

Neptune and Titan Observed with Keck Telescope Adaptive Optics

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ABSTRACT

We report on observations taken during engineering science validation time using the new adaptive optics system at the 10-m Keck II Telescope. We observed Neptune and Titan at near-infrared wavelengths. These objects are ideal for adaptive optics imaging because they are bright and small, yet have many diffraction-limited resolution elements across their disks. In addition Neptune and Titan have prominent physical features, some of which change markedly with time. We have observed infrared-bright “storms” on Neptune, and very low-albedo surface regions on Titan, Saturn’s largest moon. Spatial resolution on Neptune and Titan was 0.05-0.06 and 0.04-0.05 arc sec, respectively.

Keywords: adaptive optics, Neptune, Titan

1. ADAPTIVE OPTICS SYSTEM AND INFRARED CAMERA

The Keck II adaptive optics system¹ is located on an optical bench at the Nasmyth platform of the telescope. The Xinetics deformable mirror has 349 degrees of freedom, of which approximately 249 are illuminated at any given time as the hexagonal pupil of the telescope rotates on the round deformable mirror. The Shack-Hartmann wavefront sensor is based on a 64x64 pixel Lincoln Laboratories CCD with read noise of approximately 6 electrons per pixel. The real-time computer is based on the Mercury RACE architecture, and uses sixteen Intel i860 floating-point CPUs. Overall system bandwidth is typically about 30 Hz using bright natural guide stars² as a wavefront reference.

The high-resolution camera used for the commissioning and science verification of the Keck adaptive optics system was KCam. The detector for this camera is a 256x256 pixel NICMOS HgCdTe array. KCam is an interim adaptive optics science instrument, pending arrival of NIRC2 (the facility 1024x1024 high-resolution camera) and NIRSPEC (an infrared spectrograph recently mated to a scale-changer for adaptive optics use).

2. OBSERVATIONS OF NEPTUNE

2.1 Background and physical motivation

Neptune is one of the solar system's "giant planets", and unlike the terrestrial planets it does not have a solid surface. However Neptune hosts some of the most violent weather in the solar system^{3,4}, with circumferential wind speeds greater than 400 m/s and very high wind shear as a function of latitude: the atmospheric rotation period varies from near 18 hours near the equator to about 12 hours near the poles. It has been hypothesized that the energy source for these unusually high winds may lie within Neptune's deep interior, which emits about 2.6 times as much heat as the planet receives from the Sun.

During the 1989 Voyager 2 fly-by of Neptune, a persistent dark oval was observed in the southern hemisphere when viewed in visible light⁵. This "Great Dark Spot" seen by Voyager (and similar spots later seen by the Hubble Space Telescope^{6,7}) had greatest contrast at blue wavelengths, and had a longitudinal spatial extent up to 10,000 km. The fact that these dark spots were able to persist for periods up to several months in the face of Neptune's large latitudinal wind shears suggests that they are stable vortex structures.

Voyager observed an elongated companion cloud that was very bright in methane-band images at 8900 Å, accompanying Neptune's Great Dark Spot along its southern border. This cloud has been inferred to consist of high-reflectivity condensates at high altitudes (pressures < 0.1 bar) in Neptune's atmosphere⁷. Hammel and Lockwood⁶ found that a common feature of every dark spot discovered to date was "an association with the single brightest methane-band feature on the planet at that time."

The nature and physical composition of the methane-bright features remain poorly understood. They can be elucidated by near-infrared adaptive optics imaging^{8,9} where the methane-bright clouds are clearly visible in both broad-band and methane-band filters, and by adaptive optics spectroscopy to study the chemical composition and altitude structure of the clouds. We do not yet know how long a typical infrared-bright cloud can persist in Neptune's atmosphere in the face of the large prevailing wind shear. The latter issue can be addressed by synoptic ground-based observations with adaptive optics.

2.2 Observational results: Neptune

Neptune images were obtained in May, June, and October 1999, using the KCam near-infrared camera. Figure 1a shows an H band (1.65 μm) image of Neptune without adaptive optics from May 25, 1999 UT. North is up; east to the right. There are two bright but fuzzy regions in the south, each with diameter about 1/3 of the disk.

Figure 1b shows an adaptive optics image taken within a few minutes of Figure 1a. Several types of features become apparent with adaptive optics:

- 1) Thin circumferential cloud bands are seen in both hemispheres, at latitudes corresponding to +20 to +30 deg and - 30 to - 60 deg. We believe that these correspond to the very thin circumferential structures seen by Voyager⁵. If they have the feature widths measured in the Voyager fly-by images, these circumferential cloud bands are unresolved by the Keck adaptive optics system. We will return to this point in Sect. 2.3.

2) The equatorial region, between latitude +20 and -15 deg, is dark at H band.

3) An intense concentration of infrared-bright clouds is seen in the southern hemisphere on the east (right) side of the image near the limb, between latitudes -25 to -45 deg and longitudes 70 to 105 deg. (Here longitudes are measured relative to the rotation of Neptune's magnetic field). Although one can see circumferential sub-structure in this bright region, the infrared-bright clouds appear to be much more continuous in latitude on the eastern limb when compared with the western limb. The latter appears to be a collection of circumferential cloud bands with substantial dark lanes between them. One can also see in Figure 1b that some light extends over the southern limb of Neptune. This is due to the "halo" of the adaptive optics point spread function, and is more obvious on the south because of the infrared-bright clouds there.



Figure 1a. Image of Neptune at 1.65 μm without adaptive optics, May 25, 1999 UT.

Figure 1b. Image of Neptune at 1.65 μm with Keck adaptive optics, May 25, 1999 UT.

Figure 2 shows a magnified view of the infrared-bright region from the lower right of Figure 1b. Whereas the "color map" for Figure 1 used a square root scaling for the correspondence between greyscale intensity and Neptune's measured brightness, Figure 2 uses a linear color map to emphasize spatial structure near the area of peak brightness. Each pixel subtends 0.017 arc sec on the sky, which corresponds to ~ 375 km at the distance of Neptune. It is clear from this image that the Keck adaptive optics system is able to see spatial variations across two to three pixels, corresponding to a spatial resolution of 0.034 to 0.051 arc sec, or a linear distance of 750 to 1125 km at Neptune

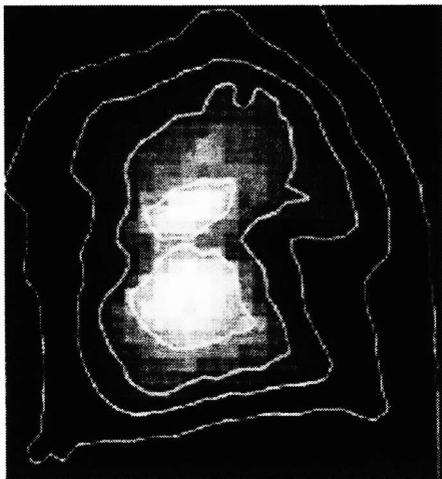


Figure 2. Magnified view of bright region seen on lower right of Fig. 1. Each pixel corresponds to 0.017 arc sec, or about 375 km at Neptune.

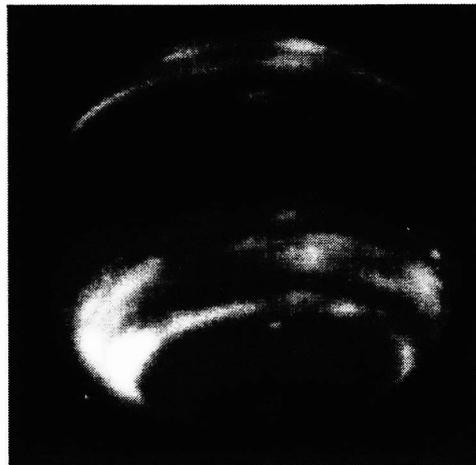


Figure 3. Adaptive optics image of Neptune at wavelength of 1.65 μm , June 28, 1999.

Figure 3 shows Neptune at 1.65 μm using adaptive optics on June 28, 1999. As with the May 25 image, at this epoch a bright region in the south is also seen. Compared to the earlier bright region, this structure is more extended in longitude, more compact in latitude, and is a bit farther south: it lies between latitudes -45 - -60 deg and longitudes 135 - 170 deg. The bright region extends beyond around the limb as well.

We do not know if the two infrared-bright regions seen in May and June of 1999 are related, or if they are independent phenomena. If the cloud pattern in May had been merely sheared out by the prevailing equatorial winds, a region that had been coherent on May 25 would be entirely pulled into thin circumferential bands a month later. But it is intriguing that the June bright region is slightly more spread-out in longitude and more compact in latitude than the bright region seen in May, and is at roughly the same latitudinal position. If these infrared-bright regions correspond to stable vortex structures analogous to the Great Dark Spot, it is possible that we are witnessing the slow evolution of one of these vortices under the influence of Neptune's strong wind shear.

2.3 Point spread function using Neptune as a "guide star"

Neptune subtended an angle of ~ 2.3 arc sec during these observations. Because of its large angular extent, it was not an ideal "point source" to use for an adaptive optics wavefront reference. This means that the point spread function (PSF) could not be measured by closing the adaptive optics loop on a nearby star of the same magnitude and color, because the adaptive optics performance with a star would differ from that obtained using Neptune itself as a wavefront reference. Instead we have had to develop two other independent ways to estimate the PSF for these Neptune observations.

First, we used the fact that the circumferential cloud bands are not resolved by the 0.017 arc sec pixels of the KCam camera. We closed the adaptive optics loop on Neptune, and plotted the measured variation of intensity as a function of the distance across one of

these unresolved circumferential cloud bands, in a direction perpendicular to the band structure along the line shown in Figure 4. The trace of intensity versus distance across the cloud band is shown in Figure 5. The full width at half maximum gives us an estimate of the width of the one-dimensional PSF: 0.05 – 0.06 arc sec.



Figure 4. Close-up view of the Northern cloud band seen in Figure 1b, showing line along which the one-dimensional point spread function was measured.

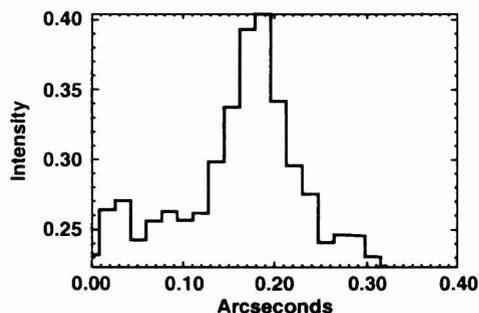


Figure 5. One-dimensional "slice" along line shown in Fig. 4. Vertical axis is intensity; horizontal axis is distance along "slice." FWHM is 0.05 - 0.06 arc sec.

Neptune's moon Triton (apparent diameter 0.13 arc sec) was of course resolved in adaptive optics images for which Neptune was the wavefront reference. We used Triton to obtain an independent estimate of our PSF. We created a model of Triton (a uniform Lambert sphere), and used this model to deconvolve the observed Triton image, recovering a PSF. The deconvolved PSF was slightly elongated but showed a resolution of 0.05 arc sec, consistent with the measurement obtained from the cloud band.

3. OBSERVATIONS OF TITAN

3.1 Background and physical motivation

Titan is Saturn's largest moon, and has many intriguing similarities to Earth despite the obvious differences in solar heating and surface temperature. Titan's atmosphere, like Earth's, is made largely of nitrogen. Its surface atmospheric pressure is similar to that of Earth (1.5 bar), and its atmospheric chemistry is thought to have many processes in common with the chemistry of the early Earth.

When the Voyager spacecraft flew by Titan, its visible-light camera saw only a featureless orange "smog" that obscured the surface. This haze is thought to be due to hydrocarbons created by the photolysis of methane by UV (sunlight). In 2004 the Huygens probe will be launched from the Cassini spacecraft to make a landing on Titan, to observe its surface features and chemistry. Hence observations of Titan's surface are growing in urgency.

It is now known that one can "see through" Titan's haze layers¹⁰ by observing in several narrow infrared spectral windows where the methane absorption is low. Hubble Space Telescope has done this with some success in the methane windows available to its CCD cameras (wavelengths < 1 micron)¹¹. However the optical depth is lower in methane windows at wavelengths > 1 micron, and these are accessible from the ground via

adaptive optics. Imaging in these near-infrared methane windows has been done successfully by several adaptive optics groups using 3 – 4 meter telescopes^{12,13,14}.

Theoretical predictions of the nature of Titan's surface are also very intriguing. It is thought^{15,16} that ultra-violet photons from the sun will photolyze methane in the atmosphere, making ethane which should condense out and fall as rain to the surface. What happens to the ethane next is controversial. Predictions that the ethane would form "global oceans" have been proven false by radar mapping¹⁷. Perhaps the ethane collects in surface depressions such as lowlands, basins, or craters. The signature of these deposits of liquid ethane would be regions of very low albedo (surface reflectivity) on Titan's surface.

Speckle interferometric imaging observations at the Keck I telescope¹⁸ have shown that there are indeed regions on Titan's surface with albedo < 0.03 , a value which would be consistent with the existence of localized "lakes" or "seas" made of liquid ethane or other dark hydrocarbons. The speckle images also showed regions of higher albedo (~ 0.15) which could be ice or ice-rock highlands, or perhaps continental structures.

3.2 Observational results: Titan

We observed Titan with the Keck adaptive optics system in February and October of 1999. We used the KCam near-infrared camera. Figure 6a shows a typical image of Titan taken without adaptive optics; the 0.8 arc sec disk (suggested by circle) barely resolved.

Figure 6b shows an observation of Titan obtained on February 26, 1999 using adaptive optics, at a wavelength of 1.65 μm . The adaptive optics wavefront reference was Titan itself. This image was then deconvolved using a Lucy-Richardson algorithm with a point spread function measured using a nearby star. (This is a more reliable procedure for Titan than for Neptune, since Titan's angular size of ~ 0.8 arc sec is close to that of a "real" star as seen in the wavefront sensor.) All main features in 5b, including dark regions, limb brightening, and bright region in the south, are visible in the undeconvolved image.

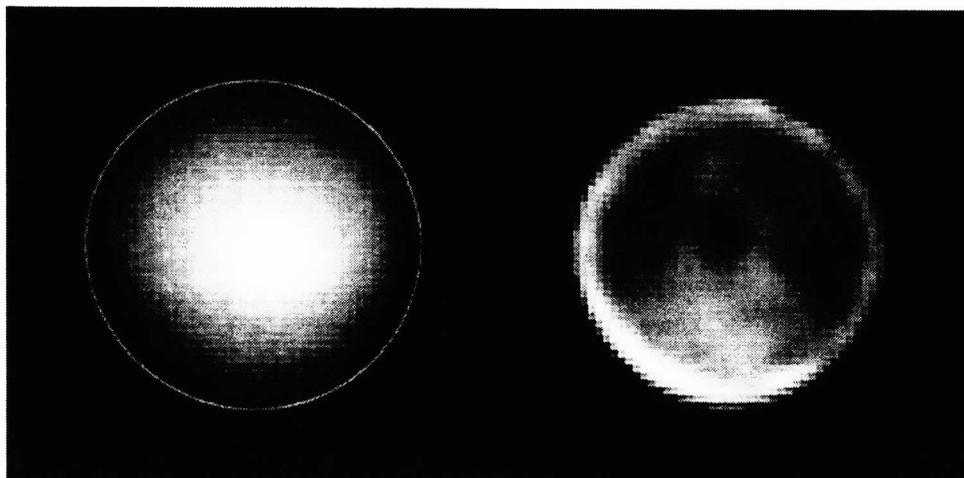


Figure 6a. Titan without adaptive optics, at a wavelength of 1.65 microns.

Figure 6b. Titan with Keck adaptive optics, at a wavelength of 1.65 microns.

To obtain quantitative results on the surface albedo implied by this image, it will be necessary to make models of the atmospheric scattering and to “subtract” the effects of the atmosphere in order to “see” the surface. This process is underway. It is already clear that there is significant contrast between bright and dark regions on this face of Titan.

4. CONCLUSIONS AND FUTURE DIRECTIONS

Adaptive optics on the new generation of 8 – 10 m telescopes is proving to be a powerful tool for solar system research. Most planets and their major moons are bright enough to used as a wavefront reference. Solar system objects have interesting surface detail, and show significant changes with time. For planets such as Neptune that are smaller than a few arc sec in angular size, the Keck adaptive optics system has achieved resolutions of 0.05-0.06 arc sec or better, with many tens of resolution elements across the disk.

On Neptune we have characterized the spatial structure of infrared-bright clouds at an angular scale corresponding to 1000 km or less at Neptune. The next step is to achieve sufficiently complete temporal monitoring of these bright clouds to be able to understand whether they represent relatively “stable” vortex structures that can persist in the face of Neptune’s huge wind shears, or whether they are transient features constantly being re-created by processes arising in Neptune’s interior. The advent of capable infrared spectrographs behind adaptive optics systems will allow us to determine the chemical make-up and vertical structure of the cloud and haze layers within these bright infrared cloud complexes, and to couple them with realistic models of the atmospheric structure.

On Titan, adaptive optics spectroscopy in the near-infrared will allow us to understand atmospheric chemistry, as well as to identify the surface composition (solid and liquid). Cassini's Huygens probe will land on Titan in 2004. But with a lifetime of less than one hour, Huygens will obtain only a snapshot in space and time. Ground-based adaptive optics observations will provide crucial context for the interpretation of these data.

5. ACKNOWLEDGEMENTS

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