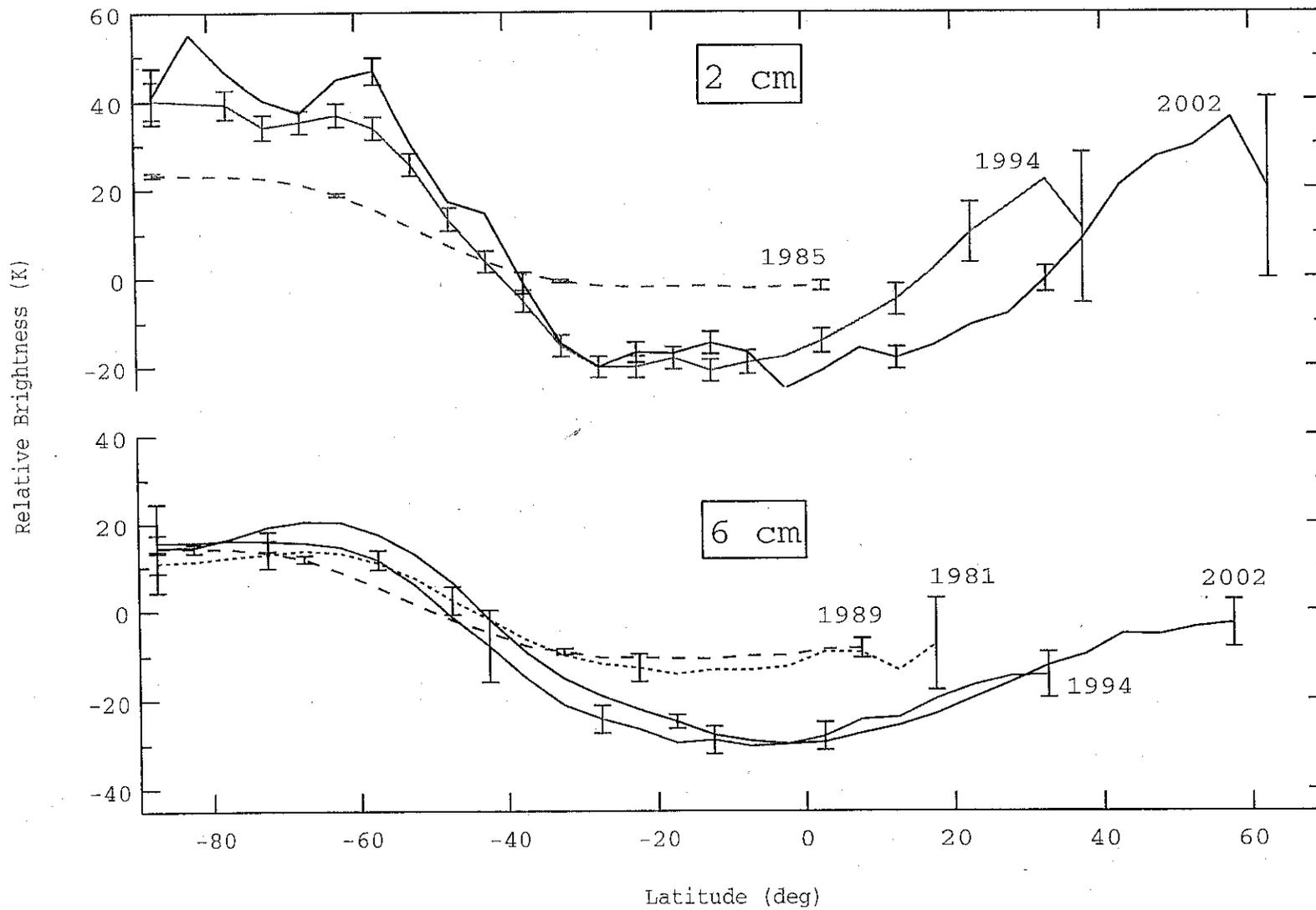


Figure 2: Time history of the zonal structure. To better compare the images of Fig. 1, we have corrected for limb darkening and averaged the maps zonally into latitude bins 5° wide. Error bars indicate the uncertainty in the shape of each curve. Calibration errors can cause any curve to be shifted relative to the others by ~ 10 K, and we have taken advantage of this to more clearly show relative changes: the 1981 6 cm curve has been shifted upward by 5 K and the 2002 6 cm curve downward by 10 K. Note how, at both wavelengths, the pole to equator contrast appeared to increase significantly between 1989 and 1994. This cannot be explained by the differing viewing geometries and beam sizes. Atmospheric properties must have changed.

Since the radio brightness is controlled by atmospheric opacity and temperature as functions of height, one or both of these properties must be varying spatially to create the bright pole seen in all the maps. In addition, sometime between 1989 and 1994, this pattern changed temporally, increasing the pole-to-equator contrast. Atmospheric properties appeared relatively stable throughout the 1980's, however, and have been stable since 1994.

Creating Horizontal and Temporal Brightness Variations

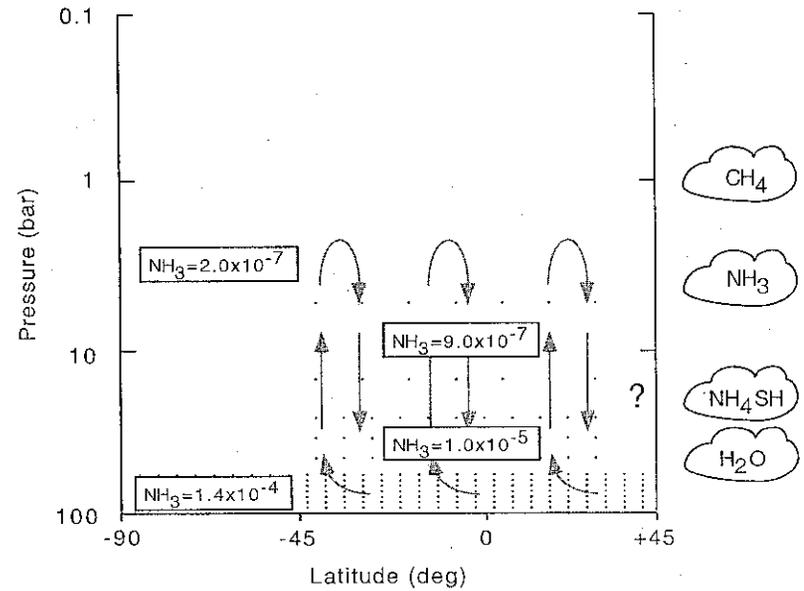
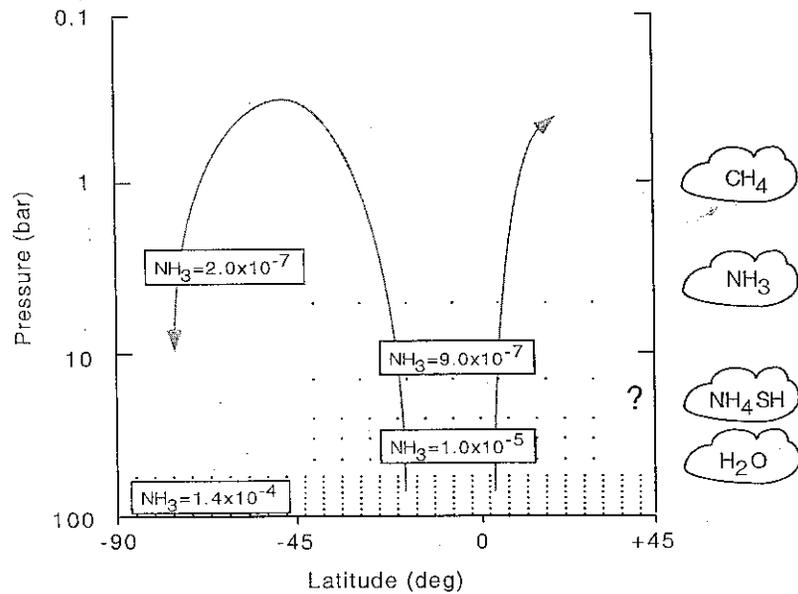
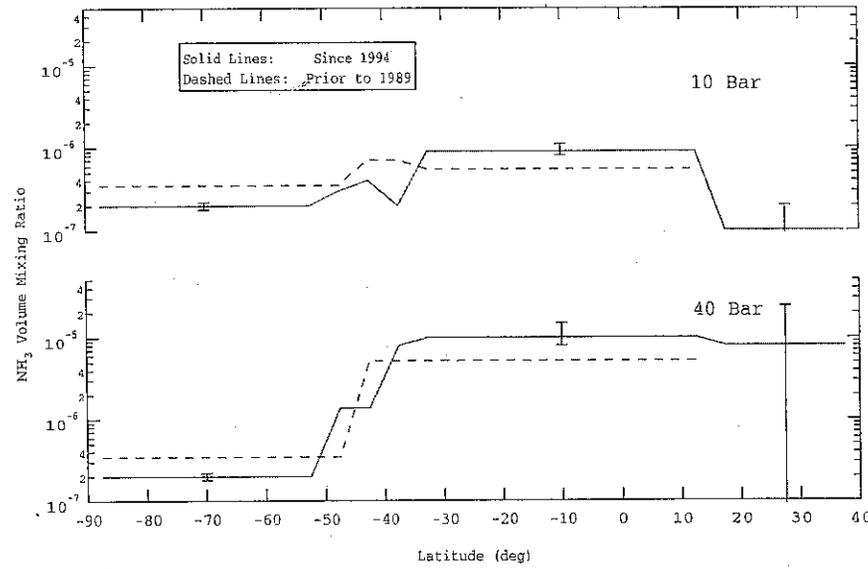


Figure 3: These plots show the opacity variations needed to match the data, assuming horizontal temperature variations are small. Bright regions of the planet are interpreted as being less opaque (less opacity allows us to see deeper, hotter regions of the atmosphere). Our 2 cm data are sensitive to the atmosphere in the 5 to 20 bar pressure region, and call for the pole to be ~5 times more absorbing than the equator in the 1994 and 2002 maps, but only about 2 times more absorbing in the 1985 data (topmost figure). The 6 cm data, probing to the 50 bar level, require much stronger pole-to-equator variations in each epoch: a factor of 50 since 1994, 15 before then.

Since the primary opacity sources (NH_3 and H_2O vapor) are condensable, cloud formation driven by atmospheric circulation could create these horizontal gradients. Cartoons of this are shown on the bottom, where the density of dots indicates the abundance of absorber for the most recent data. On the left we show how a single, deep seated Hadley-like circulation cell would explain the observations (Hofstadter 1990). At low latitudes an absorber rich upwelling keeps the atmosphere opaque, though condensation does cause the opacity to decrease with altitude. These absorber depleted parcels move poleward at high altitude and descend, keeping the South Pole relatively absorber-free. The strength of this circulation (relative to meridional transport mechanisms?) must have changed between 1989 and 1994 to explain the different pole-to-equator gradients. The cartoon on the right shows the same absorber distribution maintained by smaller scale convective processes at low-latitudes, working in tandem with an unidentified depletion mechanism near the pole (Briggs and Andrew 1980).

Creating Horizontal and Temporal Brightness Variations (continued)

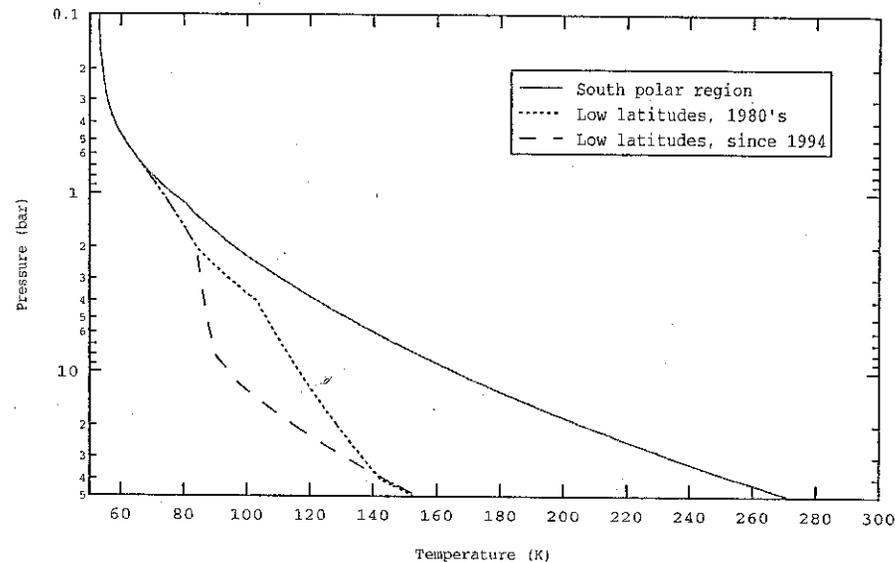


Figure 4: This plot shows representative temperature variations needed to explain the data, assuming composition is not a function of latitude. In this interpretation, regions are bright because their physical temperature is higher. In the 1980's, horizontal temperature variations of more than 60 K are needed. Since 1994 the horizontal gradients are similar in magnitude, but begin higher in the atmosphere. There is no obvious mechanism to create these large spatial gradients, and it seems difficult to change the temperature in regions of the deep atmosphere by 20 K between 1989 and 1994. (For comparison each season lasts 21 years on Uranus.) For these reasons we consider the abundance interpretations of Fig. 3 to be more likely.

Single-Dish Measurements Complement VLA Results

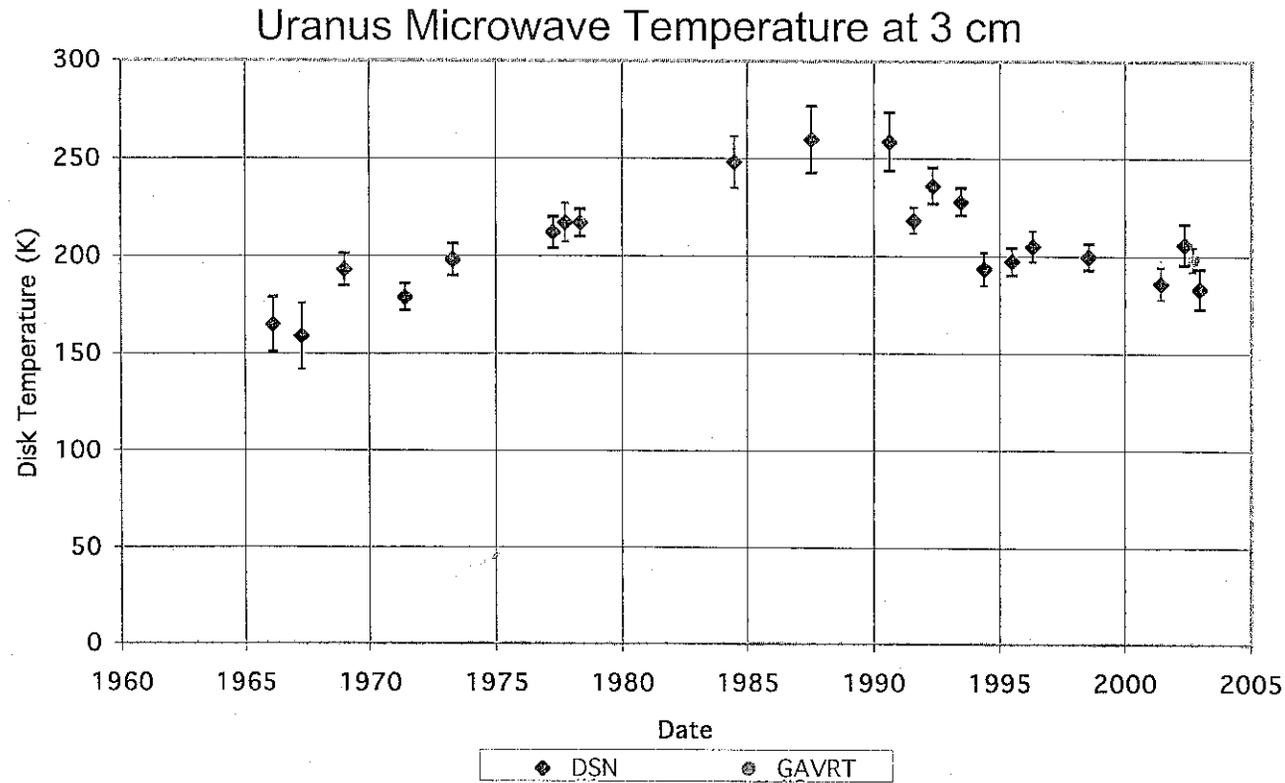


Figure 5: Disk-averaged measurements of Uranus (from Klein et al. 2002). While radio mapping of Uranus became possible only in 1980, disk averaged measurements have been made since the 1960's. This figure show how the average brightness has changed over nearly half a Uranian year. Note that, in agreement with the VLA data, it shows a rapid change in the planet during 1992 and 1993, with relative stability just before and after. Regular monitoring by GAVRT will compliment future VLA mapping campaigns.

Summary

- Latitudes from the South Pole to -45° are always much brighter than other regions.
- Between 1981 and 1989, and then again between 1994 and 2002, the brightness pattern was relatively stable. Sometime between 1989 and 1994, however, the contrast between bright and dark regions increased significantly, while the transition latitude and the location of some smaller-scale features remained constant.
- Brightness features can be caused by horizontal temperature gradients of 20 to 60 K, and/or by absorber abundance variations by factors from 2 to 50.

Future Work

- We will continue to observe Uranus through its upcoming equinox passage in 2007, in hopes of seeing additional seasonal effects. Symmetry arguments suggest the South Pole will darken while a bright region will form at northern latitudes.
- We are coordinating with observers at other wavelengths (Hammel, Rages, Lockwood), and with the GAVRT science education partnership. We also intend to test the ability of improved dynamical models to create the observed variations.

References

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