THE SHORT ROTATION PERIOD OF NEREID

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Received 2003 February 2; accepted 2003 May 22; published 2003 June 4

ABSTRACT

We determine the period, \( p = 11.52 \pm 0.14 \) hr, and a light-curve peak-to-peak amplitude, \( a = 0.029 \pm 0.003 \) mag, of the Neptunian irregular satellite Nereid. If the light-curve variation is due to albedo variations across the surface, rather than solely to the shape of Nereid variations, the rotation period would be a factor of 2 shorter. In either case, such a rotation period and light-curve amplitude, together with Nereid’s orbital period, \( p = 360.14 \) days, imply that Nereid is almost certainly in a regular rotation state, rather than the chaotic rotation state suggested in work of Schaefer & Schaefer and of Dobrovolskis. Assuming that Nereid is perfectly spherical, the albedo variation is 3% across the observed surface. Assuming a uniform geometric albedo, the observed cross-sectional area varies by 3%. We caution that the light curve found in this Letter only sets limits on the combination of albedo and physical irregularity and that we cannot determine the orientation of Nereid’s spin axis from our data.

Subject heading: planets and satellites: individual (Nereid)

1. INTRODUCTION

N II Nereid, one of the irregular satellites of Neptune, was discovered in 1949 by G. Kuiper from McDonald Observatory (Kuiper 1949). Nereid is physically large (~175 \pm 25 km radius) for an irregular moon (Smith et al. 1989; Thomas, Veverka, & Helfenstein 1991) and has an extremely eccentric orbit (\( e \sim 0.75 \)).

The photometric and rotational properties of Nereid are still undetermined, despite numerous ground-based and space-based observations. Reported light curves give amplitudes from an upper limit of 0.05 mag reported by Buratti, Goguen, & Mosher (1997) to 1.5 mag reported by Schaefer & Schaefer (1988). Reported rotation periods range from hours to as much as a year. It should be noted that a recent study by Schaefer & Tourtellotte (2001) suggests that a large opposition effect might explain much of the controversy. The large intranight variations reported by Schaefer & Schaefer (1988) and Williams, Jones, & Taylor (1991), however, still remain unexplained.

The uncertainties in Nereid’s rotation state would be of relatively little concern were it not for the theories of Nereid’s origin and possible chaotic rotation state. It is suggested that Nereid formed as a regular satellite around Neptune but was ejected to its present orbit by Triton after Triton was captured from heliocentric orbit and its orbit was tidally circularized (McKinnon 1984; Goldreich et al. 1989; Banfield & Murray 1992). Furthermore, it has been suggested that the reported large-amplitude photometric variations are the result of chaotic tumbling due to the overlap of resonances between the spin and orbit periods of Nereid, similar to that predicted (Wisdom, Peale, & Mignard 1984) and observed (Klavetter 1989a, 1989b; Black, Nicholson, & Thomas 1995) for the Saturnian moon Hyperion. Dobrovolskis (1995) has studied the effect of spin-orbit resonances and tidal evolution on Nereid in detail. He suggests that tides slowed Nereid’s rotation period to a few days or weeks while Nereid was in orbit close to Neptune. After Nereid was scattered by Triton, the satellite has been further despun to a period of the order a month as it reached its current 360 day orbit. Dobrovolskis (1995) also points out that for rotation periods of longer than about 2 weeks, Nereid is likely to be in spin-orbit resonance if it is nearly spherical (less than 1%). Otherwise, Nereid’s rotation is likely chaotic, with its period and obliquity changing from year to year. However, for rotation periods shorter than 2 weeks, Nereid is unlikely to be in spin-orbit resonance or to be tumbling chaotically.

In this Letter, we report new, accurate relative photometry of Nereid. In the next section, we review previous observational results on the photometry of Nereid. In § 3, we discuss our observations and data reduction procedures. In § 4, we report the characteristics of Nereid’s light curve. In the final section, we summarize our conclusions.

2. PREVIOUS OBSERVATIONS

Kuiper’s original magnitude estimate of 19.5 was the only available photometry until Schaefer & Schaefer (1988) reported large-amplitude photometric variations (1.5 mag) and a possible rotational period of 8–24 hr in observations of Nereid over the period of 1987 June 18–26. A number of subsequent studies found similar results. Bus, Larson, & Singer (1988) and Bus & Larson (1989) reported photometric variations, with a peak-to-peak amplitude of approximately 0.5 mag, in observations covering 14 nights in 1988 June and July and in 1989 June. Williams et al. (1991) reported 1.3 mag amplitude variations over six consecutive nights in 1990 July and argued for a 13.6 hr period. Schaefer & Schaefer (2000) reported their entire collection of 224 photometric observations of Nereid from 1987 to 1997, in which they confirmed large brightness variations with a total amplitude of 1.83 mag on timescales ranging from hours to approximately a year. They also reported a shift in the brightness variations, from large-amplitude rapid variations with intranight changes before ~1991 to slower, smaller amplitude variations with no detectable intranight changes.

On the other hand, Voyager 2, in 1989, found no brightness variations greater than 10% (Thomas et al. 1991) and no evidence that Nereid is significantly aspherical, although the res-
olution (43.3 km pixel\(^{-1}\) and later 61 km pixel\(^{-1}\)) could not constrain this beyond the general radius determination of 175 ± 25 km (Smith et al. 1989). Buratti et al. (1997) observed Nereid on three nights in 1995 July with the Palomar 5 m telescope and found no large brightness variations, although they did report a 0.14 mag decrease between their two first nights (their first night only allowed a few images because of a forest fire). They addressed the discrepancy between their first data set (and that of Voyager) and the data sets reported by Schaefer & Schaefer (1988), Bus et al. (1988), and Williams et al. (1991), suggesting that the large brightness variations observed were due to significantly understated errors of the earlier observations.

Brown & Webster (1998) observed Nereid in the \(R\) band on two consecutive nights and found no variation beyond a 0.09 ± 0.05 mag increase between the two nights (a 3 \(\sigma\) result that did not include any systematic errors). They concluded that their data are consistent with a light curve with \(\Delta m < 0.1\) mag, although a long periodic large-amplitude light curve could not be ruled out.

Most recently, Schaefer & Tourtellotte (2001) used 57 \(V\) magnitudes collected over 52 nights in the period from 1998 June 20 to October 26 to determine the opposition surge of Nereid. They found a surprisingly large phase coefficient of 0.38 mag deg\(^{-1}\) for phase angles less than 1° and 0.03 mag deg\(^{-1}\) for phase angles greater than 1°. Schaefer & Tourtellotte (2001) noted that although the large brightness variations found in many of the runs (11 of 16) from 1987 to 1998 could be explained by such an opposition surge, not all of the apparent variation could be accounted for by phase effects alone. A closer examination of the available data reveals that four of the five runs that cannot be explained by the phase effects are from 1987 to 1990 when Nereid was only 13°–17° away from the Galactic center. The star density in these areas makes accurate photometry very difficult with even state-of-the-art methods. All of these runs also have intranight variations, which further makes the accuracy of these observations questionable.

3. OBSERVATIONS AND DATA REDUCTION

We observed N II Nereid during a pencil-beam search for faint Neptunian satellites using the 8k MOSAIC camera and a \(VR\) filter (Allen, Bernstein, & Malhotra 2001) on the CTIO 4 m Blanco telescope on 2001 August 9–13 and 2002 August 12–16. Nereid was only observed on one night in 2001, but in 2002 our search fields were placed such that they slightly overlapped, ensuring that Nereid was observed on all four nights. The exposure times used were 480 s with a temporal resolution of 10–15 minutes in 2001 and 20–40 minutes in 2002 (see Table 1). The 2001 search strategy consisted of staying on one single field throughout the night, while in 2002 alternating exposures between two fields was used. The pointing of the CTIO 4 m Blanco telescope is accurate to about 10–20 pixels, ensuring that even with Nereid’s motion of ~15 pixels hr\(^{-1}\), the moon stayed within ~100 pixels throughout the night. It is known that the CTIO 8k MOSAIC camera causes a variation in the zero point across the field of view (FOV). Depending on the night, Nereid moved either radially or tangentially across the FOV. Together with the small change in radial distance from the FOV center during the night, the maximum change in zero point is ~0.002 mag, within the statistical errors of our data.

The images were bias-subtracted, flat-fielded, and relative aperture photometry was performed (Howell 1989). The FWHM of each image was measured (1°–175). An aperture with radius 1.2–1.5 times the FWHM (1°–2°) was used to ensure the maximum signal-to-noise ratio (S/N; Dacosta 1992) and, at the same time, to minimize the chance of contamination from faint background sources. The same aperture was used on a set of 10–12 reference stars common to all fields throughout a night (all the reference stars were closer than ~5° and taken from the same CCD chip that contained Nereid). Comparing the instrumental magnitude of Nereid with the instrumental magnitude of the reference stars on the image and comparing this difference with that of other images will reveal any brightening or fading throughout the night. This method does not require photometric conditions and efficiently removes effects due to air mass and transparency. To test this method, we applied it to several stars with brightness similar to Nereid in the field. The resulting \textit{“light curves”} were flat with an rms scatter of 0.003 mag. We take this to be our systematic error and add this to the formal photometric errors in quadrature. To avoid contamination from faint background stars and galaxies, we stacked all the images from each night and found no faint sources down to \(VR \sim 25.0\) mag.

The magnitude differences between the individual nights were determined by using the procedure described above on one of the fields from each night, but using 10–15 reference stars that were common between the two nights compared. Thus, we were able to put our nightly relative photometry on the same relative scale for all the nights in 2002. Only a few observations of standard stars (Landolt 1992) were performed since the main focus of our run was a search for Neptunian satellites. The fact that the observations were done using a \(VR\) filter (centered on 6000 Å with a width of 2000 Å) further complicates the situation. The standard stars used have \(V-R\) colors between 0.49 and 0.54, which is slightly higher than the color of Nereid at \(V-R = 0.44 \pm 0.03\) (Schaefer & Schaefer 2000), so we used the \(R\) magnitude given by Landolt (1992) to derive a zero point for our observations. Due to the similarity in colors, the wider filter lets through approximately the same relative amount of flux for both the standard stars and Nereid. Using the newly derived zero point on our object, we get an...
approximate $R$ magnitude of $\sim$18.8. This is consistent with the magnitudes reported by Schaefer & Tourtellotte (2001) after accounting for the phase effects.

Due to the size of the telescope aperture and the generally excellent observing conditions at the Cerro Tololo site, we obtained relative photometry of Nereid with 0.003–0.006 accuracy (the S/N of the object was 600–700). This accuracy is significantly better than any photometry of Nereid reported to date.

4. RESULTS

Figure 1 shows our results, clearly indicating a periodicity on the order of hours. Using a Levenberg-Marquardt fitting method (Press et al. 1995), we fit the data with the simple model

$$\Delta m = a \cos \left[\frac{2\pi}{P} (t - t_0)\right] - k(\alpha - \alpha_0),$$

(1)

where $t$ and $\alpha$ are the time and phase angle of the observations, respectively, and $a$, $P$, and $k$ are the amplitude, period, phase coefficient, respectively. We fix the phase-angle reference point, $\alpha_0 = 0^\circ.4$. In addition to these parameters, we allow the sinusoidal curve to move along the time axis (by letting $t_0$ be a free parameter). We also allow the single night from 2001 to move freely along the magnitude axis, resulting in six free parameters in total.

The fit gives a rotational period of $11.52 \pm 0.14$ hr (with an apparent single harmonic period of $5.76$ hr) with a peak-to-peak amplitude of $a = 0.029 \pm 0.003$ mag and a phase coefficient of $k = 0.14 \pm 0.08$ mag deg$^{-1}$. To evaluate the fit, we determined the $\chi^2$. With 68 degrees of freedom (74 observations minus six parameters), we get a $\chi^2$ of 80.1. We further estimate the goodness of fit with the incomplete gamma function, $Q(0.5N, 0.5\chi^2)$, where $N$ is the numbers of degrees of freedom (Press et al. 1995). The result, $Q = 0.17$, gives the probability that this variation can occur by chance with the given model. We have also fitted the data with higher order harmonics to attempt to distinguish shape-induced variations from those resulting from surface variegations, but we see no significant improvement over the simple sinusoid with the available data.

It should be noted that the period can be well fitted by values that differ by integer multiples of $1.60 \times 10^{-4}$ days or $\sim 14$ s, the change in period that results from a one-half additional revolution between the 2001 and 2002 observations. Obviously, we cannot determine the period that well with the data at hand. Furthermore, there is a correlation between the amplitude $a$ and phase coefficient $k$. As the period is decreased, the phase-effect coefficient increases and the amplitude decreases. As the period is increased, the phase-coefficient decreases and the amplitude increases. We estimate the uncertainty in the rotation period by the limits at which $Q(0.5N, 0.5\chi^2) = 0.001$. This yields a rotation period between 11.40 and 11.68 hr and phase coefficients between 0.19 and 0.05 mag deg$^{-1}$. Interestingly, Buratti et al. (1997) report a decrease of 0.05–0.025 mag over a 5.5 hr period in their second and third nights, although they state that this decrease was not statistically significant.

The peak-to-peak amplitude of 0.029 $\pm$ 0.003 mag does not constrain the shape or albedo variegations of Nereid independently. Assuming that Nereid is perfectly spherical, the albedo variation is less than $3\%$ across the observed surface. Recall that Voyager 2 constrained the brightness variations of Nereid over a large range of phase angles to $\lesssim 10\%$, its radius to $r = 175 \pm 25$ km, and its geometric albedo to $0.180 \pm 0.005$ (Smith et al. 1989; Thomas et al. 1991). Our own observations show that by assuming a uniform geometric albedo, the observed cross-sectional area varies by $3\%$. However, we caution that we cannot determine the orientation of Nereid’s spin axis from our data and that if the observations are pole-on, the equatorial irregularity could well be more than $3\%$.

5. CONCLUSIONS

From observations on one night in 2001 August and on four consecutive nights in 2002 August, we have established the rotational period, $p = 11.52 \pm 0.14$ hr, and a light curve peak-to-peak amplitude, $a = 0.029 \pm 0.003$ mag, of the Neptunian irregular satellite Nereid. The peak-to-peak amplitude constrains the shape and/or albedo variations of Nereid. Assuming that Nereid is perfectly spherical, the albedo variation is $3\%$ across the observed surface. Likewise, assuming a uniform geometric albedo, the observed cross-sectional area varies by $3\%$. Viewed from a random angle, this implies a nearly spherical body with a limit of $\sim 3$ km out-of-round, based on the radius estimate from Voyager 2 (Smith et al. 1989; Thomas et al. 1991). Again, we caution that we cannot determine the orientation of Nereid’s spin axis from our data.

Nereid’s short rotation period and long orbital period place it near the 750 : 1 spin-orbit resonance. The phase space is essentially free of chaos for high rotation rates, those beyond the 40 : 1 spin-orbit resonance, regardless of the shape of Nereid (Dobrovolskis 1995). Thus, little or no dynamical chaos is expected in the rotation of Nereid. Without such a chaotic region, it seems highly unlikely that Nereid could have changed its rotational state in recent years. Since the rotation state of Nereid is perfectly normal for a distant irregular satellite, no
implications for an unusual formation history of Nereid can be drawn.

We dedicate this Letter to the memory of James J. Klavetter, who gave M. J. H. his first instruction in CCD photometry and who started this project in 1988. Dr. Klavetter, shortly thereafter, wisely concluded that it would be better to wait a decade until Neptune had cleared the plane the Milky Way than to proceed with the data in hand. We would like to thank A. Rivkin, K. Stanek, C. Kochanek, M. Lecar, and J. Wisdom for helpful discussions. We also thank A. Harris for a very helpful review. T. G. is a Smithsonian Astrophysical Observatory Predoctoral Fellow at the Harvard-Smithsonian Center for Astrophysics, Cambridge. This work was supported by NASA grants NAG5-9678 and NAG5-10438.

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