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Aerosols and methane in the ice giant atmospheres inferred from spatially resolved, near-infrared spectra: I. Uranus, 2001–2007

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ABSTRACT

We present a radiative transfer analysis of latitudinally resolved H (1.487–1.783 µm) and K (2.028–2.364 µm) band spectra of Uranus, from which we infer the distributions of aerosols and methane in the planet's atmosphere. Data were acquired in 2001, 2002, 2004, 2005, and 2007 using the 200-inch (5.1 m) Hale Telescope and the Palomar High Angular Resolution Observer (PHARO) near-infrared adaptive optics (AO) camera system (Hayward, 2001). Observations sample a range of latitudes between ~80°S and ~60°N on the Uranian disk. At each latitude, a vertical distributions of aerosols was retrieved using a custom non-linear constrained retrieval algorithm. Two layers of aerosols are needed to match the observations: a thin upper layer peaking just below the 100-mb tropopause and a lower clouds at ~1.9 bars. Latitudinal variations in aerosols are interpreted in context of notional circulation models, while temporal changes suggest potential seasonal effects. We infer significant reduction in aerosol scattering optical thickness in southern latitudes between 2001 and 2007, in agreement with trends reported in studies covering part of the same period using different data and retrieval algorithms (e.g., Irwin et al., 2009, 2010, 2012; Sromovsky et al., 2009). Best fits to the data are consistent with proposed models of polar depletion of methane (e.g., Karkoschka and Tomasko, 2011). Finally, a discrete cloud from 2007 is analyzed in context of simple parcel theory, with the goal of identifying likely formation mechanisms. The low scattering optical thicknesses of the discrete high cloud are consistent with formation associated with vortices and shallow lift rather than deep convection.

1. Introduction

The atmosphere of Uranus has a history of variable cloud activity, but the processes responsible for the observed cloud distributions and their variability are not well understood. The clouds and hazes may be expected to respond to the seasonal forcing associated with Uranus' extreme axial tilt, but the ice giant's great distance, long seasonal cycle, and typically subtle atmospheric features make detailed observations of the clouds and their variability challenging.

Numerous spectroscopic and photometric measurements have led to our current knowledge of Uranus' clouds and hazes. Though a variety of cloud models have been employed, there is a consensus that two or more vertical layers of aerosols are required to reproduce the observed reflectance—including, at least, a high tenuous haze above a more substantial cloud layer––within an atmosphere of increasing methane with depth (e.g. Baines and Bergstralh, 1986; Pollack et al., 1986; Sromovsky and Fry, 2007; Sromovsky et al., 2011; Irwin et al., 2009, 2010, 2012a, 2015; Tice et al., 2013). With recent improvements in methane absorption coefficients, near-infrared (NIR) radiative transfer studies have been particularly fruitful in characterizing cloud vertical structure, latitudinal variation, and aerosol properties (Irwin et al., 2010, 2012c, 2015).

Nevertheless, uncertainties in the aerosol concentrations and methane mole fraction remain due to inherent challenges in constraining each remotely. Both methane and aerosols are expected to vary spatially and both contribute to the reflectance over much of the observed spectrum, making it difficult separate the precise contribution of each. In the NIR studies, this problem has often been dealt with by assuming methane profiles guided by theory and limited data, while retrieving aerosol profiles consistent the observed spectra (e.g. Irwin et al., 2010, 2012c, 2015); given the interdependence, uncertainties in the methane profile produce uncertainties in the retrieved aerosol profiles.

Voyager radio occultation data combined with infrared IRIS observations provided a range of possible methane and temperature

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profile combinations (Lindal et al., 1987). More recently, the best estimates of the stratospheric methane mole fraction have come from observations in the far infrared, where the contribution from aerosols is minimized (Orton et al., 2014; Lellouch et al., 2015). Analysis of Spitzer IRS spectra at wavelengths from 7.4 to 9.5 µm suggest a methane profile with a stratospheric mole fraction of $(1.6 + 0.2/{-0.1}) \times 10^{-5}$, far less than saturation limited and what is inferred in Neptune's atmosphere (Orton et al., 2014; Lellouch et al., 2015). Subsequent analysis of Herschel/PACS and HIFI data by Lellouch et al. (2015) found a 6 times greater methane mole fraction at the 200-mbar height and suggested that the two values could be reconciled if the methane mole fraction decreases sharply from 4.7×10^{-5} at the 89 mbar temperature minimum to match the Spitzer value at 2 mbar. As we will show, the latter methane profile would require significantly more aerosol in the haze layer to match observations.

Deeper in the atmosphere, wavelengths with varying sensitivities to methane and hydrogen absorption have been used to mitigate degeneracies. By comparing of hydrogen and methane absorption in HST-STIS spectra from 300 to 1000 nm, Karkoshcka and Tomasko (2009) found that the methane abundance in the 1–3 bar heights varied with latitude, with depletion towards the poles indicative of dynamical circulation (Karkoschka and Tomasko, 2011). Sromovsky et al. (2011) and Sromovsky et al. (2014) also determined methane depletion at the poles, but with slightly greater abundance at depth. How these latitudinal variations change with time has yet to be determined.

Details of how aerosols and methane distributions may change with the seasons are only emerging as detailed observations continue to sample the atmosphere over a collectively greater fraction of the Uranian seasonal cycle. Comparing observations over several years, significant changes in aerosols can be seen between 2006 and 2011 (Irwin et al., 2009, 2010, 2011, 2012c; Sromovsky et al., 2009), with a trend in diminishing reflectance at southern latitudes suggesting seasonal changes.

Against a backdrop of seasonal scale variability, occasional transient discrete cloud features appear that usually change on scales of months or less with undetermined formation dynamics (Sromovsky and Fry, 2005). Reports of occasional discrete bright cloud features on Uranus extend at least as far back as 1870, with some spots persistent enough to be observed over multiple nights and bright enough to significantly increase the perceived disk-brightness. Likewise, observers noted bright equatorial zones and adjacent dark belts, likened to those on Jupiter, beginning in the 1880s and continuing into the first half of 20th century (for an historical perspective, see Alexander, 1965 and references therein). By the 1970s, cloud activity on Uranus appears to have diminished, and the lack of attenuating aerosols in spectroscopic data had led some at the time to speculate whether or not the visible atmosphere was entirely devoid of clouds (Belton et al., 1971; Belton and Price, 1973). When Voyager 2 encountered Uranus is 1986, visible images of the sunlit, southern hemisphere (shortly after solstice) had captured only low-contrast features and subtle banding on an otherwise indistinct disk (Smith et al., 1986). The few discrete cloud features seen were interpreted as high clouds, likely composed of methane, and thought to possibly be signs of localized increased convective activity (Smith et al., 1986).

In the years since the Voyager 2 encounter, discrete cloud activity on Uranus appears to have increased, and modern technology has facilitated study of the enhanced activity. Using the Hubble Space Telescope (HST) and terrestrial telescopes fitted with adaptive optics, observers have documented a number of particularly bright features on Uranus at mid-Northern latitudes since the early 1990s (Karkoschka, 1998, 2001; Sromovsky et al., 2000, 2007; Sromovsky and Fry, 2004; Fry et al., 2012; de Pater et al., 2015). Some features at roughly 30°N latitude appear to be part of a long-lived complex that produced exceptional bright clouds in Keck observations from August 2005 and June 2007 (Sromovsky et al., 2009). The complex appeared to drift in longitude and oscillate in latitude, and it was likely associated with a dark spot seen at the same latitude seen by HST in 2006 and likely again by Keck in the 2007 observations (Sromovsky et al., 2009; Hammel et al., 2009), inevitably calling to mind the Great Dark Spot and companion clouds of Neptune as seen by Voyager 2. Observations in 2014 captured clouds of brightness and extent unprecedented in the modern era at similar latitudes (see de Pater et al., 2015). What mechanisms lead to the occasional formation of these clouds is an open question, but some potential clues into discrete cloud dynamics may be inferred from analysis of their vertical structure.

In the present study, we add to previous investigations into the distribution of Uranus' clouds and hazes by analyzing an unpublished data set of spatially resolved, near-infrared spectral data—acquired 2001 and 2007 using the Hale 200-inch telescope at the Palomar Observatory, aided with adaptive optics. Using a customized constrained inversion algorithm, vertical profiles of clouds and hazes are retrieved over a range of latitudes as several methane models are investigated. The retrieved aerosol distributions are in good agreement with previously published results (e.g. Irwin et al., 2009, 2010), despite differences in retrieval techniques and modeling assumptions. The consistency of the acquisition and analysis provides an ideal opportunity for analyzing potential seasonal changes in the years leading up to equinox, complimenting other temporal studies that sampled only part of the same period using a variety of data sets (e.g. Irwin et al., 2009, 2010, 2011, 2012c; Sromovsky et al., 2009). Apparent seasonal trends in the clouds and hazes are reported, consistent with the findings from subsequent observations. Finally, a lone, discrete cloud feature is analyzed; with the retrieved vertical structure and optical thickness, a simple thermodynamic parcel theory model is used to argue in favor of a formation associated with shallow lift as opposed to deep convection. Section 2 describes the data set, followed by the analysis techniques in Section 3, and results in Section 4. Section 5 presents a discussion of the results, concluding with a summary in Section 6.

2. Data

2.1. Observations

Observations of Uranus were made annually between 2001 and 2007 at Palomar Observatory, using the 200-inch (5.1 m) Hale Telescope and the Palomar High Angular Resolution Observer (PHARO) near-infrared adaptive optics (AO) camera system (Hayward, 2001). The PHARO instrument captured spatially resolved images and spectra in both the H (1.487–1.783 µm) and K (2.028–2.364 µm) bands. Images had a plate scale of 40 mas per pixel, with Uranus extending ~93 pixels in diameter in the 1024 × 1024 array images. The corrected seeing discs (i.e. the point spread function through the atmosphere following the adaptive optics correction) were estimated from the full width at half maximum of Uranian satellites; depending on the atmospheric seeing and AO performance, corrected seeing disks were typically four to seven pixels in diameter near the planet center, equivalent to roughly 2160 km to 3780 km of spatial scale at the sub-observer point on Uranus—far short of being diffraction limited. The spectrograph had a resolving power of roughly R~1500. Passing through a 0.5″ slit (~13 pixel), the observed flux was dispersed by grating prism across a 1024-pixel detector at a resolution 0.285 and 0.332 nm/pixel for H and K, respectively. The slit of the spectrograph was aligned roughly along the planet's central meridian, yielding spectra as a function of latitude across the disc. Precise alignment was not possible due to operational constraints imposed by the AO system. The final calibrated