# First Ground-Based Adaptive Optics Observations of Neptune and Proteus

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**Abstract:**

High angular resolution (0.15”) K-band images of Neptune were obtained in August 1995, with the University-of-Hawaii adaptive optics system mounted on the 3.6-m Canada-France-Hawaii telescope. The images show bright high contrast features that are believed to be high altitude clouds. They confirm that low latitude (< 30˚) cloud activity has shifted since Voyager from the south hemisphere to the north hemisphere, whereas higher latitude activity seems more permanent. Proteus can be seen at the locations predicted from Voyager data. Its K-magnitude is 19.0 ± 0.03. The corresponding geometrical albedo is identical to that measured in the visible by Voyager.

## Introduction

Voyager 2 images of Neptune revealed an unexpectedly high atmospheric activity, raising questions about the driving source of energy (Smith et al., 1989). Attempts have been made to follow from Earth the evolution of atmospheric features seen by Voyager, both with ground-based telescopes and with the Hubble Space Telescope (HST). HST has provided the highest angular resolution images since Voyager, first in 1991 (before repair), (Sromovsky et al. 1995), then in 1994 (Hammel et al., 1995), but only at wavelengths below 1 μm. Ground-based observations made in the K-band (2.2 μm) benefit from a higher contrast, because clouds are seen against a planet background darkened by strong methane absorption, but the angular resolution is severely limited by seeing.

We present here what we believe to be the first ground-based adaptive optics observations of Neptune. Adaptive optics (AO) is a means for real-time compensation of wave-front distortions produced by turbulence in the Earth's atmosphere. This technique has allowed us to produce the sharpest K-band images of Neptune ever obtained with an angular resolution of 0".15, providing 15 resolution elements across Neptune's equatorial diameter.

## Observations and data reduction

Observations were made with an experimental AO system specifically developed at the University of Hawaii (UH) for astronomical observations (Roddier et al., 1991). A small (30-mm diameter) image of the telescope entrance aperture is formed on a 13-actuator deformable mirror which compensates wave-front aberrations. The mirror –called bimorph– consists of two piezoelectric wafers glued together. The correction rate (1.2 kHz) is sufficiently high to compensate wave-front distortions introduced by the atmosphere. Near infrared (1-2.5 μm) images are recorded with a 1024 x

1024 pixels HgCdTe infrared camera developed by Hodapp et al. (1995). Immediately before the camera, light shortward from 1 μm is reflected toward a wave-front sensor. An array of 13 photon-counting avalanche photodiodes detect any unbalanced illumination between oppositely defocused images of a guide source. The output signals relate to local errors in the wave-front curvature. They are used to drive the deformable mirror through a computer. For the observations presented here, Triton was used as a guide source. At the time of the observations, the angular distance between Triton and Neptune was 14”. This was found to be close enough for the atmospheric distortions to be almost the same for Neptune and Triton.

The instrument was mounted at the Cassegrain f/35 focus of the 3.6-m Canada-France-Hawaii Telescope (CFHT) with the main purpose of observing the rings of Saturn as the Earth was crossing the ring plane (August 1995). We took opportunity of this observing run to record a few observations of Neptune. The data consist of four 5-minute exposures taken through a standard K-band filter. The exposures were taken on August 12, 1995, starting about half an hour after midnight (local time), that is on August 12 around 10:30 am (UT). For each of the 4 exposures, the exact mid-exposure time in decimal hours is: 10.4683, 10.5928, 10.6994, 10.8167. The plate scale and North direction were calibrated using the Saturn data. The pixel size is 0”.035, or 740 km at Neptune’s distance (for comparison, the pixel size of HST images is 990 km). The top of each frame is slightly eastward from north, at a position angle of +0.65 degrees. The effect of planet rotation is clearly seen when comparing successive frames. Adopting a 16 hour rotation period (Sromovsky et al. 1995), the blur produced at the sub-Earth point by a five minute exposure is one pixel, and was deemed acceptable. The blur due to the motion of the guide source (Triton) relative to Neptune was 0.4 pixel.

A remotely controlled offset mirror in the AO system allows the telescope to be pointed anywhere up to 20” away from the guide source. This mirror was used to record Neptune on four different locations on the 1024 x 1024 infrared array, thus avoiding the need for recording a separate background exposure. Sky flats were recorded at sunrise for flat-field corrections. Each image was flat-fielded with these sky flats and background subtracted. Adaptive optics produces images with a sharp diffraction-limited core. However, the core is surrounded with a halo of light scattered by uncompensated small scale wave-front errors. The halo produces a loss of contrast in the recorded images. The situation is similar to (but not as severe as) that of the impaired HST. The image contrast can be restored by deconvolution. To do that, we have estimated the point spread function (PSF) in two different ways. Firstly we used images of Triton recorded on the same frame. This has the advantage that they were taken at the same time under exactly the same conditions. However, the angular diameter of Triton was 0.13” which is comparable to the PSF full width at half maximum, that is Triton was almost resolved. Secondly we used stellar images taken some time later. In this case the source was unresolved, but the seeing conditions may have changed. Both PSFs yielded similar results. Best results were obtained by taking the median of all the available references (Triton and stellar). This approach has the advantage of improving the signal-to-noise ratio (SNR) on the halo which surrounds the PSF, a factor we found important for proper removal of the image blur caused by this halo.

Because Neptune is quite dark in the K-band and the image is highly magnified, intensity levels in a 5-minute exposure are quite low and each of the four images is noisy. As a result, deconvolution of individual images was found to be ineffective. To improve the signal-to-noise ratio, we considered adding all four images. However, when doing this the rotation of the planet produces a significant blur. Over a 20 minute interval, a 16h rotation period produces a blur of the order of one resolution element. To avoid this blur, we decided to remap each image slightly as if it were taken precisely at the same time, arbitrarily chosen at 10h 38m (UT). The Jacobian of the geometric transformation was calculated assuming that irradiance was independent of direction, an approximation deemed acceptable for small corrections. We attempted to determine the rotation period that would best match the cloud positions in the first and the last image. We clearly found that a longer period was needed for the low latitude clouds in the northern hemisphere than for the high latitude clouds in the southern hemisphere. The best match gave 21h for the north and 18h for the south. Given the uncertainty on these values (± 1 hour at least), they are not inconsistent with Voyager results (Hammel et al., 1989). Because remapping is a non-linear transformation, one should in principle deconvolve each image first, then remap and co-add them to improve the SNR. However, the deconvolution of individual images being ineffective and the correction due to remapping being small, we remapped and co-added the images first. The resulting image was then deconvolved, with the benefit of a better SNR. We used the Lucy-Richardson algorithm. This algorithm is best suited to restore optical data which are dominated by photon shot noise with Poisson statistics, and gives a maximum likelihood estimate. It was widely and successfully used to restore early images from the impaired HST, the PSF of which is similar to that of our images. It is also widely used to further improve images produced by adaptive optics. A discussion on the application of this algorithm to such images can be found in Roddier et al. (1996). We were able to use up to 20 iterations of the algorithm with good results. The resulting deconvolved image is shown here in Fig. 1.

## Results and discussion

### *Neptune clouds*

Fig. 1 shows high contrast bright features, presumably clouds extending above the level where methane absorption becomes important at this wavelength. To locate these features, we used a pole position based on the JPL Neptune pole model derived from Voyager observations (Jacobson et al., 1991). The latitude of the sub-Earth point (-26˚.11070) and the position angle of Neptune's North pole (+3˚. 25912) at the time of our observations were kindly provided to us by Phil. Nicholson. The largest uncertainty comes from the determination of the disk center. This was done by reference to Triton's position. The resulting equal latitude lines are shown in Fig. 1 for 0˚, ±30˚ and ±60˚, together with the position of the south pole. The diameter of the reference sphere was somewhat arbitrarily taken to be 70 pixels or 2".45. This corresponds to a physical diameter of 51,800 km slightly larger than the usually assumed planet diameter, allowing for the height of high altitude clouds.

A striking feature is the absence of clouds between the equator and 30˚S. It confirms the observations made after Voyager that all the high-altitude activity seen by Voyager at these latitudes has now disappeared (Sromovsky et al. 1995; Hammel et al. 1995). Instead, highly active regions can now be seen at low latitude in the Northern hemisphere, confirming that low latitude activity has shifted from the Southern hemisphere to the North hemisphere. Indeed, HST observations made in 1991 failed to detect the "Great Dark Spot" (GDS 89) that was seen by Voyager, drifting northward from 26˚S to 18˚S. The HST 1991 observations showed a notable lack of clouds between the equator and 40˚S, but revealed isolated cloud features both south of 40˚S and north of equator (Sromovsky et al. 1995). HST observations made in October and November 1994 in blue light (Hammel et al., 1995) show a new dark feature similar in size to GDS 89, but in the northern hemisphere, at a latitude of +30˚ (GDS 94). Like GDS 89, GDS 94 was clearly associated with bright features seen in the methane band.

Fig. 1 shows bright elongated features between 20˚N and 25˚N. If these features are associated with

GDS 94, then GDS 94 must have drifted south. A decrease of 10˚ in latitude in 10 months gives a drift rate of 1˚ per month toward the equator, similar to the northward drift of GDS 89 observed by Voyager. One may speculate whether such an activity (the formation of a GDS) alternates every 5 years between the northern and southern hemispheres. The total period would be 10 years which might explain why Neptune has shown brightness fluctuations with a period apparently close to that of the solar cycle (Lockwood & Thompson, 1991). Fig. 1 also shows clouds between 30˚S and 60˚S with the brightest spot at 50˚S. This is again in agreement with previous observations, since both Voyager data and HST data have shown systematic activity at these latitudes (Sromovsky, 1995). Unlike low latitude cloud activity, higher latitude activity appears more constant and does not alternate between north and south.

*Proteus*

On all 4 frames a faint unresolved point source can be seen 2”.5 away from the center of Neptune’s disk at a position angle of about 344˚, that is slightly west from north. From frame to frame a slow but clear westward motion of the source relative to Neptune shows that it is not a background star. Projection of the observed position onto Neptune’s equatorial plane give a physical distance of 117,000 km ± 2,000 km, quite close to the orbital radius of Proteus (117,600 km). The observed motion is also consistent with the orbital motion of Proteus. We believe this the first ground-based detection of Proteus.

We measured the source position on all 4 frames and took the mean value. For the mean time of our observations (10h 38m), it gave us the following offset in right ascension and declination:

ΔRA= - 0”70 ± 0”.04

ΔDEC = 2”.45 ± 0”.04

An expected position for Proteus was kindly provided to us by Phil Nicholson, based on Voyager measurements (Owen et al., 1991). The values for August 12 at 10h 38m are in remarkable agreement:

ΔRA = - 0”69 ± 0”.04

ΔDEC = 2”.50 ± 0”.04

We believe these values are entirely consistent with our observations. It shows that no perturbation has significantly affected the motion of Proteus since the Voyager observations.

Knowing Proteus’ orbital motion, we have then physically moved each of the four images of Proteus along its orbit to the position it would have occupied at 10h 38m and co-added them. The center of the resulting image was found to have the same coordinates as determined above. The co-added image of Proteus can be seen in Fig. 1, after further deconvolution. The SNR improvement in the composite image has allowed us to do aperture photometry and estimate the K magnitude of Proteus. For comparison we used a standard calibration star (FS 4) of the United Kingdom Infrared Telescope (UKIRT). We also measured the K magnitude of Triton. The accuracy was clearly limited to about 0.3 mag by fluctuations of the sky transparency. The mean value for Triton was 12.95 mag. For comparison Lebofsky et al. (1981) give three values for Triton’s K magnitude with a mean value of 12.5. Hence our magnitudes may be overestimated due to a temporary decrease of sky transparency during our observations of Neptune. For Proteus we found a magnitude of 19.0. Assuming Proteus has a mean radius of 200 km and taking -28.2 as the solar K-magnitude gives a geometrical albedo of $0.058 \pm 0.016$, consistent with the nearly wavelength independent geometrical albedo of 0.06 found in the visible by Thomas and Veverka (1991) from Voyager data. Looking for analogues among small bodies in the outer solar system, we note that this uniform albedo is reminiscent of the flat spectrum from the visible through the near infrared exhibited by the Centaur

2060 Chiron (Hartmann et al. 1990) which is known to be a cometary object. Proteus is clearly very different from the extremely red spectrum of another Centaur, 5145 Pholus (Fink et al. 1992).

## Conclusion

Neptune's weather pattern can now be monitored from the ground using adaptive optics on a 4-m class telescope. This technique has also allowed us to observe Proteus for the first time since its discovery by Voyager. Proteus is the largest of the six dark satellites discovered by Voyager. Adaptive optics systems are now being built for the new generation of 8- to 10-m telescopes. They will undoubtedly enable us to observe fainter satellites. They may also enable us to detect Neptune's ring arcs directly, and answer questions about their stability and the composition of the particles that compose them.

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**Figure caption:**

K-band image of Neptune reconstructed from four 5-minute exposures taken on August 12, 1995, with the UH adaptive optics system mounted on the 3.6-m CFH telescope. The field-of-view is 4.5" x 5.6". North is up and east is left. Latitudes of 0˚, ±30˚ and ±60˚ are indicated as well as the location of the south pole. Proteus can be seen above Neptune, slightly west from north.