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DETECTION OF ORBITAL AND SUPERHUMP PERIODS IN NOVA V2574 OPHIUCHI (2004)

Tae W. Kang,[1] Alon Retter,[1] Alex Liu,[2] and Mercedes Richards[1]
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ABSTRACT

We present the results of 37 nights of CCD unfiltered photometry of nova V2574 Oph (2004) from 2004 and 2005. We find two periods of 0.14164 days (≈3.40 hr) and 0.14773 days (≈3.55 hr) in the 2005 data. The 2004 data show variability on a similar timescale, but no coherent periodicity was found. We suggest that the longer periodicity is the orbital period of the underlying binary system and that the shorter period represents a negative superhump. The 3.40 hr period is about 4% shorter than the orbital period and obeys the relation between superhump period deficit and binary period. The detection of superhumps in the light curve is evidence of the presence of a precessing accretion disk in this binary system shortly after the nova outburst. From the maximum magnitude–rate of decline relation, we estimate the decay rate $t_2 = 17 \pm 4$ days and a maximum absolute visual magnitude of $M_{V_{\rm max}} = -7.7 \pm 1.7$ mag.

Key words: accretion, accretion disks — novae, cataclysmic variables — stars: individual (V2574 Ophiuchi)

1. INTRODUCTION

Novae are a subclass of cataclysmic variables (CVs) that contain a white dwarf and a solar-like companion that fills its Roche lobe. Typically, the white dwarf accretes mass from an accretion disk that surrounds it. After of order 10^4 yr, the white dwarf accumulates enough material for a thermonuclear-runaway event, which results in the observed nova outburst (e.g., Warner 1995). It is believed that the nova eruption disrupts the accretion disk, which is re-formed several weeks or months later (e.g., Retter 2004).

Nova V2574 Oph ($\alpha_{2000.0} = 17^{\rm h}38^{\rm m}45^{\rm s}$, $\delta_{2000.0} = -23°28'18\farcs5$) was discovered by Akira Takao (Kitakyushu, Japan) at $V \approx 10.2$ on 2004 April 14.80 UT (Yamaoka 2004). Mason et al. (2004) reported that echelle spectra (390–900 nm, resolution 48000) of V2574 Oph, obtained on 2004 April 17.32 and 18.37 UT at La Silla with the 2.2 m telescope, were dominated by Hα, Na D, and Ca II emission lines, which are flanked by double P Cygni profiles. From the minima of the P Cygni absorptions, the measured expansion velocities were estimated as 400 and 1050 km s^{-1} for Hα and 400 and 1000 km s^{-1} for Na D.

Rudy et al. (2004) observed V2574 Oph 73 days after maximum and found that the nova was still in an "O I" phase, in which the O I lines at 0.8446 and 1.1287 μm that are fluorescently excited by Lyβ have strengths comparable to Hα. The optical region showed numerous multiplets of Fe II, which characterize this class as novae. The low expansion velocities of the ejecta mentioned above seem to rule out the possibility that V2574 Oph is a hybrid nova that evolved to the He/N class from the Fe II type (Della Valle & Livio 1998). The overall appearance of the spectra indicated a substantial evolution with respect to early reports and suggested that this is a slow nova caught at maximum light (Bond & Walter 2004).

So far, there are about 50 novae with known orbital periods (Warner 2002). Typical nova periods range from about 2 to 9 hr. Finding the orbital period of a nova yields an estimate of the secondary mass (e.g., Smith & Dhillon 1998). In addition, detecting several periodicities in novae can help in classifying the system into different groups of CVs, such as magnetic systems, intermediate Polars, and/or permanent superhump systems (e.g., Diaz & Steiner 1989; Baptista et al. 1993; Retter et al. 1997, 1998, 1999, 2003; Patterson et al. 1997, 2002; Skillman et al. 1997, 1999; Patterson & Warner 1998; Retter & Leibowitz 1998; Patterson 1999, 2001; Retter & Naylor 2000; Woudt & Warner 2001, 2002; Lipkin et al. 2001; Warner 2002; Ak et al. 2005; Balman et al. 2005; see also Retter et al. 2002, 2005). This yields valuable information about the magnetic field of the white dwarf and reveals the presence or absence of the accretion disk.

We have an ongoing program to observe novae with small telescopes to search for periodicities in their optical light curves. In this paper, we present extensive photometric observation of V2574 Oph, which suggests the presence of orbital and superhump periods.

2. OBSERVATIONS

V2574 Oph was observed on 23 nights during 2004 May, June, and August, and on 14 nights during 2005 May and June. The observations span 379 nights and consist of 37 nights (203 hr in total). Table 1 presents a summary of the schedule of the observation. The photometry was carried out with a 0.3 m f/6.3 telescope coupled to an ST7 NABG CCD camera. The pixel size of this CCD was 9×9 μm. This camera is attached to an Optec f5 focal reducer, giving an image field of view of $15' \times 10'$. The range of seeing for the data was $2\farcs5$–$3''$. The telescope is located in Exmouth, Western Australia, and no filter was used. The exposure times were between 30 and 60 s every 120 s. Our total number of data points is 7219. Aperture photometry was used in the reduction, with an aperture size of 12 pixels. For the data taken during 2004 May and June, we estimated differential magnitudes with respect to GSC (Guide Star Catalog) 6827−640 ($V = 12.6$, the comparison star, denoted "C"), using another star ($1\farcm2$ south of the comparison star) in the field, which is not listed in the GSC, as the check star, "K" ($V = 13.4$). The magnitudes of the comparison stars were added to the differential magnitudes to give a rough estimate of the V magnitudes. With the fading of the nova and because of some instrumental constraints, different comparison stars were used for two other subgroups of the data. For 2004

[1] Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Lab, University Park, PA 16802; tkang@astro.psu.edu; retter@astro.psu.edu; mtr@astro.psu.edu.

[2] Norcape Observatory, P.O. Box 300, Exmouth 6707, Australia; asliu@onaustralia.com.au.

TABLE 1

The Observations Time Table

Date (UT)	Time of Start (HJD −2453000)	Run Time (hr)	Number of Points	Comments
2004 May 31......	157.07290	7.8	219	
2004 Jun 22	179.00080	8.5	235	
2004 Jun 23	180.03790	7.4	205	
2004 Aug 04......	222.00030	5.2	386	
2004 Aug 05......	223.01050	5.1	371	
2004 Aug 07......	225.00060	5.2	286	
2004 Aug 08......	226.03010	4.0	177	
2004 Aug 09......	227.01290	5.0	219	
2004 Aug 10......	227.99230	4.9	221	
2004 Aug 12......	229.98880	5.3	181	
2004 Aug 13......	231.00440	4.9	199	
2004 Aug 14......	232.01670	5.0	203	
2004 Aug 15......	233.01580	4.9	199	
2004 Aug 16......	234.00970	5.0	206	
2004 Aug 17......	235.01410	4.6	189	
2004 Aug 18......	236.03860	2.8	127	
2004 Aug 20......	238.00240	4.5	191	
2004 Aug 22......	240.06770	2.9	129	
2004 Aug 26......	244.07070	3.1	142	
2004 Aug 27......	244.98720	4.2	190	
2004 Aug 28......	245.96630	4.7	209	
2004 Aug 29......	247.01970	3.8	161	
2004 Aug 30......	248.01820	3.9	152	
2005 May 07......	498.14124	6.3	176	
2005 May 08......	499.14860	6.2	166	
2005 May 09......	500.14133	6.4	177	
2005 May 10......	501.14419	6.1	170	
2005 May 11......	502.13795	6.4	176	
2005 May 12......	503.14005	6.4	175	
2005 May 13......	504.14247	6.5	176	
2005 May 14......	505.14854	6.3	169	
2005 May 16......	507.13301	6.3	177	
2005 Jun 07	529.08677	7.1	176	clouds
2005 Jun 10	532.08986	6.9	165	clouds
2005 Jun 11	533.08452	4.9	109	clouds
2005 Jun 13	535.09411	6.6	187	
2005 Jun 14	536.06776	7.9	223	

August 4–10, we observed the a star 0′.76 southwest of the variable as the comparison star and another star, 1′.4 southwest of the nova, as the check star. Their estimated V magnitudes were 13.66 and 14.06, respectively. For the remaining nights, we obtained differential magnitudes with respect to a star 3′.42 southwest of the variable as the comparison star and another star, 3′.1 south of the variable, as the check star. Their estimated V magnitudes were 12.30 and 13.40, respectively. The standard deviation of the errors in the V magnitudes was about 0.02 mag. The magnitudes of the stars were derived from the SBIG CCDOPS software.

Figure 1 displays the visual light curve of the nova from outburst until 2005 June. The data were compiled from the Association Francaise des Observateurs d'Etoiles Variables (AFOEV) and from the American Association of Variable Star Observers (AAVSO). By combining the data from these associations of amateur observers with our data, we obtained 7308 individual data points. The times of our observations are marked on the graph as well. Since our data were taken with an unfiltered CCD camera, we compared them with the AAVSO data when the observations were nearly simultaneous, and added 2 mag to our estimates to compensate for the difference between the visual and unfiltered data. The light curve shows that the fading of the nova was relatively smooth. We estimate that the maximum visual magnitude was $V = 9.5 \pm 0.2$.

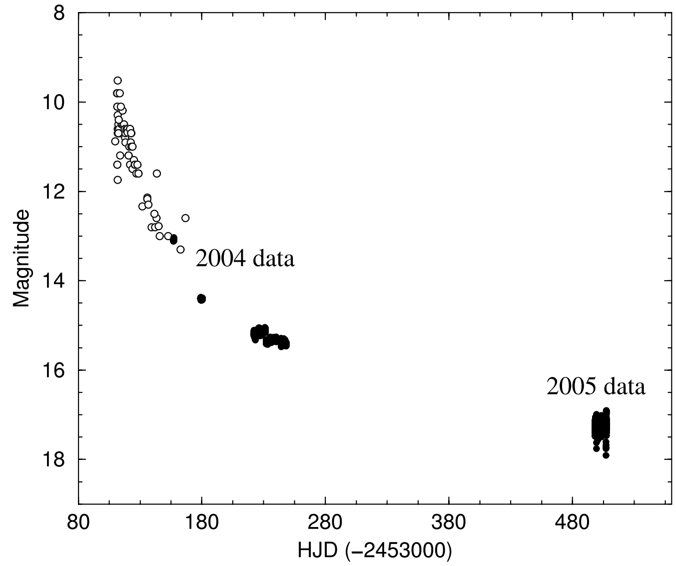

Fig. 1.—Long-term light curve of V2574 Oph. Open circles represent visual estimates made by amateur astronomers, compiled by AFOEV and AAVSO. Filled circles correspond to our observations. Our data points were shifted by 2 mag to compensate for the difference between visual and unfiltered data.

We present the light curves of our observations of V2574 Oph obtained in 2004 and 2005 separately in Figure 2. The top panel displays the 2004 light curve. We did not include the first three nights in this graph because of the large time gap and amplitude difference between these and the other nights. During the time interval spanned by these observations in 2004, the nova declined by 0.32 mag. The bottom panel of Figure 2 represents the observations in 2005.

3. DATA ANALYSIS

3.1. *The Long-Term Light Curve of V2574 Oph*

By using the maximum visual magnitude of $V = 9.5 \pm 0.2$ we measured the time required for a decline of 2 mag from

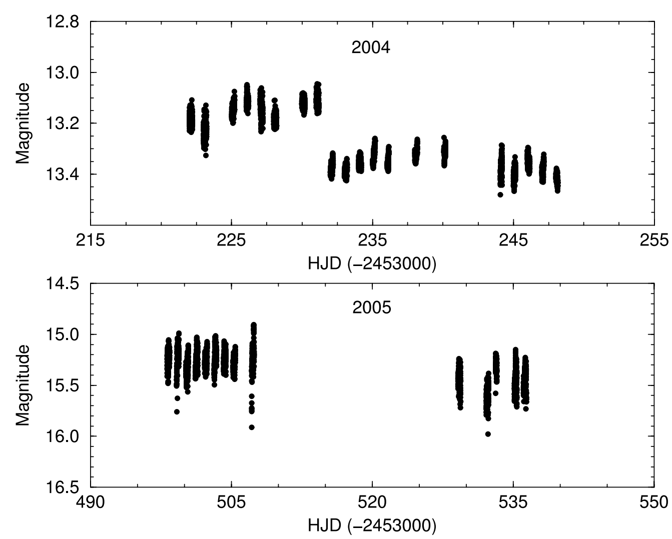

Fig. 2.—Light curves of V2574 Oph obtained in the observations in 2004 (*top panel*) and 2005 (*bottom panel*). The first three nights in 2004 are not shown because there was a large time gap and amplitude difference between these and the other nights.

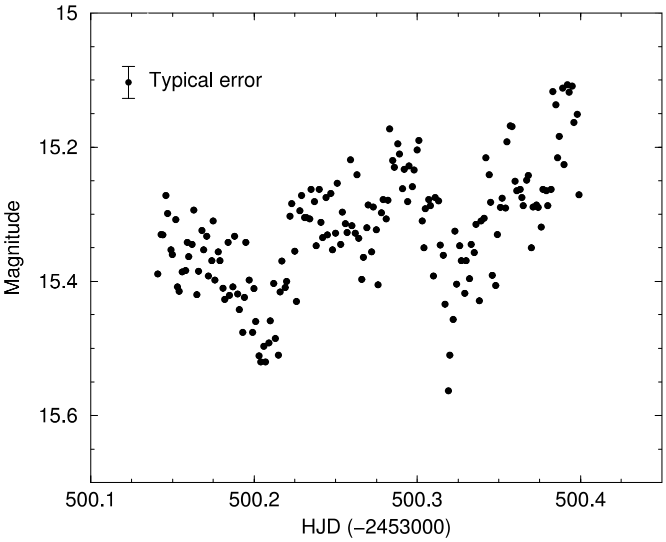

FIG. 3.—Sample of a nightly light curve of V2574 Oph. The data were obtained 2005 May 9.

maximum $t_2 = 17 \pm 4$ days. This makes V2574 Oph a fast nova according to the classification given in Table 5.4 of Warner (1995). This is inconsistent with the suggestion of Bond & Walter (2004) that V2574 Oph is a slow nova (§ 1). We calculated the visual absolute magnitude at maximum brightness using equation (5.3) of Warner (1995), $M_{V\max} = a_2 \log t_2 + b_2$, where $a_2 = 2.41 \pm 0.23$, $b_2 = -10.70 \pm 0.30$, and $t_2 = 17 \pm 4$ days, and obtained $M_{V\max} = -7.7 \pm 1.7$ mag.

3.2. *The 2005 Light Curve*

We begin with our 2005 data, since the periods were identified during this season. The noise level of the power spectrum is high when we combined the first run (first nine nights) and the second run (last five nights) (Fig. 2, *bottom panel*) because there was a 25 day gap between two runs. In addition, most nights in the second run in 2005 were affected by clouds. Thus, we decided to focus our analysis on the first nine nights, because they are almost consecutive and there is no large amplitude difference between the nightly means. A sample light curve from 2005 May 9 is shown in Figure 3; it shows a variation on a timescale of the order of 3 hr.

The power spectrum (Scargle 1982) of the raw data of the first nine nights in 2005 is displayed in Figure 4*a*. The power spectrum at midfrequencies is dominated by two similar alias patterns around two central frequencies, $f_1 = 7.060$ day^{-1} and $f_2 = 6.769$ day^{-1}, which correspond to the periodicities of 0.14164 ± 0.00010 and 0.14773 ± 0.00010 days. The highest peaks marked 1, 2, and 3 day^{-1} are a result of the daily spacing between the nights. Those peaks at low frequencies are not real because the power spectrum of the check star minus comparison star (K − C) data has a similar pattern (see Fig. 4*b*).

The power spectrum after subtracting the nightly trend from each night is displayed in Figure 4*c*. The 1, 2, and 3 day^{-1} peaks disappear. Figure 5*a* displays an expanded version of Figure 4*a*.

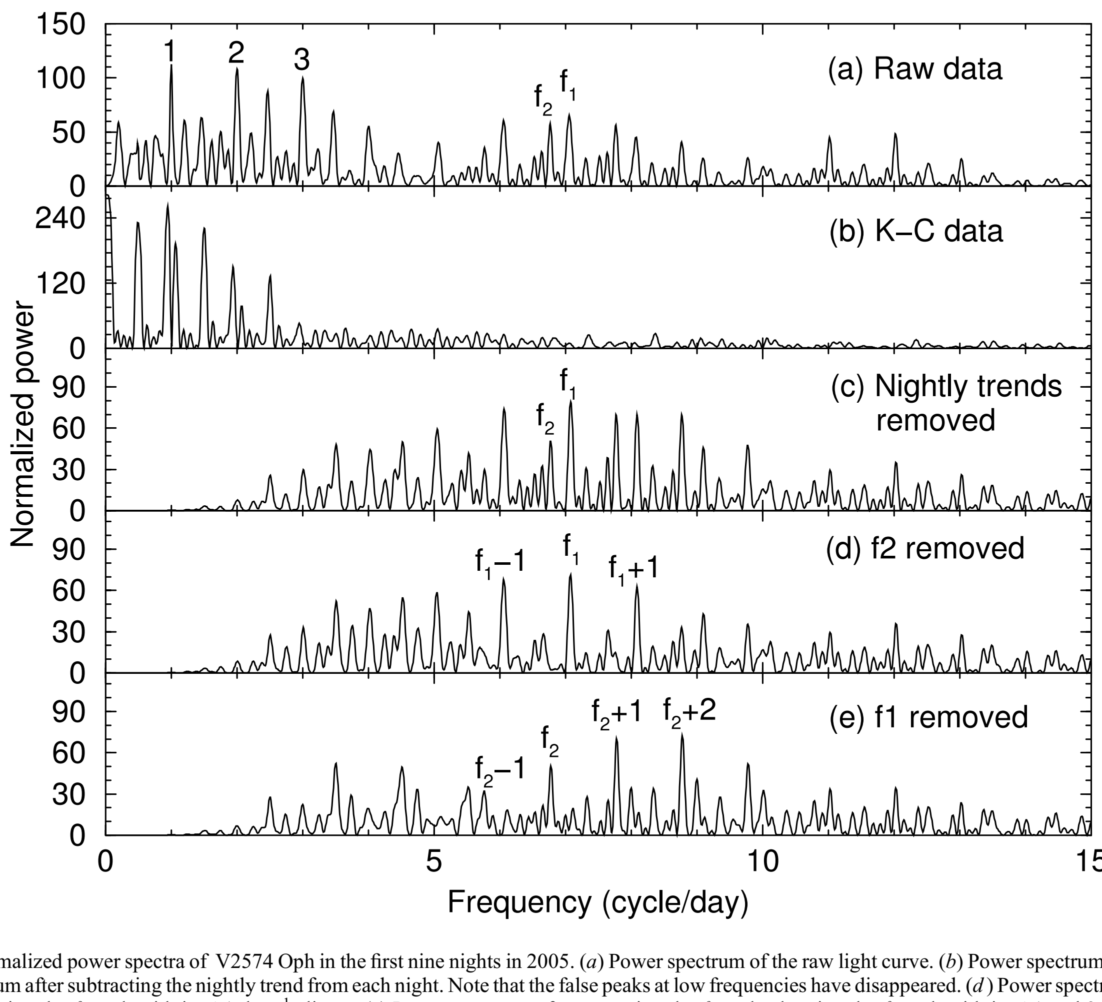

FIG. 4.—Normalized power spectra of V2574 Oph in the first nine nights in 2005. (*a*) Power spectrum of the raw light curve. (*b*) Power spectrum of the K − C data. (*c*) Power spectrum after subtracting the nightly trend from each night. Note that the false peaks at low frequencies have disappeared. (*d*) Power spectrum after removing the f_2 peak, showing the f_1 peak with its ±1 day^{-1} aliases. (*e*) Power spectrum after removing the f_1 peak, showing the f_2 peak with its ±1 and 2 day^{-1} aliases.

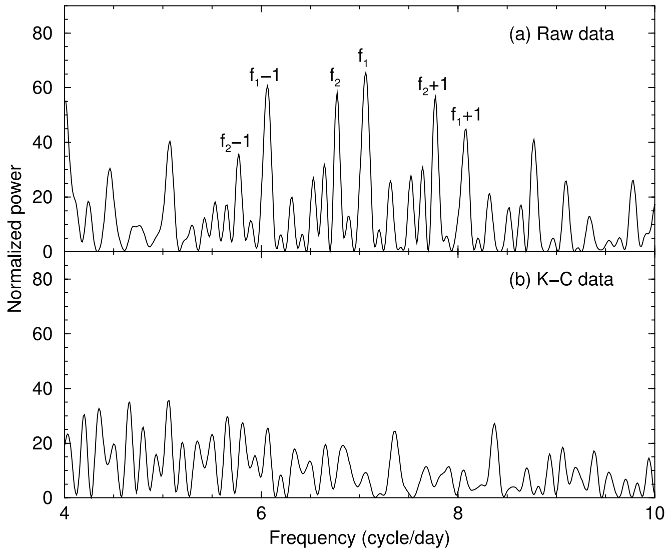

FIG. 5.—(*a*) Power spectrum of the first nine nights in 2005 (see Fig. 4*a*) zoomed into the 4–10 day^{-1} range of frequencies. The two frequencies (f_1 and f_2) are marked, along with their ±1 day^{-1} aliases. (*b*) Power spectrum of the K − C data. It does not display any significant periodicity.

It shows the two strong peaks, f_1 and f_2, with their ±1 day^{-1} aliases. Figure 5*b* represents the zoomed K − C power spectrum.

3.2.1. *Tests*

To confirm that the f_1 and f_2 peaks were real, we performed several tests. First, we checked to see if the f_1 peak in the power spectrum was an artifact of the window function. This was done by creating a noiseless simulation (i.e., planting a pure sinusoidal variation in the data with no errors) of the first nine nights in the 2005 data. There was no evidence for significant power at the location of the peak.

We also checked whether the K − C power spectrum had a similar power and pattern near the f_1 peak. However, the K − C power spectrum did not show any strong power near the f_1 peak (see Figs. 4*b* and 5*b*).

To further check the significance of the f_1 peak, we used the bootstrap method. First, we scrambled the magnitude values, arbitrarily assigned them to the times of the observations, and calculated the corresponding power spectrum. Then we found the power of the highest peak in the power spectrum. Finally, we plotted the histogram of the highest peaks of the 1000 simulations. This suggested that the f_1 peak was about 43 σ significant. Thus, we confirmed that the peak was real. The results were similar for the tests applied to the f_2 peak.

3.2.2. *Significance of the Two Peaks*

To check the significance of two independent periodicities in the light curve of the nova, we applied a few tests. First, we fitted and subtracted the first harmonic of the f_2 frequency from the data. The power spectrum of the residuals clearly showed f_1 as the dominant peak in the graph. Conversely, when the f_1 frequency was removed from the data, f_2 and its daily aliases dominated the residual power spectrum. We present these power spectra in Figures 4*d* and 4*e*, respectively.

We also checked the significance of a second periodicity in the presence of the first. We created an artificial light curve from the times of the actual observations by superimposing a sinusoidal wave on one of the two periodicities over a random distribution of points representing white noise. The power spectrum of each of these synthetic light curves showed only the corresponding imposed periodicity, surrounded by an alias pattern similar to that of the actual data, with no trace of the other periodicity.

To check whether uncorrelated noise could be responsible for the presence of the candidates periods, we added noise to the model light curves of the first nine nights in 2005. The noise in the original data was defined as the root mean square (rms) of the data minus the f_1 frequency. We then searched for the highest peak in a small interval (6.72–6.82 day^{-1}) around the f_2 peak. In 1000 simulations, no peak reached the height of the f_2 frequency. Similarly, for the f_1 frequency, we did 1000 simulations in the interval 7–7.1 day^{-1}. No peak reached the height of the f_1 peak either. So both periods seem to be real.

As a final test for the presence of the two frequencies, we divided our 2005 data into two parts. In the power spectra of both parts of the observations, the same peaks appeared as the strongest ones in a 1 day^{-1} frequency interval on both sides of the peaks (i.e., up to the 1 day^{-1} aliases). Thus, we concluded that the two peaks in the 2005 data indicate real periodicities.

In a search for a third frequency, we fitted and subtracted the f_1 and f_2 frequencies from the data. The power spectrum of the residuals did not show any additional significant peaks.

3.3. *The 2004 Light Curve*

The 2004 data were analyzed to search for the two periods found in the 2005 data. The 2004 data seem to have variations on timescales similar to the periodicities detected in the 2005 data. However, we could not find any convincing evidence of any coherent periodicity. This result is further discussed below.

3.4. *The Structure of the Periodicities*

In Figure 6 we present the first nine nights in the 2005 data of V2574 Oph folded on the 0.14773 day period (*top panel*) and on the 0.14164 day period (*bottom panel*). The points in the figure are the average magnitude values in each of the 40 equal bins that cover the 0–1 phase interval. The peak to peak amplitudes of the mean variations were found to be 0.082 ± 0.007 and 0.077 ± 0.007 mag for the f_1 and f_2 frequencies, respectively. The amplitudes were derived by fitting a sinusoidal function to the mean light curve.

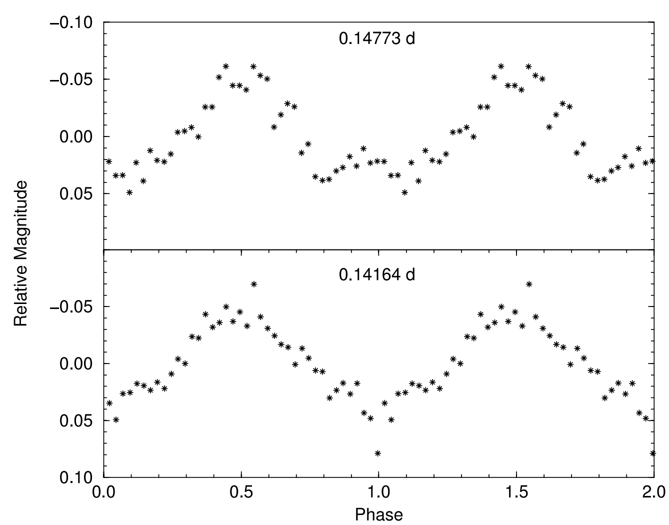

FIG. 6.—Light curve of V2574 Oph obtained in the first nine nights in 2005, folded on the 0.14773 day period (*top panel*) and the 0.14164 day period (*bottom panel*), and binned into 40 equal bins. Two cycles are shown for clarity.

The best fitted ephemerides of the periodicities are:

$$T_{1,\min}(\mathrm{HJD}) = 2{,}453{,}498.215 + 0.14164E \pm 0.040 \pm 0.00010,$$
$$T_{2,\min}(\mathrm{HJD}) = 2{,}453{,}498.117 + 0.14773E \pm 0.041 \pm 0.00010.$$

4. DISCUSSION

The photometric data of V2574 Oph show the presence of two independent periodicities in the light curve: $P_1 = 3.40$ hr and $P_2 = 3.55$ hr, which correspond to f_1 and f_2, respectively. The orbital period distribution of novae has a peak at 3–4 hr (Diaz & Bruch 1997; Warner 2002). Thus, we suggest that one of the periods we found is the orbital period of the underlying binary system. We explore two possibilities, namely, that the second periodicity could result from a spin period in a nearly synchronous Polar system or a superhump.

4.1. *A Nearly Synchronous Polar?*

The AM Her stars (magnetic CVs) differ from the nonmagnetic systems in two important qualitative respects: (1) a strong magnetic field on the primary star funnels the infalling gas onto one or two localized accretion shocks near the white dwarf's magnetic pole(s), where X-ray bremsstrahlung and polarized optical/infrared cyclotron emission arise; and (2) the white dwarf spin and binary orbital motions are locked in a rigid corotating geometry (e.g., Schmidt & Stockman 1991).

Nearly synchronous Polars are a subclass of magnetic CVs, sharing many of their properties with AM Her stars, but having a white dwarf that rotates with a period that differs by $\sim$1% from the orbital period. There are four known nearly synchronous Polars: V1500 Cyg (e.g., Schmidt et al. 1995), BY Cam (e.g., Mason et al. 1998), V1432 Aql (e.g., Geckeler & Staubert 1997), RX J2115−5840 (Ramsay et al. 2000), and one candidate, V4633 Sgr (Lipkin et al. 2001).

Warner (1995) explained that as the primary of the binary system rotates asynchronously, the accretion flow is more variable than for a phase-locked Polar. Accretion occurs on both magnetic poles, but at any given time accretion onto the pole nearest the secondary is most favored.

Stockman et al. (1988) proposed that the reason for the asynchronization is a recent nova outburst. In one case, V1500 Cyg, the asynchronous rotation is clearly associated with its nova eruption in 1975. Two other nearly synchronous Polars may also have undergone a recent nova events: V1432 Aql (Schmidt & Stockman 2001) and BY Cam (Bonnet-Bidaud & Mouchet 1987). Similarly, V4633 Sgr, which has been proposed as a nearly synchronous system (Lipkin et al. 2001), is a postnova.

The difference between the two periods of V2574 Oph that we found in the 2005 data, about 1 yr after outburst, is $\sim$4%. This is much larger than all values found in the nearly synchronous Polars (Lipkin et al. 2001). This difference cannot be attributed to the proximity in time of our observations to the nova outburst, because the low value of asynchronization in V1500 Cyg was already observed about 3 months after its nova outburst (Semeniuk et al. 1976). This is much sooner after the nova event than our observations. Thus, a nearly synchronous Polar model does not seem to apply to V2574 Oph.

4.2. *Permanent Superhumps*

Patterson & Richman (1991) initially suggested the term "permanent superhump" for the subclass of CVs whose light curves show quasi-periodicities slightly different from their binary orbital periods. Unlike SU UMa systems (see Warner [1995] for a review of SU UMa systems and CVs in general), which display this behavior only during superoutbursts, permanent superhump systems show the phenomenon during their normal brightness state.

Whitehurst & King (1991) suggested that superhumps occur when the accretion disk extends beyond the 3 : 1 resonance radius. According to Osaki (1996), permanent superhump systems differ from other subclasses of nonmagnetic CVs by having relatively short orbital periods and high mass-transfer rates, resulting in accretion disks that are thermally stable but tidally unstable. Retter & Naylor (2000) provided observational support for this idea.

In permanent superhump systems, periods longer and shorter than the orbital periods have been observed. These are called positive and negative superhumps, respectively. A positive superhump, a periodicity that is a few percent larger than the orbital period, is explained by the beat period between the binary motion and the precession of an eccentric accretion disk in the apsidal plane. Observations of positive superhumps have shown a roughly linear relation between the period excess, expressed as a fraction of the binary period and the binary period itself (Stolz & Schoembs 1984; Retter et al. 1997; Patterson 1999). A negative superhump is a period slightly shorter than the orbital period, and is explained by the beat periodicity between the nodal precession of the accretion disk and the orbital period (Patterson et al. 1993; Patterson 1999). Negative superhumps also show a roughly linear correlation between the period deficit and the binary period itself (Patterson 1999), and Retter et al. (2002) proposed that the ratio of the negative superhump deficit over the positive superhump excess in systems that show both types of superhumps is connected to the orbital period.

Two periods were detected in the light curve of V2574 Oph from the 2005 data (§ 3.2). If $P_1 = 3.40$ hr is the orbital period, then $P_2 = 3.55$ hr is a positive superhump. Alternatively, if P_2 is the orbital period, then P_1 is a negative superhump. Using $\Delta P \approx 4\%$, we can check which of the two scenarios better fits the two relations for positive and negative superhumps. If P_1 is the orbital period, P_2 is a positive superhump, and the superhump period excess is then about 4%. According to the relation shown in Figure 1 in Patterson (1999), the positive superhump excess should be $\sim$7% for an orbital period of 3.40 hr. Therefore, this case does not seem to apply to V2574 Oph. If P_2 is the orbital period, P_1 is a negative superhump, and the superhump period deficit is then about 4%. This nicely fits the relation in Figure 1 of Patterson (1999). Thus, we interpret $P_2 = 3.55$ hr as the orbital period and $P_1 = 3.40$ hr as the negative superhump period.

4.3. *The Presence of the Accretion Disk*

It was initially believed that accretion disks around white dwarfs are destroyed by nova outbursts and take a few decades to reform. However, permanent superhumps have been observed in V1974 Cyg about 2 yr after its nova outburst (Retter et al. 1997; Skillman et al. 1997; Retter 1999). The detection of superhumps is evidence of the early presence of the precessing accretion disk in this system. Similarly, the presence of superhumps in V2574 Oph suggests that an ellipic accretion disk existed in V2574 Oph about 1 yr after outburst.

4.4. *The 2004 Data*

We did not detect any coherent frequencies in the 2004 data (§ 3.3). We suspect that no periods were found in these data for three reasons: (1) the light curve might have been affected by a significant contribution from the nebula and/or by optically thick winds; (2) the accretion disk might have been in an unstable state at that time and could have still been reforming, thus adding more noise and reducing the chances of detecting any frequencies; and (3) apart from the first three nights, which were obtained very early after the nova eruption, the nightly runs in the 2004 data were shorter than in the 2005 data (see Table 1). Therefore, the results from the 2004 data were less reliable.

5. SUMMARY AND CONCLUSION

1. By using the maximum visual magnitude of $V = 9.5 \pm 0.2$, we measured the decay time $t_2 = 17 \pm 4$ days from the long-term light curve. This makes V2574 Oph a fast nova. We estimated a visual absolute magnitude in maximum of $M_{V_{\rm max}} = -7.7 \pm 1.7$ mag.

2. We found two periods of 0.14164 days ($\approx$3.40 hr) and 0.14773 days ($\approx$3.55 hr) in the 2005 data.

3. We interpret the longer 3.55 hr period as the orbital period of the binary system, and the 3.40 hr period as a negative superhump period.

4. More observations (including radial velocity studies) are required to confirm our results and to follow the evolution of the periodicities in time.

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