Origin & Evolution of Storms, Clouds, and Hazes on Uranus and Neptune

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Shane CoverSheetID: 2018B_S000
Instrument: ShARCs/ShaneAO
Time Request: We request frequent 1-hour observations, run from script as often as possible by the observer on duty (details in the proposal). Minimum time request is 12 hours (12 one-hour observations).

Abstract

In recent years, the *Kepler* mission and ground-based spectroscopic follow-up have revolutionized our understanding of extrasolar planets. The composition and dynamics in atmospheres of transiting exoplanets can now be characterized (e.g. Swain et al., 2014; Ranjan et al., 2014). Models for exoplanet atmospheres are largely derived from planets in our own Solar System, yet many aspects of our own giant planets, especially our ice giants, remain elusive. Their global circulation patterns are still unknown; these can be studied via the vertical structure of the atmosphere, and the locations and migrations of cloud features. On Uranus and Neptune, cloud systems may form and evolve on timescales of hours to days. In the near-infrared we probe from the stratosphere down to a few bars in these atmospheres; observations with AO can resolve the cloud morphology, while data at two wavelengths (H and K bands) place constraints on cloud depths. **We request frequent, brief observations of Uranus and Neptune with ShARCs/ShaneAO to observe the evolution of cloud features and the associated timescales, and place constraints on global circulation patterns in these planets' atmospheres.**

1 Science Justification

1.1 Neptune

The atmosphere of Neptune is active and highly time variable; spatially-resolved near-infrared observations consistently detect cloud systems in the upper stratosphere. Variability spans a range of timescales from changes in cloud morphologies over days or weeks, to the substantial, broad-scale changes in cloud characteristics that have been observed since Voyager era (Martin et al., 2012). Near-infrared observations at multiple wavelengths can constrain the vertical structure of these clouds, while high-cadence observations can track the evolution, lifetimes, locations, and migrations of such features. These properties improve our understanding of zonal circulation (Fitzpatrick et al., 2013; Tollefson et al., 2018), and our models of Neptune's cloud systems and vortices.

A bright and unusually long-lived outburst of cloud activity on Neptune was observed in 2015. This detection led to speculation about whether the clouds were convective in nature, or bright companions to an unseen dark vortex (similar to the Great Dark Spot studied in detail by Voyager 2). HST OPAL images (Wong et al. 2018) at blue wavelengths finally answered this question by discovering a new dark vortex at 45°S. Dark vortices on Neptune are rare; this vortex is only the fifth ever seen. Follow-up observations with HST to observe the vortex have been reported and are in publication (Wong et al. 2018). The contrast of the storm has diminshed over the past two years, and the storm has drifted poleward. The drift of these vortices is highly sensitive to horizontal and vertical wind shear, making them valuable probes into the structure of Neptune's atmospheric jets.

While near-infrared observations are not sensitive to dark vortices, they do clearly detect the bright companion clouds that accompany these features. The companion clouds to the new vortex were first observed in July 2015 and were repeatedly observed afterwards by several telescopes including Lick Observatory (2015B; 2016B, PI de Kleer; Hueso et al., 2015, 2017). Over time, the feature brightness decreased, with only a few sightings in November. According to the Stratman et al. (2001) model, this is consistent with an increase in the altitude of the vortex top, perhaps due to growth of a new dark vortex.

Observations of Neptune's cloud features with ShARCs/ShaneAO will allow us to measure the temporal evolution and aerosol structure of Neptune's clouds during these months. A particular emphasis of the proposed 2018B observations will be on observing the dissipation of bright clouds coincident with the presence of the dark vortex and new equatorial storm (see Section 1.3), which presents a rare opportunity for improving our understanding of the life cycle of Neptunian vortices and the structure of planetary jets. Consistent observations will reveal any changes in brightness, size, shape, or position of the companion clouds, which will be useful for timing the demise of the dark vortex, something never before seen on Neptune, and constraining models of vortex dynamics (Le Beau and Palotai 2016, DPS). Tracking these changes will assist regular HST observations of Neptune via the OPAL program (Simon et al. 2015).

1.2 Uranus

When Voyager 2 arrived at Uranus in 1986, the south pole was facing the sun, and a featureless bright south polar haze was seen at high latitudes. The south polar haze was still present in 2002, and even as the haze subsequently cleared, the region remained free of discrete cloud features. As Uranus approached its 2007 equinox, numerous cloud features became evident, indicative of extreme dynamic activity. Examples are prominent clusters of discrete cloud features at 30°S and 30°N; both clusters were seen for many years, and exhibited large changes in brightness and extent near equinox.

Although storm activity has decreased substantially since Uranus' 2007 equinox, we were surprised by a gigantic storm on UT August 6, 2014, which measured 30% of the total light reflected off Uranus in K' band under cloud-free conditions. This is the brightest storm ever seen at this wavelength (Figure 2; de Pater et al., 2015). As shown in Fig. 2, numerous other smaller storms were visible as well. There appeared to be a sudden up-surge in dynamic activity, an event that was not expected so long after equinox (Sussman et al., 2012).

Estimates of a storm cloud's composition can be derived from its vertical location in the atmosphere using either spectroscopy or filter imaging in and out of CH_4 and H_2 gas absorption bands, particularly in the near-IR (e.g. Sromovsky et al., 2012; Irwin et al. 2017). For example, the bright storm in August 2014 is located at pressure levels of ∼300-600 mbar (de Pater et al., 2015). Equilibrium cloud condensation models can then be used to relate pressure levels to composition, suggesting that the bright storm clouds are composed of CH_4 ice (Atreya and Wong 2005; Wong et al. 2015a). Deeper condensation clouds, such as the main streak of the so-called "Berg" feature at a pressure level of ∼2 bars, are likely composed of H_2S (de Pater et al., 1991).

There also appears to be a hemispheric asymmetry in the vertical structure of Uranus' atmosphere: high (methane) clouds are almost exclusively restricted to the northern hemisphere with significant numbers of clouds seen north of 45°N, and no discrete clouds seen south of 45°S since 1986. Interestingly, methane gas is depleted both at high southern and northern latitudes (e.g. de Kleer et al., 2015), which makes the presence of cloud features near only one pole surprising; will this hemispheric asymmetry persist, or will the current discrete cloud activity near the north pole be suppressed or fully masked in the future (and if so, when)? Knowledge of the altitudes of the cloud features helps to define their composition and would help develop models of seasonal suppression of high latitude methane. The spatial variability of CH_4 is a key tracer of large-scale vertical motions. Subsidence from above the condensation level causes local depletion, while upwelling enriches the atmosphere in methane.

1.3 Proposed Program

We propose to determine the frequency, time evolution, and vertical location of cloud features on Uranus and Neptune by obtaining frequent, brief images of these planets with ShARCs/ShaneAO. Storm systems may form and evolve in a matter of days; the latitudes at which they form, as well as their subsequent migration, place constraints on global circulation models (see e.g., de Pater et al., 2014). With the recent vortex activity on Neptune and the bright storm system on Uranus in 2014, the proposed observations are particularly timely, and will tell us whether the activity on each planet constituted isolated events, or the initial stages of a longer phase of activity. Lick observations have been vital for tracking a new unusual equatorial strom on Neptune, imaged with Keck by Co-I Edward Molter this past summer, before it suddenly disappeared sometime in August before seemingly reappearing in October. Figures 3 and 4 show AO images from our 2017B program and tracking results of the new equatorial storm, predicting a velocity of 202 m/s. Our Lick data were also able to constrain the lifespan of a storm outbreak - about 1.5 months - since data without a visible equatorial storm were taken during the early and late summer (Molter et al., in prep). Last October, data from Lick helped catch the equatorial storm's sudden reappearence (Figure 5). Follow-up with amatuer observers helped tracked the storm, which seemed to increase in velocity to 237 m/s. However, only larger observatories like Lick can constrain cloud-top altitudes by observing with mulltiple bands. In addition, the spread in residulas show changes in the storm system morphology, which Lick can constrain much better than amateur observations. Short-lived, bright storms have been associated with rare dark vortices on Neptune, such as the Great Dark Spot which was paired with an equatorial storm before disappearing. Continuing our 'ToO' Lick program is crucial for monitoring new features in Neptune's dynamic atmosphere.

"Voluntary ToO" Scheduling

We request a 1-hour observing block for each activation of our program, to be run using a simple script by the observer on duty (should they voluntarily choose to activate). We request at least 12 activations during the semester, with more details given in Section 3.1. These observations are possible during twilight.

1.4 Justification of Program Continuation

This program is a continuation of our 2016B, 2017A, and 2017B programs (S002; S014; S000). We have obtained data over thirty nights from these programs to date. These data include coverage of a bright equatorial and southern storm systems on Neptune (see Figure 4), and are being correlated with observations of Neptune's storm systems from other telescopes, including Keck, HST, and ALMA. By extending our observations into 2018B, we will increase the time baseline for this analysis.

1.5 Figures

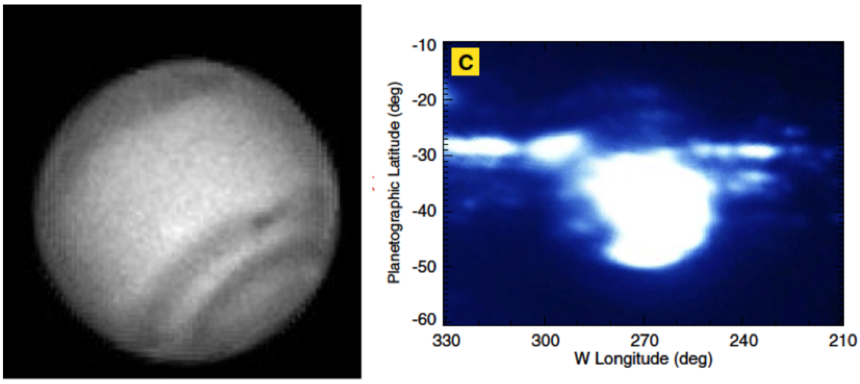

Figure 1: A new dark vortex in 2015 on Neptune. (Left) HST OPAL observations on 2015-09-18 at 467 nm showing the dark spot (Wong et al. 2018). (Right) Keck 1.6-micron map of the bright companion feature in August 2015 (Hueso et al. 2017). Highly-reflective clouds cover an area larger than the extent of the vortex itself.

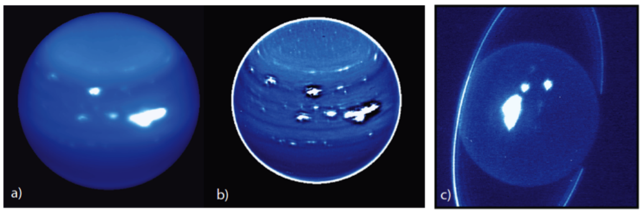

Figure 2: Storms on Uranus on UT 6 August 2014. (a) H-band image. Note the polar haze forming over the N. pole, and the storm system on Uranus' disk. (b) Same image, after applying a high-pass filter. Note the numerous features that become visible; we have never seen so many small clouds near the equator. (c) Image in K' band (north pole at 3:30 pm). The bright cloud feature is the brightest storm ever seen in K' band. Several other features are prominent in this band as well. The rings are also visible on the image. [de Pater et al., 2015; Sromovsky et al., 2015].

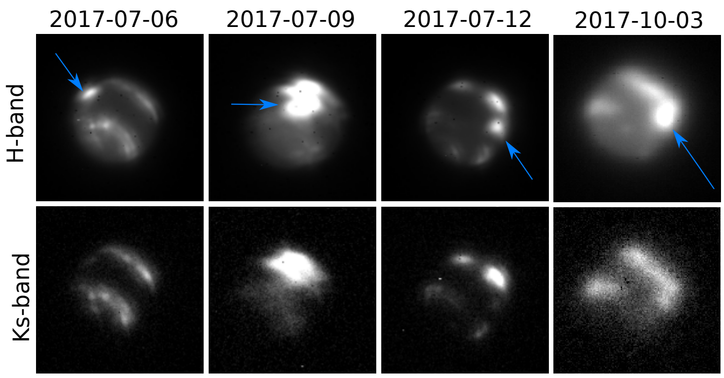

Figure 3: AO observations of Neptune from our 2017B ShaneAO/ShARCs program (S000). Each image is a single 120-second exposure time, and illustrates the data quality we expect for each of the five exposures requested per night in this program. Specifically, a new bright equatorial storm is plainly visible and suitable for tracking. After seemingly disappearing in August and September, an equatorial storm is again seen in October 2017.

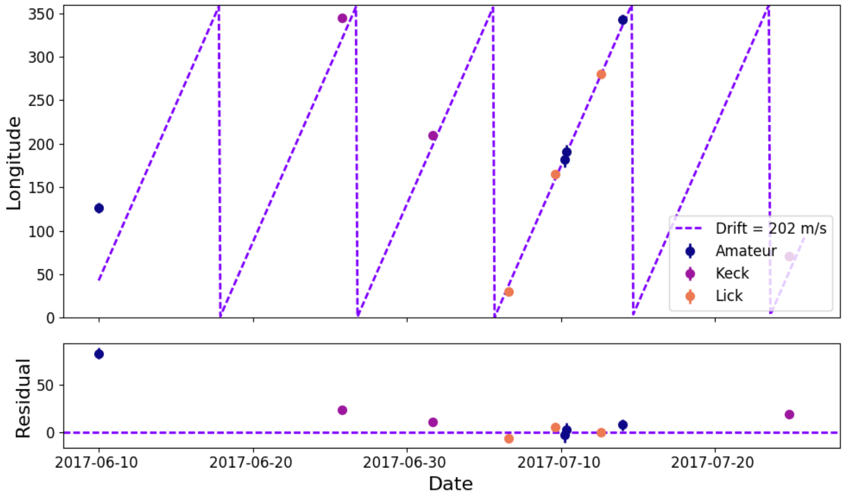

Figure 4: Tracking results of Neptune's new bright equatorial storm (see Fig. 3). The storm was first seen in Keck II AO images, but subsequent Lick observations have been crucial for tracking the storm and monitoring its disappearence, estimated sometime in early August.

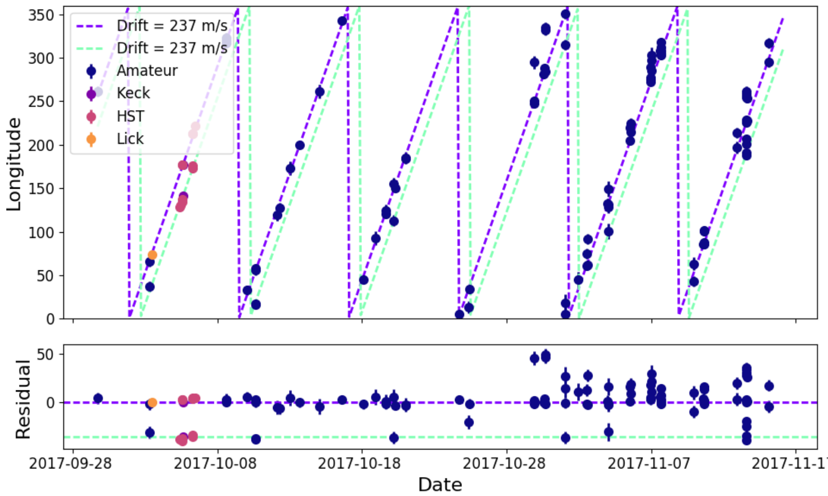

Figure 5: Tracking results of Neptune's bright equatorial storm after its reappearance. Its velocity increased to 237 m/s, highlighting the dynamic activity of Neptune's clouds. Continued observations of Lick will be helpful in constraining the brightness, altitude, and velocity of this and other storm features.

1.6 References

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Tollefson, J., et al., 2018. Icarus. *Accepted, with revisions.*
Wong, M.H. et al., 2015. Icarus 245, 273-281.
Wong, M.H. et al 2018. AJ. 155, 117.

2 Technical Remarks

2.1 Targets and Exposures

Uranus
RA: 02:01:10, DEC: +11:45:16 (non-sidereal target; coordinates as of 2018-Aug-01)
Apparent magnitude: ∼5.8
Angular diameter: ∼3.57"
Neptune
RA: 23:09:08, DEC: -06:31:19 (non-sidereal target; coordinates as of 2018-Aug-01)
Apparent magnitude: ∼7.8
Angular diameter: ∼2.34"

We request activation of our program at least 12 times in 2018B, under a "Voluntary ToO" type scheduling model (see Section 3.1), which we ran successfully in 2016B, 2017A, and 2017B. For each activation, we request one hour of time, which includes 10 minutes per target per filter (H and Ks), and 10 minutes of instrument and target acquisition overhead per target, based on our previous successful programs (see example data in Figure 4). Each of the targets will be observed with ShaneAO/ShARCs in both H and Ks filters with five 120 second exposures in a 4x4 arcsecond dither pattern, as we have done in the past. We will use the AO system in NGS mode, using the targets themselves for wavefront sensing.

Both targets are bright, and observations can take place during any lunar phase, or during twilight. Analysis is based on contrast between cloud features and background atmosphere, and absolute photometric calibration is not required. We therefore do not request standard star observations. A sky frame will be constructed from the median-average of the dithered images.

2.2 Supplementary Observations

No other observations are required to meet the science goals. However, data from HST program (#14492) led by Co-I Wong over 4 orbits of Neptune observations were obtained showing the dark spot and bright companion cloud, and an ALMA program (#2016.1.00859.S) led by PI Tollefson obtained data for Neptune in Cycle 4. An additional ALMA Uranus program (PI Molter) was accepted in Cycle 5 and data are being obtained. Additional ALMA proposals to image Uranus and Neptune are being submitted in Cycle 6. The temporal coverage of the proposed Lick program will provide context for interpreting these observations.

Non-UC Collaborator Luszcz-Cook is a former graduate student at UC Berkeley, and is part of a continuing collaboration with the UCB team. She has developed the radiative transfer code for calculating the altitude of Neptune's cloud features.

2.3 Status of Previously-Approved 3-m Programs

2017B: PI Tollefson "Origin & Evolution of Storms, Clouds, and Hazes on Uranus and Neptune" (ShaneAO/ShARCs) - Voluntary ToO program
Data have been obtained on over a dozen nights. Images obtained in July 2017 were used to track a new equatorial storm on Neptune. He is advising UC Berkeley astronomy undergraduate Christine Nguyen with Lick data reduction, navigation, and brightness changes in cloud systems before and after the outbreak of the equatorial storm. (UC Berkeley).
2017A: PI de Kleer. "Origin & Evolution of Storms, Clouds, and Hazes on Uranus and Neptune" (ShaneAO/ShARCs) - Voluntary ToO program
Data have been obtained on ten nights to date. Data reduction has been done on some nights to identify cloud features via the assistance of undergraduate student Samuel Vizvary (UC Berkeley).
2016B: PI de Kleer. "Origin & Evolution of Storms, Clouds, and Hazes on Uranus and Neptune" (ShaneAO/ShARCs) - Voluntary ToO program
Data have been obtained on a dozen nights. Data reduction has been done on some nights to identify cloud features via the assistance of undergraduate student Samuel Vizvary (UC Berkeley).
2015B: PI de Kleer. "Origin & Evolution of Storms, Clouds, and Hazes on Uranus and Neptune" (ShaneAO/ShARCs) - 4 hours allocated

Data are reduced. Detections of a bright storm on Neptune have been combined with observations from other facilities to determine the drift rate (Hueso et al. 2015). Supporting VLA data have been taken; the multi-wavelength analysis will take place once the radio data are received and reduced.

2.4 Graduate Students

PI Tollefson and Co-I Edward Molter are graduate students at UC Berkeley. A letter for PI Tollefson from thesis advisor Imke de Pater is attached at the end of this file.

3 Supplementary Technical Remarks

3.1 Technical Concerns - "Voluntary ToO" Scheduling

We request a 1-hour observing block for each activation of our program, to be run using a simple script by the observer on duty (should they voluntarily choose to activate). The script will use previously-tested exposure times based on our successful programs in 2015B, 2016B, 2017A, and 2017B.

Storms can form and evolve rapidly on both planets, and frequent observations are requested in order to get the best possible time coverage. We request as many activations as possible throughout the semester, with a minimum of 12 activations.

Two activations in one night, or activations on consecutive nights, are also valuable to achieve coverage of as many longitudes as possible. Activations should be separated by at least 6 hours, because the Uranus and Neptune rotation periods are 17 and 16 hours, respectively.

These observations are possible during twilight times, making them especially amenable to activation by observers whose programs are limited to dark time.

Modeled after the UCO policy for TOO programs, our co-authorship invitations as follows:
Single activation in 2018B: Invite observers on duty + program PI
Multiple activations in 2018B: Invite full program team
Engineering time: Invite staff observers on duty

3.2 Back-up Program

Program suitable as is for marginal observing conditions.

3.3 Experience and Publications

PI Tollefson is a fifth-year graduate student in the EPS department at UC Berkeley, writing his thesis on topics including wind speeds and cloud dynamics in the atmosphere of Neptune based on near-infrared, optical, and radio data. He is the PI of an ALMA Neptune program and has experience working on near-infrared AO observations and data reduction from Keck observations. Note the PI change from the previous 2016B and 2017A programs - former PI de Kleer is graduating from UC Berkeley this year.

Co-I de Kleer is a postdoctoral fellow in the Division of Geological and Planetary Sciences at Caltech and former UC Berkeley graduate student. She is currently working on characterizing the atmospheres and surfaces of the galilean satellites based on observations from visible to mm wavelengths. She has experience with near-infrared AO observations and data reduction including ShaneAO/ShARCs data of Uranus and Neptune, as well as modeling of ice giant atmospheres based on near-infrared spectroscopy.

Co-I de Pater is a planetary astronomer who has worked extensively on planetary atmospheres, surfaces, rings, comets, asteroids, satellites, and Jupiter's magnetic field. She specializes in radio and infrared AO observations of solar system bodies.

Co-I Wong contributes models of cloud condensation, and conducts optical imaging of Uranus and Neptune with HST as a member of the OPAL team and PI of a Neptune program.

Co-I Luszcz-Cook is an expert in the atmospheres of Uranus and Neptune, in particular in using radiative transfer modeling in the millimeter and infrared to understand the global atmospheres.

Co-I Molter is a second-year graduate student in the Astronomy department at UC Berkeley. He has an interest in the cloud dynamics in the atmosphere of Uranus and is involved in an ALMA proposal to understand opacity sources in Uranus' atmosphere.

Co-I Gates has extensive experience with Lick/ShaneAO, including observations of Uranus and Neptune. She will be instrumental in setting up the program and facilitating execution of the program by observers.

Co-I Gavel has extensive experience with Lick/ShaneAO, including observations of Uranus and Neptune. He will be instrumental in setting up the program and facilitating execution of the program during engineering time.

Selected Publications

Tollefson, J., et al., 2018. Icarus, Accepted. (Neptune atmosphere from Keck observations)
Luszcz-Cook, S., et al., 2016. Icarus, 276, 52. (Neptune atmosphere from Keck OSIRIS data)
Wong, M.H. et al., 2015. Icarus 245, 273-281. (Cloud modeling)
Wong, M.H. et al 2018. AJ. 155, 117. (Neptune Dark Spot)
de Kleer, K., et al., 2015. Icarus, 256, 120. (Uranus atmosphere from Keck OSIRIS data)
de Pater, I., et al., 2015. Icarus, 252, 121-128. (Record-breaking Storms on Uranus in 2014)
de Pater, I., et al., 2014a. Icarus, 237, 211-238. (Neptune's GCM, multi-wavelength campaign)
de Pater, I., et al., 2013. Icarus, 226, 1399-1424. (2007 Uranus Ring Plane Crossings)
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de Pater, I., & 9 co-authors, 2013. Icarus, 226, 1399-1424. (Uranus RPX campaign)
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de Pater, I., et al., 2006. Science, 312, 92-94. (Uranus: red ring, blue ring)

3.4 Resources and Publication Timescale

PI Tollefson is supported by the NASA/NESSF graduate fellowship. Additional grant funding comes from NSF grants.

ShARCs data will be reduced immediately, and bright cloud features will be identified for comparison with past activity and HST observations. Analysis and publications will combine this data with that of other observatories, to form the most complete picture of storm activity based on all available temporal and spectral coverage.