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Uranus's Tropospheric Circulation and Composition with ALMA and the VLA

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Abstract

We present ALMA and VLA spatial maps of the Uranian atmosphere, probing pressures from 0.5-50 bar. The atmosphere is very bright northward of ∼50° N at all wavelengths; radiative transfer modeling attributes this brightening to a factor of ∼20 H_2S depletion over the north pole that extends down to at least 50 bar. This depletion in condensible molecules suggests large-scale downwelling in the north polar vortex region. The ALMA maps reveal previously-undiscovered zonal bands of upwelling (radio-dark) and downwelling (radio-bright) air; however, the depletions in condensible species is much less pronounced in these regions than in the north polar spot, and the lower sensitivity and resolution of the VLA maps, which probe deeper pressures, makes the vertical extent of these features uncertain. The observations also constrain the spatial distribution of methane and the ortho-para H_2 fraction in Uranus's troposphere.

1. Introduction

The low self-luminosity, extreme seasonal forcing, and surprisingly dynamic cloud activity on Uranus provide an extreme test of our understanding of the structure, composition, and circulation of planetary atmospheres. Central to these questions is Uranus's global circulation pattern, which remains poorly understood. Previous VLA observations revealed bright poles on Uranus that are interpreted as a relative lack of H_2S and NH_3 opacity in the deep troposphere down to ∼50 bar, pointing to large-scale subsidence of dry air [1, 2, 3]; a polar depletion in methane at higher altitudes discovered by HST corroborates this finding [4]. These discoveries led to the adoption of a non-seasonal equator-to-pole meridional circulation pattern. However, observations of convective cloud features in the midlatitudes [5, 6] at infrared wavelengths imply localized convective regions in the deep troposphere and favor more complex circulation patterns. Indeed, extremely bright storm activity in 2014 in spite of an expected decline in convective activity following Uranus's 2007 equinox [7] underlined the inadequacy of current circulation models to explain observed weather patterns. An alternative model [8] prescribing circulation in three vertical layers may better explain Uranus's cloud structure; this model has not been confirmed by data.

2. Observations and Results

We obtained VLA and ALMA images between 2015 and 2018 in eight frequency bands, spanning a broad spectral range from 13 cm to 1 mm. A disk-subtracted ALMA 3-mm image of Uranus disk is shown in Figure 1; the image's ∼0.2" resolution, which translates to ∼3000 km at Uranus's distance, is the highest ever obtained at radio wavelengths. Bright bands at 20°S, 0°, and 20°N suggest depletion in condensing species, likely due to downwelling at those latitudes; these downwelling regions point to a more complex circulation pattern than predicted by models [9, 8], which suggested upwelling near 30°N and S and subsidence at the equator and poles. The same zonal structures are also observed in the other two ALMA images at 2.1 and 1.3 mm, suggesting they extend at least from 0.5-5 bar. The north polar bright spot is observed at all wavelengths from 13 cm to 1 mm, suggesting the same circulation cell extends continuously from 0.5-50 bar. However, localized regions of upwelling or a temporally variable circulation pattern at the north pole cannot be ruled out. The boundary of the spot at ∼50°N appears sharply defined, constraining the H_2S depletion to the same region as the infrared-inferred north polar methane depletion [8], which extends from ∼40°N. The boundary also coincides spatially with the developing north polar haze collar [10].

Uranus's spectrum is a"quasi-continuum" defined by a number of highly broadened absorption lines of H_2S, NH_3, and possibly PH_3, as well as H_2 collision induced absorption. A depletion in the abundance of one of these species or deviations from equilibrium in the hydrogen ortho/para ratio decreases the radio opacity of the atmosphere, producing millimeter/radio brightness increases. We employed the RadioBEAR radiative transfer modeling code[1] to determine which of these opacity sources must be depleted, and to what level, to explain the north polar brightening. We find that our nominal model, appropriate for a parcel of humid upwelling air with 10× the Solar abundance of H_2S and CH_4, provides a good fit at the equator of Uranus. Only a factor of ∼20 depletion in H_2S (down to 0.5× Solar) can produce a brightness increase as large as seen at Uranus's north pole, although additional depletions in CH_4, PH_3, and/or NH_3 may also be present.

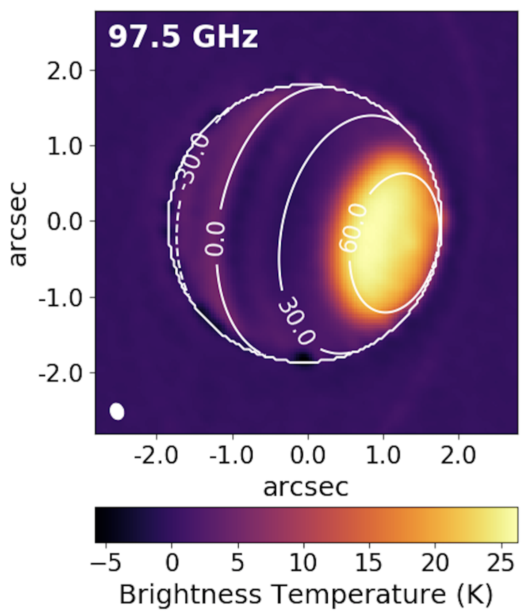

Figure 1: Disk-subtracted ALMA image of Uranus at 3.1 mm. The synthesized beam is shown as a grey ellipse in the bottom left corner of the image.

3. Summary

- VLA and ALMA spatial maps of the Uranian troposphere from 2015-2018 achieve the highest spatial resolution ever at mm-cm wavelengths
- Equatorial and mid-latitude bands revealed for the first time in ALMA images suggest a complex circulation pattern at ∼1 bar
- North polar circulation cell extends from 0.5-50 bar and requires a factor of ∼20 depletion in H_2S above 50°N latitude

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