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An Atmospheric Rotation Period of Neptune Determined from Methane-Band Imaging

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Direct imaging of Neptune through an 8900-Å methane-band filter with the University of Hawaii 2.24-m telescope at Mauna Kea Observatory shows discrete atmospheric cloud features. A rotation period of 17.86 ± 0.02 hr is derived from the observations of two transits of a bright feature in the southern hemisphere during May and June 1986. This period is consistent with earlier observations of cloud motion on Neptune. The imaging also shows that bright features in Neptune's northern hemisphere seen as recently as in 1983 by earlier investigations have disappeared, markedly changing the overall distribution of reflected light from the planetary disk.

INTRODUCTION

The rotation period of Neptune has been sought with a number of different techniques over the last 10 years (see Table I). From the diversity of periods, investigators have concluded that Neptune probably has a zonal wind system (Belton *et al.* 1981, Golitsyn 1979). By direct imaging of the planet, we hope to determine the rotation periods at various latitudes on the planet and depths in the atmosphere.

The first digital images of discrete cloud features on Neptune were reported by Smith *et al.* (1979). Observing at the 8900-Å methane-band wavelength in 1979, they found a pointlike source in the northern hemisphere and a broad bright feature south of −30°. Though their time base was too short to determine a rotation period, they deduced prograde motion. Methane-band imaging by Heasley *et al.* (1984) showed that the same distribution of reflectivity continued through 1982; a darker equatorial band separated bright features at midlatitudes (Heasley *et al.* 1984, Heasley 1984). Observations in 1983 showed a similar distribution, with bright regions at midlatitudes (±30°) in both the northern and southern hemispheres. By tracking these features over seven rotation periods of the planet, a period of 17.83 ± 0.1 hr was derived (Belton and Terrile 1984, Terrile and Smith 1983, Smith 1984).

We present new data that refine this period and show substantial atmospheric changes have occurred at least in the northern hemisphere: no bright features were seen at latitudes greater than −30°.

OBSERVATIONS

The observations reported here were made on 20 May and 4 June 1986 (see Table II). These data were selected from a larger set (17 May through 1 July 1986) because they show the unambiguous crossing of a bright feature across the disk of Neptune (see Fig. 1). We observed the feature both appearing and disappearing at the planetary limb on other nights but did not include those data in the analysis because of the difficulty in determining accurate positions near the limb.

Observations were made through an imaging-quality 8900-Å filter (FWHM 200 Å) with the Galileo/Institute for Astronomy

0019-1035/87 $3.00

TABLE I

PUBLISHED PERIODS FOR NEPTUNE

T (hr)	Method	Reference
18.17 ± 0.05	J–K color	Cruikshank 1978
19.58 ± 0.05	J–K color	Cruikshank 1978
18.44 ± 0.01	6190-Å photometry	Slavsky and Smith 1978
18.4	6190-Å photometry	Smith and Slavsky 1980
17.75	6190-Å photometry	Smith and Slavsky 1980
17.73	J–K color	Belton *et al.* 1981
18.52	J–K color	Belton *et al.* 1981
18.29	J–K color	Belton *et al.* 1981
17.73 ± 0.1	J–K color	Brown *et al.* 1981
17.83 ± 0.1	8900-Å imaging	Belton and Terrile 1984
17.86 ± 0.02	8900-Å imaging	This work

CCD system (Hlivak *et al.* 1982) on the University of Hawaii 2.24-m telescope at Mauna Kea Observatory. The image scale of the 500 × 500 array was 0.138 arcsec pixel^{-1}. Stellar FWHM values measured in the images are shown in Table II. The quoted FWHM values are the average of measurements of several field stars in each CCD frame containing Neptune. We obtained some images with an active mirror image stabilizing instrument system (ISIS) (Thompson and Ryerson 1984). The system functioned primarily as an autoguider to minimize telescope tracking errors. Both nights were photometric, although only positional information is necessary to determine the rotation period.

ANALYSIS

Multiple features were seen on Neptune on several occasions; we used two criteria to distinguish between individual features. The first was a qualitative judgment of the brightness of features. One spot was significantly brighter than all other spots; we assumed this spot was a stable atmospheric feature. The second criterion was the latitude of features, and it confirmed the judgment based on the first criterion.

To determine the latitude of a feature, we measured in the plane of the sky the x–y coordinates of the apparent center of the spot and the x–y coordinates of the center of the planet. To minimize measurement errors, we expanded each image of Neptune by a factor of 16 using a sinc interpolation function (e.g., Bracewell 1965). This process allowed us to look at the data as if we had oversampled the image by an additional factor of 16. It was thus possible to judge the center of a bright feature to within a fraction of one original pixel. The images in Fig. 1 were expanded by a factor of 4. We estimated the position of the center of the planet by visually fitting a box to the

TABLE II

NEPTUNE OBSERVATIONS

20 May 1986			4 June 1986		
Midtime (UT)	Exposure (sec)	FWHM (arcsec)	Midtime (UT)	Exposure (sec)	FWHM (arcsec)
11:24:46	60	0.75	10:27:13[a]	60	1.10
11:52:56[a]	60	0.70	10:30:03	60	1.05
13:09:37[a]	60	0.70	10:32:45	120	1.05
13:49:33[a]	60	0.70	10:54:14	120	1.15
13:51:35	60	0.70	10:58:01[a]	120	1.10
13:54:18	120	0.75	11:49:35[a]	120	1.10
14:26:59	60	0.90	12:01:10	120	1.15
14:28:38[a]	60	0.85	12:34:59	120	0.95
14:36:28	120	0.95	12:38:43[a]	120	1.00
14:39:38	120	1.00			

[a] Shown in Fig. 1.

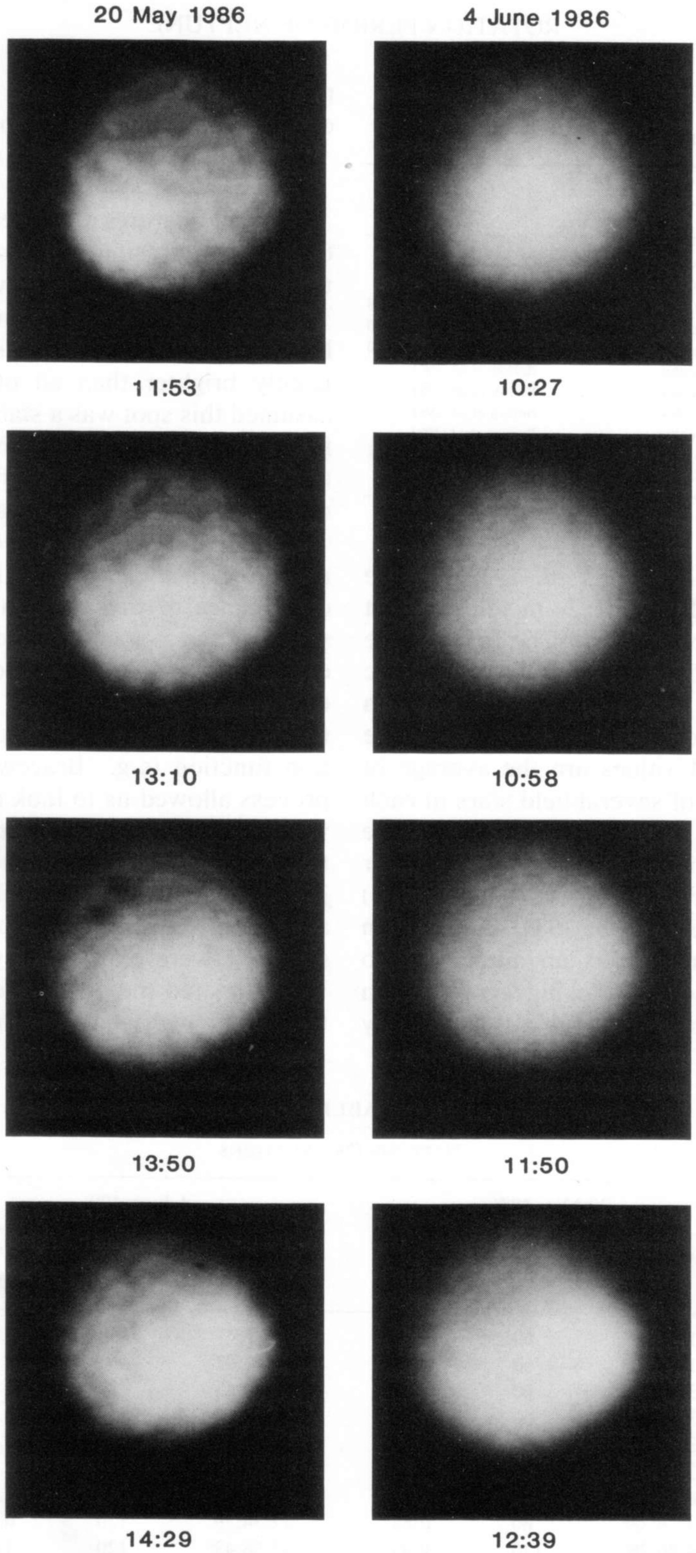

FIG. 1. Methane-band (8900-Å) images of Neptune. The data in the left-hand column were taken on 20 May 1986; the right-hand column shows data obtained 4 June 1986. The prograde advance of a feature in the southern hemisphere can be seen on both nights. Each box is 3 arcsec^2, with north up and east to the left.

outer brightness contours of the planet and using the box center as the planet's sub-Earth point. The x–y spatial coordinates were then transformed into planetocentric latitude and relative longitude assuming a spherical planet. We used the sub-Earth latitude, pole position angle, and apparent diameter published in the 1986 *Astronomical Almanac*, interpolated to the time of observation. Longitudes were calculated relative to the central meridian (sub-Earth) longitude.

All features, including faint features not presented here, were found at latitudes ranging from −30.° to −60°. More significantly, the brightest features were found at latitude −38°. This provides further evidence that we were in fact reobserving the same long-lived feature. The average of 19 observations of this bright feare yields a latitude of −38° ± 3°. (The error is the sample standard deviation. Divide by $\sqrt{19}$ to get the standard deviation of the mean.)

From the observations of this feature crossing the central meridian on two different nights, we derived a period of rotation. Figure 2 shows a plot of relative longitude versus time for both nights. The error bars represent our estimation of the uncertainty in the position of the feature due to seeing smear, possible contamination of the spot by fainter features, and the proximity of the feature to the planetary limb. The solid lines in Fig. 2 are the result of a weighted linear regression performed on each set of data. The slope of the line gives a rough estimate of the atmospheric rotation period, 17.4 ± 0.5 and 21.0 ± 0.5 hr for the 20 May and 4 June data, respectively. There are problems with this method, as can be seen from the obvious difference between the periods on these 2 nights. In the 4 June data, a fainter feature trailing behind the bright feature causes the period to appear longer (see below). This problem does not occur for the 20 May data. We therefore feel the period derived from the slope of the 20 May data, 17.4 ± 0.5 hr, is a good first estimate of the feature's true rotation period.

A better method of finding the period is to use the information from both nights. From the linear regression fits, we determined the actual times of transits to be 13.5 ± 0.2 and 10.7 ± 0.1 UT for 20 May and 4 June 1986, respectively. The elapsed time

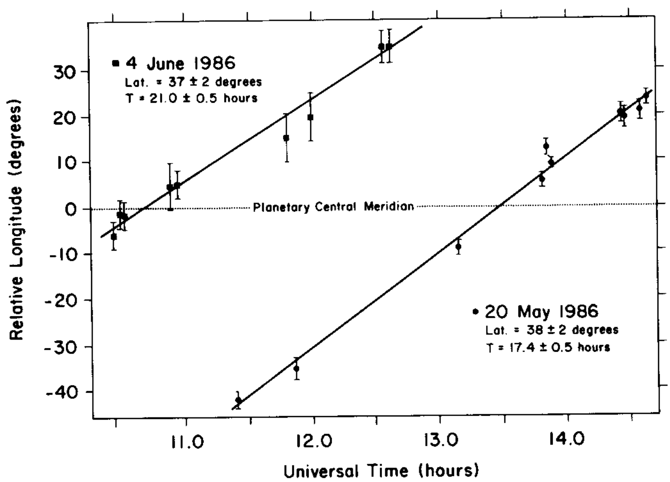

FIG. 2. Motion of the bright feature in the atmosphere of Neptune. Longitude of the feature (relative to the planetary central meridian) is plotted as a function of universal time for 2 different nights. The error bars represent an estimate of our ability to determine the location of the feature (a function of seeing, position on the disk, and contamination by other faint features). The solid lines are linear regression fits to each data set. The actual period is derived from the elapsed time between transits, not from the slope of the fits (see text).

between transits is 357.2 ± 0.3 hr, corresponding to some integral number of rotations. To determine the most likely number of rotations, we divided 357.2 hr by 17.4 hr (our best estimate of the period) to obtain 20.5 rotations.

We eliminated the period corresponding to 21 rotations (17.00 hr) because observations showed no features crossing the central meridian at predicted times. Shorter periods are also ruled out by the observations. The most probable atmospheric rotation period is 17.86 ± 0.02 hr, corresponding to 20 rotations of the planet. The 17.86-hr period predicts a transit at 11.26 UT on 1 June 1986. Although images on this night were poor due to bad seeing, a feature was seen which crossed the central meridian between 10.81 and 12.37 UT. The latitude of this feature is $-36° \pm 4°$. We rule out a longer period (18.80 hr from 19 rotation periods) mainly because of the shorter period (17.4 ± 0.5 hr) calculated from our best data (20 May 1986) and also because the longer period is inconsistent with values published in earlier work (see Table I).

As discussed above, data from a single night are not sufficient to determine a rotation period with great precision. One difficulty with an individual night's data is determining an accurate position for features close to the limb. We tried to mitigate this problem by favoring data closer to disk center, giving those points more weight in the linear regression. Another limitation is contamination of the brighter feature by faint features. This particular problem affected the data obtained on 4 June 1986. Images taken after 12.6 UT clearly show a fainter feature trailing behind the brighter feature at the same latitude. This fainter feature probably contaminates the data points near 12.5 UT (see Table II and Fig. 1). Contamination causes the feature to appear to take a longer time to cross the planetary disk. This explains why the period derived from the 4 June data alone is longer. The problem of contamination is worse near the planetary limb both for leading and trailing faint features. However, near the center of the disk the risk of contamination is small. Therefore, the 17.86-hr rotation period is determined by those points that are least sensitive to measuring errors and least likely to be contaminated by nearby features.

Another possible source of error in the period is ambiguity of the pole orientation of Neptune. The ambiguity arises from two sources—error in the published pole position and error due to rotational misalignment of the CCD camera. The pole position is determined from the gravitational moments of Neptune and the orbital elements and mass of its satellite Triton. Harris (1984) estimates that the pole position of Neptune could be in error by as much as 4° depending on the mass of Triton. Uncertainty in the pole position because of instrumental misalignment is $<5°$. Planetocentric coordinates were calculated for a range of pole position angles ($\pm 8°$ around the nominal position) to test the sensitivity of the results on pole position. As the pole position angle deviated from the predicted angle, the distribution of latitudes calculated for the feature increased. For the 20 May data, observations were equally distributed between pretransit and posttransit times (see Fig. 2). Thus variation in the pole position caused virtually no change in the average of all measurements of the bright feature's apparent latitude (from $-37° \pm 3°$ to $-38° \pm 3°$). However, most of the 4 June data were obtained after transit (Fig. 2). Errors in the pole position caused a systematic change in the measured latitude: varying the pole position angle from $-8°$ to $+8°$ around the nominal value changed the average latitude from $-35° \pm 3°$ to $-38° \pm 3°$. Longitudes were less sensitive to pole position, particularly for observations near transit. In fact, the error in transit times due to the ambiguity of the pole position is less than the error associated with the location of a feature. Similarly, the errors due to both the change in aspect of the planet between the 2 nights and the assumption of a spherical planet are smaller than the error inherent in our measurements of feature positions.

DISCUSSION

The internal rotation period of Neptune is not a well-determined quantity. Belton *et al.* (1981) recommend a period of 18.2 ± 0.4 hr as the best value for the core rotation period, based on an analogy between the distribution of zonal winds seen on Jupiter and the distribution of periods observed on Neptune. Recent occultation results indicated a shorter, but still consistent, value of 16.9 ± 1.2 hr (French *et al.* 1985), while another analysis of the same occultation produced a period of 15 (+3/−2) hr (Hubbard *et al.* 1985).

From our images, we derive an atmospheric rotation period of 17.86 ± 0.02 hr for a bright feature at latitude −38° ± 3°. Our result refines the period of 17.83 ± 0.1 hr reported in Belton and Terrile (1984). The strong contrast of the feature at strongly absorbing methane wavelengths suggests that the bright feature is caused by scattering from particulates high in the atmosphere: the reflected sunlight must be able to escape the atmosphere before being absorbed by methane. Faint features appear at other latitudes in our images, but determining their rotation periods is difficult: low contrast prevents accurate measurements of the location of features.

Images at other methane-absorption wavelengths (6190 and 7260 Å) show less contrast, but we plan to derive quantitative information from the data. Previous photometry at 6190 Å yielded a period of 18.44 hr (Slavsky and Smith 1978, Smith and Slavsky 1980). Preliminary investigation of our 6190-Å images revealed no substantial difference from our 8900-Å images (i.e., we suspect the period will be 17.86 hr). Periods derived from J–K color appear to cluster near two values, 17.7 and 18.4 hr (see Table I and summary by Belton and Terrile 1984). Our 17.86-hr period is consistent with other measurements near 17.7 hr.

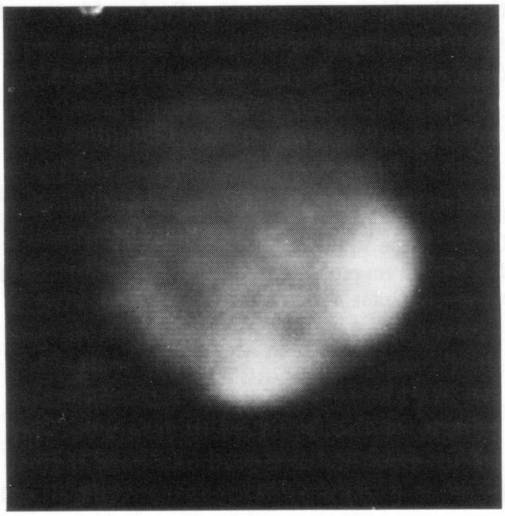

FIG. 3. Methane-band (8900-Å) image of Neptune obtained at 11:14 UT on 21 May 1986. This image shows a different view of the planet than that seen in Fig. 1. The bright feature is disappearing off the western limb. A fainter feature is apparent on the southeastern limb. No features are visible in the northern hemisphere.

No features were detected in the northern hemisphere of Neptune. This is in distinct contrast to all previously published imaging (Smith 1984, Belton and Terrile 1984, Heasley *et al.* 1984, Heasley 1984). Our complete data set covers sufficient longitude on the planet to rule out the possibility of inadequate time coverage. For example, Fig. 3 shows an image taken on 21 May 1986; the stellar profiles in this image had a FWHM of 0.6 arcsec. The bright spot is disappearing off the western limb of the planet. A fainter feature appears at a more southerly latitude. No features are visible in the northern hemisphere, although limb-brightening can be seen. Some substantial change in the distribution of reflecting material in the northern hemisphere must have occurred between May 1983 and May 1986. Major atmospheric variability has been observed and reported by earlier observers (see summary by Cruikshank 1985). The ability to detect inhomogeneities in the atmosphere of Neptune from ground-based observations implies that the Voyager spacecraft should reveal some very interesting atmospheric features during its 1989 encounter with Neptune.

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