The Shape of Nereid’s Phase Function Changed From 1998 to 1999 and 2000

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ABSTRACT

We present well-sampled light curves of Nereid for 1999 and 2000 which show symmetric shapes centered on opposition as is characteristic of a large opposition surge. Surprisingly, the phase functions for 1999 and 2000 are significantly different from the well-measured phase function for the year 1998, with the 1999 and 2000 curves being more peaked at low phase angles and substantially brighter at high phase angles. We know of neither precedent nor explanation for this mystery on Nereid.

Subject headings: Satellites of Neptune, Opposition Surge, Photometry, Phase Function

1. Introduction

Nereid has an unusual orbit around Neptune \((e = 0.75, P = 360\) days, and \(i = 28^\circ\)) which suggests that it might be a captured Kuiper Belt Object (Schaefer & Schaefer 1995, 2000). Nereid also has the most unusual known photometric history of all objects in the Solar System (Schaefer & Schaefer 1988, 2000; Schaefer & Tourtellotte 2001). From 1987 to 1991, several groups found that Nereid had fast photometric variations with amplitudes up to around one magnitude (Schaefer & Schaefer 1988, 2000; Williams, Jones, & Taylor 1991; Bus, & Larson 1989). From 1991 to 1997, Nereid’s amplitude was smaller at \(\sim 0.4\) mag.
(Schaefer & Schaefer 2000), with highly significant evidence that it showed fast variations (Buratti, Goguen, & Mosher 1997; Brown, & Webster 1998). In 1998, we observed Nereid on 52 nights and found that Nereid displayed no significant variability other than a very large opposition surge (Schaefer & Tourtellotte 2001).

This unique behavior of large-and-small variations that change from year to year could be caused by chaotic rotation (Dobrovolskis 1995), much like Hyperion (Klavetter 1989). This possibility is appealing because Nereid has the necessary ingredients of a > 1% out-of-round shape (due to its small size) and a highly eccentric orbit around a planet with a large J2 component in its gravity. Unfortunately, Dobrovolskis has shown that Nereid’s rotation will be chaotic only if its rotational period is longer than roughly two weeks, and this requirement is not consistent with the observed brightness changes on time scales of one day. Thus, the cause of Nereid’s variations is not known (Schaefer & Tourtellotte 2001).

The 1998 light curve (Schaefer & Tourtellotte 2001, see Figure 1) displayed no significant brightness changes other than those associated with the normal changing of the solar phase angle, \( \alpha \), and the opposition surge. The phase function (see Figure 2) shows an opposition surge of 0.52 magnitudes over a range of 2\(^\circ\) in phase and this is among the largest known in our Solar System. The shape of the phase function is definitely not linear, while a broken line fits well.

Given Nereid’s long history of changes in its variability, it is prudent to continue photometric monitoring. The Yale 1-m telescope on Cerro Tololo is operated in a queue mode by a resident operator, and hence is perfect for the long-term synoptic study of Nereid. So again we have used this telescope to monitor Nereid, this time during its 1999 and 2000 oppositions. We find that Nereid’s phase function has significantly changed its shape from 1998 to 1999 and 2000.

2. Photometry

All photometry was taken with the Yale 1-m telescope (operated by the YALO consortium) with the ANDICAM CCD camera which has a 2048 \( \times \) 2048 array of 0.29” pixels. All exposures were through a standard V-band filter for 900 seconds of exposure. A complete description of our analysis procedures are presented in Schaefer & Tourtellotte (2001).

In 1999, we obtained a total of 54 usable images on 54 separate nights in a 130 day interval between 20 June 1999 (JD 2451350) and 28 October 1999 (JD 2451480). Nereid passed through opposition on 27 July 1999 (JD 2451386) and was at maximum phase angle on 26 April 1999 (JD 2451294) and 25 October 1999 (JD 2451476).
In 2000, we obtained a total of 14 usable images on 14 separate nights in a 102 day interval between 22 July 2000 (JD 2451748) and 1 November 2000 (JD 2451850). Nereid passed through opposition on 28 July 2000 (JD 2451753) and was at maximum phase angle on 28 April 2000 (JD 2451662) and 26 October 2000 (JD 2451843).

All our V-band photometry is presented in Table 1. The first column gives the heliocentric Julian Date of the start of the exposure. The second column gives solar phase angle, $\alpha$, in degrees as given by the JPL Horizons program (http://ssd.jpl.nasa.gov/cgi-bin/eph). The third column gives our observed V magnitude and one-sigma uncertainty. The fourth column gives the V magnitude corrected to the 1998 opposition distance of 29.123 AU as $V_{OPP} = V - 5 \log(\Delta/29.123)$ where $\Delta$ is the Earth-Nereid distance in units of AU, to allow direct comparisons with the 1998 phase function. The error bars for $V_{OPP}$ are the same as for $V$ in the previous column. (The total range of variation of the Sun-Nereid distance over the observed time intervals in 1998-2000 was only 0.08 AU, thus resulting in a negligible correction of under 0.003 mag from the mean.) The light curves are displayed in Figure 1.

We notice that the one measurement with $\alpha < 0.11^\circ$ in 1999 (on JD 2451386.829) is bright by $\sim 0.2$ mag when compared to observations taken a few days before and afterwards. We have carefully examined this image for bad columns, measured Nereid’s image shape for evidence of cosmic rays, checked other deeper images for background stars, and checked Nereid’s position on the CCD chip with other images for hot pixels, all with the result that we have no grounds for impeaching this ‘bright’ magnitude. (Actually, similar checks were performed on all our Nereid images.) The coincidence of this bright Nereid with phase angle zero suggests that this might be evidence of a narrow spike in Nereid’s phase function (much like that for four of the Uranian moons (Buratti, Gibson, & Mosher 1992). Yet such a spike does not appear in the well-sampled 1998 light curve, so the ‘spike’ would have to be time variable if it exists.

3. Phase Function

In 1999, the observed light curve comes to a peak around 26 July 1999 and a minimum in October 1999 with a symmetric light curve around the peak. In 2000, the observed light curve comes to a peak around 26 July 2000 and a minimum in October 2000. The coincidence of the observed maximum and minimum dates with the opposition and quadrature dates as well as the symmetric light curves are the hallmarks of brightness variations caused by the opposition surge. Thus, it appears that (as in 1998), most of the variations arises from simple phase effects. The phase functions for 1999 and 2000 are presented in Figure 2.
We first tried to fit the 1999 and 2000 data to linear and broken-line functional forms. For the 1999 data, the broken-line form is strongly preferred over the linear form. The best fit is $V_{OPP} = 18.97 + 1.09\alpha$ for $\alpha < 0.29^\circ$ and $V_{OPP} = 19.25 + 0.13\alpha$ for $\alpha > 0.29^\circ$ with a chi-square of 40.3 for 50 degrees of freedom. The 1999 data is strongly inconsistent with the 1998 broken-line fit (Schaefer & Tourtellotte 2001). The 1999 and 2000 data have nearly identical fits.

Fits to lines and broken-lines have the virtue of simplicity, but they have no physical motivation. Hapke (1993) developed a physical model that predicts the opposition surge component of the phase function to vary as $V_{OPP} = V_0 - 2.5 \log \left\{ \frac{1 + B_0}{(1 + 0.5\alpha/h)} \right\} / \left[ 1 + B_0 \right]$ in the small angle limit. Here, $V_0$ is the V-band magnitude at zero phase angle, $B_0$ is a measure of the amplitude of the opposition surge, and $h$ is the angular width of the opposition surge. The use of this physical model has the disadvantage that it might not be a complete description of the physics (see discussion in the next section). Also, the physical model does not describe the observed variations over small ranges of phase angles, in particular at low phase angles.

The best fit for the 1999 data has $V_0 = 19.01$ mag, $B_0 = 0.72$, and $h = 0.19^\circ$ for a chi-square of 48.8 with 51 degrees of freedom. The best fit for the 2000 data has $V_0 = 19.07$ mag, $B_0 = 0.78$, and $h = 0.34^\circ$ for a chi-square of 9.6 with 11 degrees of freedom, although the 2000 errors are relatively large and correlated. The fit parameters are similar for 1999 and 2000. The best way to show this is by evaluating the chi-squares for each year with the other year’s fit. The 1999 data have a chi-square of 52.1 for the 2000 best fit; while the 2000 data have a chi-square of 16.4 for the 1999 best fit. The reduced chi-square values are near unity and F-Tests show that the cross-fits are not significantly different from each other. A joint fit of the 1999+2000 data reveal a best fit with $V_0 = 19.04$ mag, $B_0 = 0.73$, and $h = 0.25^\circ$ for a chi-square of 49.4 + 12.0 = 61.4 with 65 degrees of freedom. Again, the differences in chi-square are not significant. Hence, it appears that the phase functions in 1999 and 2000 were similar if not identical. So we will adopt the best fit to the Hapke model for the joint 1999+2000 data as a good description of the phase function for both years.

Is the 1998 phase function (Schaefer & Tourtellotte 2001) the same as what we are here reporting for 1999 and 2000? The 1998 data were fitted to the Hapke model with $V_0 = 19.07$ mag, $B_0 = 1.32$, and $h = 0.52^\circ$ for a chi-square of 70.0 with 54 degrees of freedom. Both the 1998 and the 1999+2000 model phase functions are drawn in all three panels of Figure 2. In examining this figure, the answer is obvious that the observed phase function has changed from 1998 to 1999+2000. In particular, the observed 1999+2000 phase function appears to be more peaked at low phases and substantially brighter at large phases when compared to the observed 1998 phase function.
The 1998 phase function and light curve is flat at low phase angles, while the 1999+2000 phase function and light curve is strongly peaked to opposition. To be quantitative, in bins of 0.05° phase from 0.00° to 0.30°, the 1998 observed values are 19.143 ± 0.026, 19.137 ± 0.021, 19.105 ± 0.020, 19.14 ± 0.05, 19.118 ± 0.027, and 19.199 ± 0.028 mag. Similarly the 1999+2000 binned phase function is 19.064 ± 0.022 (or 19.087 ± 0.024 if the point nearest opposition is arbitrarily ignored), 19.12 ± 0.03, 19.155 ± 0.019, 19.180 ± 0.018, 19.173 ± 0.026, and 19.253 ± 0.032 mag. All 1998 points with 0.00° < α < 0.26° are consistent with a perfectly flat phase curve at 19.126 ± 0.011 mag. The 1999+2000 magnitudes form a simple linear decline that is not consistent with a flat phase function. Formal fits for the slopes yield 0.12 ± 0.12 mag deg⁻¹ for 1998 and 0.73 ± 0.14 mag deg⁻¹ for 1999+2000 (0.63 ± 0.14 mag deg⁻¹ if the near opposition datum is excluded despite the lack of grounds).

At large phases with α > 0.85°, all 1998 points lie below the 1999+2000 fit and all 1999+2000 points lie above the 1998 fit. (Both statements have a single exception which in both cases is the one point with the largest error bar.) Taking points with α > 1.5°, the weighted averages for 1998 and 1999+2000 are 19.551 ± 0.013 and 19.485 ± 0.010 mag respectively, for a difference of 0.066 ± 0.016 mag which is significant at the 4.0 sigma level. Hence, the observed phase function at large phases changed significantly after 1998.

Overall, the change in the shape of the phase function can be tested by comparing the fits to the Hapke model. The 1998 phase function when applied to the 1999+2000 data yields a chi-square of 119.3 + 19.9 = 139.2 for 68 degrees of freedom (versus a chi-square of 61.4 for the 1999+2000 phase function), and this strongly rejects the 1998 function for the 1999+2000 data. Similarly, the 1999+2000 phase function when applied to the 1998 data yields a chi-square of 120.7 for 57 degrees of freedom (versus a chi-square of 70.0 for the 1998 phase function), and this strongly rejects the 1999+2000 phase function for the 1998 data. Thus, Nereid’s phase function changed from 1998 to 1999+2000.

This is an unprecedented result, so it is prudent to consider whether there is any realistic possibility of observational error. For example, what if we adopted magnitudes for the 1998 comparison stars used at high phase angles that are too faint by 0.07 mag due to some calibration error? (This would still not resolve the difference in the slope at low phases, so a separate error would have to be postulated.) A 0.07 mag error is far larger than any reasonable statistical error, and our repeated independent derivation of all the calibrations argues against numerical errors. The same telescope, CCD chip, filters, analysis procedures, and many of the same Landolt standard stars were used throughout each of the three years. The presence of undetected light cirrus clouds that might dim the comparison star images in comparison to the standard star images is ruled out since the α > 1.3° comparison star data in 1998 was independently calibrated against Landolt standard stars on three separate
nights and these all agree to within \(\sim 0.015\) mag. Similarly, the comparison stars for the 1999 data with \(\alpha > 1.3^\circ\) were independently calibrated on three nights with the YALO telescope and one night with the McDonald 2.1-m telescope. Nereid crossed its own path on nights around 20 June 1998 and 20 October 1999, for which our independent calibrations of the comparison stars are in agreement to within \(0.03 \pm 0.03\) mag. In all, we have strong reasons to be confident in our photometry and thus we conclude that Nereid’s phase function did indeed change from 1998 to 1999+2000.

Nereid has a long history of photometric variations, so could the phase function changes actually be small amplitude long-term changes? Conceptually, it is difficult to know how the two cases can be distinguished, especially when we do not know the cause of the variability. Certainly we could postulate changes in Nereid’s overall brightness (but not its surface texture) that happen to make it faint in September and October 1998 (or bright in September and October of both 1999 and 2000) as well as fade Nereid by \(\sim 0.2\) mag in the week centered on the 1998 opposition (or brightened Nereid in the week centered on both the 1999 and 2000 oppositions). But such a postulate would require two rather improbable coincidences. The first coincidence is that the fading in 1998 is centered on the opposition date, since this time is only special from an Earthly viewpoint. (At this time, Nereid is far from Neptune and its 360 day orbital period means that it will be at roughly the same orbital phase for the oppositions from 1998-2000.) The second coincidence is that Nereid’s brightness always returns to the same magnitude the five times when \(0.4^\circ < \alpha < 0.8^\circ\) (early July 1998, middle August 1998, early July 1999, middle August 1999, and middle August 2000). The point to these coincidences is that Nereid’s brightness appears to be correlated with the position of the Earth. This correlation only makes sense if the observed variations are caused by a changing phase function which is explicitly a function of the Earth’s position. So again, we are concluding that Nereid’s phase function changed from 1998 to 1999+2000.

4. Implications

The best fit for the 1998 data has \(B_0\) significantly larger than unity, whereas the model of Hapke requires \(B_0 \leq 1\). This is actually a fairly broad problem, as many objects throughout the Solar System have this same difficulty (Helfenstein, Veverka, & Hillier 1997). The likely solution is that the true situation is more complex than given in the basic model, perhaps involving a combination of coherent-backscattering plus strongly backscattering single-particle phase functions.

The narrow width of the opposition surge for Nereid has precedents from four Uranian moons (Miranda, Ariel, Titania, and Oberon) with high albedos (Buratti, Gibson, & Mosher
simple shadow-hiding cannot account for such narrow widths without presuming a very low filling factor for objects in the regolith, with \( \sim 1\% \) being a typical value (cf. Hapke 1993, equations 8.84 and 8.85). Such a low value seems implausible, although Hapke (1983) has proposed that scatterers might be concentrated towards the surface of a relatively deep and transparent medium. Nevertheless, the narrow component in the opposition surge is generally thought to arise from coherent-backscattering (Hapke 1993). In this case, \( h \approx \frac{\lambda}{4\pi L} \) where \( \lambda \) is the wavelength of the light and \( L \) is the photon mean free path in the medium (Hapke 1993, equation 8.88). For visible light (\( \lambda = 0.55 \mu m \)) and \( h = 0.0043 \text{ rad (0.25}\degree) \), \( L = 10.2 \mu m \).

We interpret the changes displayed in Figure 2 as due to a variable phase function, but other explanations are possible. It is always possible to postulate subtle observational errors that can explain systematic offsets of \( \sim 0.1 \text{ mag} \). Nevertheless, in our case, the stability of our equipment and procedures along with our many independent calibrations and cross checks gives us strong confidence that our results are reliable. It is always possible to postulate some arbitrary fading and brightening caused by whatever mechanism has previously made Nereid a variable, such that the light curves in Figure 1 are produced without changing the surface texture. Nevertheless, such postulated changes appear to be correlated with the Earth’s position due to the low-phase differences being centered on opposition and due to the return to the same magnitude on five occasions when the phase is \( 0.4^\circ < \alpha < 0.8^\circ \). This connection with the Earth argues that the light curve changes arise from phase function changes. These arguments give us the grounds to identify the light curve changes as arising from changes in the phase function of Nereid.

A central mystery of Nereid remains to explain its large-and-small variations, only now there is the associated mystery of how it can change its phase function on a time scale of one year. Presumably, as the phase function depends on the texture of the surface, then Nereid’s texture must have changed. Could this have been caused by the deposition of particles or the formation of ice crystals on the surface? If so, then what could have caused this surface change? How is this resurfacing mechanism related to the brightness changes seen by so many groups? Or could chaotic rotation of Nereid have moved a different hemisphere into view, with each hemisphere having different textures? Unfortunately, we do not have answers to any of these questions.

We know of no precedents for significant changes in the shape of the phase function of Solar System objects. But this statement is not as strong as might be expected, since few objects in our Solar System have been examined with well-sampled phase functions over more than one opposition with measures that can be directly compared. Likely, Nereid’s variable
phase function is related somehow to its previously reported variations, but the causes of both types of changes are unknown. To solve this mystery, a series of well-sampled light curves is certainly needed, ideally in several different bands and accompanied by spectroscopy.

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Table 1. Brightness of Nereid in 1999 and 2000.

| Julian Date | $\alpha$ | $V$   | $V_{OPP}$ |
|-------------|----------|-------|-----------|
| 2451350.914 | 1.094    | 19.42 ± 0.06 | 19.41     |
| 2451352.909 | 1.039    | 19.44 ± 0.05 | 19.43     |
| 2451354.916 | 0.984    | 19.36 ± 0.03 | 19.35     |
| 2451355.902 | 0.955    | 19.39 ± 0.03 | 19.38     |
| 2451365.891 | 0.657    | 19.26 ± 0.04 | 19.26     |
| 2451366.881 | 0.628    | 19.30 ± 0.04 | 19.30     |
| 2451367.877 | 0.596    | 19.25 ± 0.05 | 19.25     |
| 2451379.843 | 0.210    | 19.16 ± 0.03 | 19.16     |
| 2451380.844 | 0.177    | 19.14 ± 0.03 | 19.14     |
| 2451381.847 | 0.144    | 19.16 ± 0.03 | 19.16     |
| 2451382.846 | 0.111    | 19.11 ± 0.03 | 19.11     |
| 2451386.829 | 0.024    | 18.95 ± 0.05 | 18.95     |
| 2451389.847 | 0.122    | 19.23 ± 0.06 | 19.23     |
| 2451390.839 | 0.154    | 19.18 ± 0.08 | 19.18     |
| 2451391.869 | 0.189    | 19.28 ± 0.06 | 19.28     |
| 2451392.840 | 0.220    | 19.19 ± 0.04 | 19.19     |
| 2451393.837 | 0.253    | 19.20 ± 0.05 | 19.20     |
| 2451394.830 | 0.286    | 19.29 ± 0.04 | 19.29     |
| 2451396.842 | 0.351    | 19.31 ± 0.05 | 19.31     |
| 2451399.811 | 0.448    | 19.37 ± 0.04 | 19.37     |
| 2451401.817 | 0.512    | 19.35 ± 0.03 | 19.35     |
| 2451402.807 | 0.543    | 19.31 ± 0.03 | 19.31     |
| 2451403.805 | 0.574    | 19.30 ± 0.04 | 19.30     |
| 2451406.809 | 0.668    | 19.38 ± 0.06 | 19.38     |
| 2451407.793 | 0.699    | 19.36 ± 0.03 | 19.36     |
| 2451408.800 | 0.730    | 19.37 ± 0.04 | 19.37     |
| 2451410.785 | 0.790    | 19.39 ± 0.04 | 19.39     |
| 2451412.787 | 0.850    | 19.37 ± 0.06 | 19.36     |
| 2451432.738 | 1.376    | 19.40 ± 0.04 | 19.38     |
| 2451433.709 | 1.398    | 19.42 ± 0.04 | 19.40     |
| 2451441.730 | 1.562    | 19.48 ± 0.09 | 19.45     |
| 2451443.682 | 1.597    | 19.58 ± 0.15 | 19.55     |
| 2451444.670 | 1.615    | 19.34 ± 0.09 | 19.31     |
| 2451445.670 | 1.631    | 19.52 ± 0.07 | 19.49     |
| 2451446.674 | 1.648    | 19.45 ± 0.10 | 19.42     |
| 2451449.660 | 1.694    | 19.50 ± 0.05 | 19.46     |
| 2451451.657 | 1.723    | 19.54 ± 0.08 | 19.50     |
| 2451454.652 | 1.761    | 19.47 ± 0.04 | 19.43     |
| 2451455.646 | 1.773    | 19.56 ± 0.05 | 19.52     |
| 2451458.634 | 1.804    | 19.53 ± 0.04 | 19.48     |
| 2451460.662 | 1.824    | 19.59 ± 0.05 | 19.54     |
| 2451461.674 | 1.832    | 19.53 ± 0.04 | 19.48     |
| 2451463.589 | 1.847    | 19.53 ± 0.04 | 19.48     |
| 2451465.616 | 1.861    | 19.55 ± 0.04 | 19.49     |
| 2451466.679 | 1.867    | 19.53 ± 0.05 | 19.47     |
| 2451467.615 | 1.872    | 19.54 ± 0.05 | 19.48     |
| 2451468.669 | 1.877    | 19.55 ± 0.10 | 19.49     |
| 2451471.581 | 1.887    | 19.54 ± 0.06 | 19.48     |
| 2451472.576 | 1.889    | 19.54 ± 0.07 | 19.48     |
Table 1—Continued

| Julian Date | $\alpha$  | $V$     | $V_{OFF}$ |
|-------------|-----------|---------|----------|
| 2451475.577 | 1.893     | 19.49 ± 0.06 | 19.42    |
| 2451477.572 | 1.893     | 19.58 ± 0.05 | 19.51    |
| 2451478.590 | 1.892     | 19.56 ± 0.05 | 19.49    |
| 2451479.576 | 1.890     | 19.57 ± 0.04 | 19.50    |
| 2451480.580 | 1.888     | 19.60 ± 0.04 | 19.53    |
| 2451748.843 | 0.162     | 19.18 ± 0.04 | 19.18    |
| 2451750.839 | 0.096     | 19.12 ± 0.03 | 19.12    |
| 2451752.841 | 0.031     | 19.07 ± 0.03 | 19.07    |
| 2451754.827 | 0.037     | 19.10 ± 0.03 | 19.10    |
| 2451756.847 | 0.104     | 19.17 ± 0.04 | 19.17    |
| 2451758.761 | 0.166     | 19.18 ± 0.03 | 19.18    |
| 2451766.801 | 0.429     | 19.24 ± 0.04 | 19.24    |
| 2451768.805 | 0.493     | 19.36 ± 0.06 | 19.36    |
| 2451782.757 | 0.921     | 19.38 ± 0.04 | 19.37    |
| 2451784.749 | 0.979     | 19.35 ± 0.04 | 19.34    |
| 2451808.691 | 1.552     | 19.45 ± 0.05 | 19.42    |
| 2451810.684 | 1.588     | 19.52 ± 0.03 | 19.49    |
| 2451819.599 | 1.728     | 19.59 ± 0.05 | 19.55    |
| 2451850.567 | 1.880     | 19.55 ± 0.04 | 19.47    |
Fig. 1.— Nereid light curves in 1998, 1999, and 2000. The light curves for the three years show Nereid to have a smooth brightening to the date of opposition and then a smooth decline until a minimum around the time of quadrature. This is the hallmark of the opposition surge, for which Nereid has a very large and narrow surge when compared to most other bodies in the Solar System. Note that the light curve for 1998 is flat at opposition while the light curves for 1999 and 2000 are sharply peaked.
Fig. 2.— Nereid's phase functions in 1998, 1999, and 2000. We have well-measured phase functions for Nereid in 1998 (top panel, from Schaefer & Tourtellotte (2001)), 1999 (middle panel), and 2000 (bottom panel). Also plotted in each panel are the two Hapke models for the best fits to the 1998 and 1999+2000 data (with the bold solid curve being for the year of the panel and the light dashed curve for the other fit for comparison). The main point of this figure is that the phase function has changed from 1998 to 1999+2000. For $\alpha < 0.3^\circ$, the 1998 phase function is almost flat with a slope of $0.12 \pm 0.12$ mag deg$^{-1}$, while the 1999+2000 phase function is very peaked with a slope of $0.73 \pm 0.14$ mag deg$^{-1}$. For $\alpha > 0.85^\circ$, the 1998 magnitudes consistently and significantly lie below the 1999+2000 model while the 1999+2000 magnitudes consistently and significantly lie above the 1998 model.