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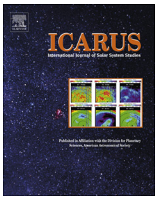

Spectral analysis of Uranus' 2014 bright storm with VLT/SINFONI ☆

P.G.J. Irwin [a,*], L.N. Fletcher [a,1], P.L. Read [a], D. Tice [a], I. de Pater [b], G.S. Orton [c], N.A. Teanby [d], G.R. Davis [e]

[a] *Department of Physics, University of Oxford, Parks Rd, Oxford OX1 3PU, UK*
[b] *University of California, Berkeley, CA 94720, USA*
[c] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*
[d] *School of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, UK*
[e] *Square Kilometre Array Organisation, Jodrell Bank Observatory, Lower Withington, Macclesfield, Cheshire SK11 9DL, UK*

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ABSTRACT

An extremely bright storm system observed in Uranus' atmosphere by amateur observers in September 2014 triggered an international campaign to observe this feature with many telescopes across the world. Observations of the storm system in the near infrared were acquired in October and November 2014 with SINFONI on ESO's Very Large Telescope (VLT) in Chile. SINFONI is an Integral Field Unit spectrometer returning 64×64 pixel images with 2048 wavelengths and uses adaptive optics. Image cubes in the H-band (1.43–1.87 μm) were obtained at spatial resolutions of $\sim 0.1''$ per pixel.

The observations show that the centre of the storm feature shifts markedly with increasing altitude, moving in the retrograde direction and slightly poleward with increasing altitude. We also see a faint 'tail' of more reflective material to the immediate south of the storm, which again trails in the retrograde direction. The observed spectra were analysed with the radiative transfer and retrieval code, NEMESIS (Irwin et al. [2008]. J. Quant. Spec. Radiat. Transfer, 109, 1136–1150). We find that the storm is well-modelled using either two main cloud layers of a 5-layer aerosol model based on Sromovsky et al. (Sromovsky et al. [2011]. Icarus, 215, 292–312) or by the simpler two-cloud-layer model of Tice et al. (Tice et al. [2013]. Icarus, 223, 684–698). The deep component appears to be due to a brightening (i.e. an increase in reflectivity) and increase in altitude of the main tropospheric cloud deck at 2–3 bars for both models, while the upper component of the feature was modelled as being due to either a thickening of the tropospheric haze of the 2-layer model or a vertical extension of the upper tropospheric cloud of the 5-layer model, assumed to be composed of methane ice and based at the methane condensation level of our assumed vertical temperature and abundance profile at 1.23 bar. We also found this methane ice cloud to be responsible for the faint 'tail' seen to the feature's south and the brighter polar 'hood' seen in all observations polewards of ~45°N for the 5-layer model.

During the twelve days between our sets of observations the higher-altitude component of the feature was observed to have brightened significantly and extended to even higher altitudes, while the deeper component faded.

1. Introduction

Although NASA's Voyager 2 spacecraft found Uranus to have a relatively featureless atmosphere during its fly-by of the planet in 1986, improved ground-based observations with ever-larger telescopes employing adaptive optics techniques have revealed the atmosphere of Uranus to be much more dynamically active than that seen by Voyager 2. In addition to larger telescopes and better imaging, a new class of instruments, Integral Field Unit (IFU) spectrometers, have become available, such as the SINFONI instrument at the European Southern Observatory's (ESO) Very Large Telescope (VLT), the NIFS instrument at Gemini-North, and the OSIRIS instrument at Keck II. Such instruments can simultaneously map planets like Uranus at thousands of wavelengths with spectral resolving powers in excess of $R = \lambda/\Delta\lambda = 1000$.

Since the mid 1990s several discrete clouds were seen in Uranus' atmosphere, generally at mid-latitudes, which became more frequent in the years leading up to the planet's northern spring equinox in 2007 (e.g. Sromovsky et al., 2007, 2009). Since equinox, Uranus continued to remain dynamically active, although overall cloud activity decreased. A notable exception to this was

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* Corresponding author.

E-mail address: irwin@atm.ox.ac.uk (P.G.J. Irwin).

[1] Present address: Department of Physics and Astronomy, University of Leicester, University Road, Leicester, LE1 7RH, UK.

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the detection of a bright spot near 25°N in November 2011 (Sromovsky et al., 2012).

Uranus cloud observations obtained with the Keck Telescope in August 2014 (de Pater et al., 2015) revealed an amazingly active Uranus; numerous cloud features were observed, amongst them the brightest cloud ever seen at a wavelength of 2.2 μm; this cloud ('Br' in their nomenclature) was seen at a latitude of ~15.5°N. These observations triggered a campaign by amateur astronomers and shortly thereafter a very bright cloud was observed in September 2014. For this feature to have been detected at visible wavelengths with amateur telescopes strongly suggests that it must have had substantial optical depth, suggesting a very significant convective event. Both from tracking the position of this feature and its latitude, it was discovered to have evolved not from the brightest 'Br' feature observed by de Pater et al. (2015), but from a smaller feature at a higher latitude (~33°N), 'Feature 2' in de Pater et al.'s nomenclature. This feature was identified as the deepest atmospheric feature seen with the Keck telescope in August 2014, at a pressure of near 2 bar. It also had an intriguing 'tail' trailing in the retrograde direction. The fact that the cloud had been observed by amateurs sparked huge international interest amongst the professional planetary astronomy community and a number of Directors' Discretionary Time (DDT) proposals were submitted to telescopes around the world and the highly unusual event triggered a Hubble Space Telescope (HST) Target of Opportunity program. However, narrow-band imaging (e.g. HST) is insufficient to probe fully the three-dimensional structure of this spectacular eruption since observations, although highly detailed, can be obtained at only a few wavelengths subject to different atmospheric absorption and thus sounding different discrete pressure levels. Here we report the results of VLT/SINFONI DDT observations of Uranus made on October 31st and November 11th 2014 which enabled us to map the feature at both high spatial and spectral resolution and thus much more precisely constrain the feature's vertical and horizontal cloud structure, also partially revealing its temporal evolution.

Table 1
2014 VLT/SINFONI H-Grism observations.

Date[a]	Target	T_{start}[b]	T_{end}[b]	N_{exp}	T_{exp} (s)	NDIT[c]	Scale	Airmass	Seeing
20141031	HD212874	01:27	01:27	1	10	2	0.1″	1.176	1.2″
20141031	Uranus[e]	01:42	02:17	24[d]	60	1	0.1″	1.211 – 1.164	1.05″
20141031[f]	Uranus	02:21	02:56	24	60	1	0.1″	1.161–1.147	0.92″
20141111	Uranus	00:36	01:12	24	60	1	0.1″	1.257–1.185	2.16″
20141111	Uranus	01:15	01:50	24	60	1	0.1″	1.183–1.15	1.44″
20141111	HD210780	02:00	02:00	1	4	2	0.1″	1.2	1.16″

[a] Dates are listed as YYYYMMDD.

[b] Times are UT.

[c] Number of Detector Integration Times (NDIT).

[d] The observation sequence for Uranus combined four sets of observations, in which for each there were five planet observations (2 × 2 mosaic plus once in the centre) and one sky observation.

[e] Uranus sub-Earth, sub-solar latitudes were 26.65° and 27.82° respectively on October 31st and 26.28° and 27.94° on November 11th. The angular diameters of Uranus on these dates were 3.69″ and 3.67″ respectively.

[f] Observations were also made on November 8th and 9th 2014 during poorer weather conditions, but these are of too low quality to present here.

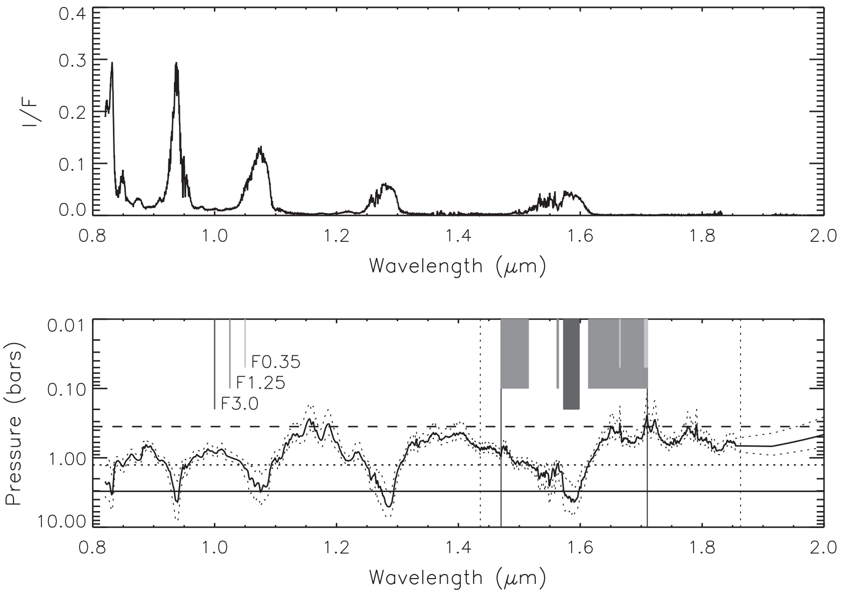

Fig. 1. Top panel shows a typical I/F spectrum of Uranus as observed by IRTF/SpeX. Bottom panel shows the pressure level in Uranus' atmosphere at which the two-way transmission to space for a cloud-free atmosphere (assuming the vertical profiles described in the text) is 0.5. Overplotted in the bottom panel are the pressure levels (dotted lines) for which the two-way transmission to space is 0.25 and 0.75, giving an indication of the vertical resolution of the observations at a single wavelength. Also overplotted in the bottom panel are the chosen cut-off pressures of 3, 1.25 and 0.35 bar. Continuum images ('F3.0') are averaged over all wavelengths where the two-way transmission to 3 bars exceeds 0.5. Medium-absorption and high-absorption images are averaged over all wavelengths where the two-way transmission at 1.25 and 0.35 bars is respectively less than 0.5, labelled respectively as 'F1.25' and 'F0.35'. The wavelengths selected by these filters in the wavelength range modelled (1.47–1.71 μm, shown by the vertical solid lines) are indicated by the grey regions in the bottom panel of differing length and darkness; a key to these filter regions is indicated by the vertical bars in the top left of the bottom panel. Finally, the bottom panel also shows the total wavelength range of the VLT H-band SINFONI observations (1.436–1.863 μm, vertical dotted lines).