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Latitudinal distribution of hydrogen sulphide and methane in the atmospheres of Uranus and Neptune

Patrick Irwin (1), Leigh Fletcher (2), Nicholas Teanby (3), Glenn Orton (4), Daniel Toledo (1), Ashwin Braude (1) and Bruno Bézard (5)
(1) Department of Physics, University of Oxford, UK, (2) Department of Physics and Astronomy, University of Leicester, UK, (3) School of Earth Sciences, University of Bristol, UK, (4) Jet Propulsion Laboratory, USA, (5) LESIA, Observatoire de Paris, France.
(patrick.irwin@physics.ox.ac.uk)

Abstract

Observations of the near-infrared spectra (1.45 – 1.80 μm) of Uranus and Neptune made with the NIFS integral-field spectrometer at the Gemini/North telescope in 2009 and 2010 have been used to directly detect, for the first time, the presence of hydrogen sulphide (H_2S) in the atmospheres of both the 'Ice Giants' [4, 5]. The observed cloud-top presence of H_2S constrains the deep bulk sulphur/nitrogen abundance to exceed unity for both planets and adds to the weight of evidence that H_2S ice likely forms a significant component of the main observable cloud deck. We also present an analysis of science verification observations of Neptune made in 2018 using the newly available Narrow Field Mode (NFM) of the MUSE integral-field spectrometer at the Very Large Telescope. This includes a collision-induced absorption band of hydrogen that can be used to distinguish between cloud-top height variations and variations in the methane (CH_4) abundance. We find that the cloud-top mole fraction of methane decreases from $\sim$ 5% at equatorial and mid-latitudes to values closer to 3% at polar latitudes, in rough agreement with an earlier analysis of HST/STIS Neptune observations [8]. A similar latitudinal variation of cloud-top methane abundance for Uranus was found by HST/STIS in earlier observations [7], which suggests similar depletion mechanisms act in both planets' atmospheres.

1. Introduction

The 'Ice Giants' of the solar system, Uranus and Neptune, have very similar radius, mass and effective temperature, but greatly different obliquities (98° for Uranus, 29° for Neptune) and greatly different ratios between their total emitted fluxes and absorbed solar flux (1.06 and 2.52, respectively). Despite these great differences, both planets have a similar latitudinal variation of zonal wind speeds, similar visual colour and both appear to have a uniform cloud deck, with a top at 2.5 – 3.5 bar, of uncertain composition, and highly variable clouds at lower pressures, assumed to be composed primarily of methane ice. The primary constituent of the main cloud deck has long been a mystery, but has generally been thought to be either ammonia ice or hydrogen sulphide ice, based on the assumption that at levels well below the observable clouds gaseous ammonia reacts with gaseous hydrogen sulphide to form a cloud of either NH_4SH or $(NH_4)_2S$ leaving the remaining, more abundant gas to condense alone at lower pressures and temperatures. For Jupiter and Saturn, where the absorption of gaseous ammonia is observed at the cloud-tops, it seems that the bulk abundance of ammonia exceeds that of hydrogen sulphide and thus that the main upper clouds we see are composed primarily of ammonia ice. For Uranus and Neptune, however, neither the spectral signature of ammonia or hydrogen sulphide has until now been detected, although observations with the Very Large Array at microwave wavelengths found a missing component of continuum absorption that was concluded to be most likely due to the pressure-broadened wings of H_2S lines [1, 2].

The retrieval of cloud-top pressure in these atmospheres is achieved by modelling the reflectance of near-infrared solar radiation from the clouds, which is modulated mainly by the absorption of gaseous methane. At wavelengths of strong methane absorption we can only detect light reflected from the upper levels of the atmosphere, while in regions of weak methane absorption, reflection from cloud particles at all levels in the atmosphere can be observed. Hence, such spectra can be 'inverted ' to 'retrieve' the vertical distribution of cloud density, provided we know the vertical profile of methane abundance. For a number of years the vertical profiles of methane observed by Voyager 2 radio-occultation observations were assumed to apply at all latitudes, but HST/STIS observations in 2002, 2003 [7, 8] found that the cloud-top mole fraction of methane reduced from $\sim 4\%$ at equatorial latitudes to $\sim 2\%$ at polar latitudes for both planets, which greatly affects cloud-profile retrievals if not properly modelled. This disentangling of cloud-top height and methane abundance latitudinal variations could be achieved with HST/STIS as its observations include the 825 nm collision-induced absorption band of H_2–H_2/H_2–He. This allows the cloud opacity to be probed at wavelengths of significant hydrogen-helium absorption (which are both well mixed gases) and low methane absorption.

2. Observations and Analysis

2.1. Hydrogen sulphide (H_2S) retrievals

Observations of Uranus and Neptune were made in 2009 and 2010 with the NIFS integral-field spectrometer at the Gemini/North telescope. These observations (made with adaptive optics) imaged the entire observable discs of both planets at sub-arcsecond resolution with each 'pixel' containing a complete spectrum from 1.45 – 1.80 μm. This spectral range includes a weak absorption band of hydrogen sulphide (H_2S), whose absorption line data has only recently been made available. Using this absorption band, which coincides with a region of weak methane absorption, we have directly detected, for the first time, the presence of this gas in the atmospheres of both the Ice Giants [4, 5]. Using our NEMESIS [3] radiative transfer and retrieval model, we estimate the cloud-top mole fraction (at 2.5 – 3.5 bar) of H_2S to be 0.4 – 0.8 ppm for Uranus and 1 – 3 ppm for Neptune. The observed cloud-top presence of H_2S constrains the deep bulk sulphur/nitrogen abundance to exceed unity for both planets and adds to the weight of evidence that H_2S ice likely forms a significant component of the main observable cloud decks. We find for Uranus that H_2S is most visible at lower latitudes, but becomes more difficult to detect near Uranus's pole. However, for Neptune we find that H_2S is most easily detected near its south pole.

2.2. Methane (CH_4) retrievals

For Neptune, we have also analysed science verification observations of the Narrow Field Mode (NFM) of the MUSE integral-field spectrometer at ESO's Very Large Telescope, covering 490 – 930 nm, which includes the collision-induced absorption band of hydrogen – helium near 825 nm that can be used to discriminate cloud-top height variations from variations in methane abundance [6]. Using NEMESIS, we find that the cloud-top abundance of methane mole fraction decreases from 5% at equatorial and mid-latitudes to values closer to 3% near the south pole, in agreement with an earlier analysis of HST/STIS observations [8].

3. Discussion and Conclusions

Gaseous hydrogen sulphide has been directly detected, for the very first time, above the clouds in the atmospheres of Uranus and Neptune. Its detection suggests that the bulk abundance of sulphur is greater than that of nitrogen in both 'Ice Giants', in stark contrast to Jupiter and Saturn, where nitrogen appears more abundant. The cloud-top abundances of H_2S and CH_4 appear to vary with latitude for both Uranus and Neptune. However, while the CH_4 latitudinal distributions appear similar, with diminished abundances seen at polar latitudes, the cloud-top H_2S latitudinal distributions are intriguingly different.

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