ABSTRACT

DETECTING WAVES IN
ACCRETION DISKS

We present observations of three cataclysmic variable stars: HV Andromedae, LQ Pegasi, and SW Sextantis. A cataclysmic variable star is a binary star system composed of a red dwarf orbiting a white dwarf. These stars orbit closely, typically in 3-4 hours. Due to this close orbit, gas spills from the red dwarf into orbit around the white dwarf. This forms an accretion disk. Accretion disks are found throughout the Universe: from planetary formation, Saturn's rings, black holes that swallow stars, to the Milky Way's spiral structure. Our goal in studying these three cataclysmic variables was to search for evidence of waves, warping, or bending of their accretion disks.

Photometry is the study of how the brightness of an object changes over time. With cataclysmic variables, much of the fluctuation in brightness is from the accretion disk. We collected time-resolved, differential photometry of three cataclysmic variables using Fresno State's remotely controlled telescope at Sierra Remote Observatories. After measuring our photometry, we searched for waves in the data.

We found strong evidence for both warping and bending waves in LQ Pegasi. We also see clear evidence for short-period waves in HV Andromedae, also with some rumbling at low frequencies. Our SW Sextantis observations show no excess periodicity indicating that no superhumps are present in the prototypical SW Sextantis star. Our observations of LQ Pegasi and HV Andromedae warrant further study in the form of radial-velocity studies.

Gerald Douglas Rude II
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DETECTING WAVES IN ACCRETION DISKS

by

Gerald Douglas Rude II

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For the Department of Physics

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Dedicated to Garlyn Elizabeth Hollingshead and Max

INTRODUCTION

Cataclysmic variable stars (or CVs) are binary star systems composed of a white dwarf and a low mass main sequence star (Robinson, 1976). The white dwarf, known as the primary star, is being orbited closely by a less-massive main sequence star, known as secondary or donor star(Hellier, 2001). This results in mass transfer from the secondary onto the primary. The result of this mass transfer is the formation of an accretion disk. Accretion disks are found throughout the Universe. Common examples of accretion disks are spiral galaxies, like our own Milky Way, protostellar disks, which are responsible for forming stars and planets, and the ultra-luminous quasars, the most powerful objects known. CVs are natural laboratories for studying accretion. Due to their short orbital periods, typically on the order of 4 hours, and broad spectral lines, astronomers are able to study the dynamics of accretion disks using even modest instruments.

The mechanism in which the secondary star transfers material to the primary star has been much studied. Due to the close proximity of the secondary star to the primary, the secondary's shape is distorted into a teardrop shape described by Roche geometry (Hellier, 2001). When the separation distance between the stars is close enough that mass transfer is possible, we call the shape of the distortion the Roche lobe. The mass transfer takes place at the inner Lagrange point L_1. Material escapes from the secondary star and spills onto the primary star at the speed of sound of the gas (Hellier, 2001). The gas is unable to fall straight onto the primary due to its angular momentum; this stream of material makes a high speed orbit about the primary star where it will come into contact with the stream forming a thin disk. As material spills from the secondary via the L_1 point, the stream will slam into the thin accretion disk forming a bright spot on the edge of the disk (Robinson, 1976).

CVs typically have orbital periods near four hours, while a few CVs can have orbital periods over five days and a number of CVs have orbital periods under 90 minutes (Ritter, 2003.) The distribution of CV orbital periods has been linked to the evolution of CVs. A histogram of orbital period distribution shows a significant gap of stars with orbital periods between approximately two hours and three hours (Hellier, 2001). This period gap is thought to be due to a change in the mechanism by which CVs evolve, essentially the mechanism that reduces their orbital separation (Warner, 1995). Since the accretion disk and bright spot are a large component of a CV's luminosity, it should be no surprise that the sample of CVs is biased toward brighter accreting CVs and we are under representing the CVs in the period gap.

The research I have performed these past two years has been looking for CVs exhibiting superhumps. Superhumps are waves in the accretion disk, and they come in two varieties. Positive superhumps, also referred to as apsidal superhumps, are caused by eccentricity in the disk and the sloshing of material throughout the disk. The period of these apsidal superhumps is slightly longer (on the order of a few percent) than that of the orbital period. Negative superhumps, also referred to as nodal superhumps, are caused by bending waves in the disks. These superhumps have a period that is slightly shorter (on the order of a few percent) than the orbital period. Superhumps are generally easy to see in the photometric light curves and commonly display prominent sawtooth waves (Harvey et al., 1995).

LQ PEGASI

Introduction

LQ Pegasi was discovered during the Palomar-Green Survey (Green et al., 1986), in which it was designated PG 2133+115 and classified as a CV. It was not listed in their preliminary report on CVs found by the survey, however (Green et al., 1982). Ferguson et al. (1984) presented visible and ultraviolet spectra that showed weak emission lines inside broad absorption wings on a blue continuum. They classified LQ Peg as a thick-disk or UX UMa cataclysmic variable, since the spectra they showed were similar to those of dwarf novae in outburst, or nova-like variables, which are thought to resemble dwarf novae stuck in outburst most of the time.

LQ Peg was listed as Peg6 by Downes and Shara (1993), who gave precise coordinates and a finding chart. So do Downes et al. (1997) and Downes et al. (2001). It was given the variable star name LQ Pegasi by Kazarovets and Samus (1997). Ringwald (1993) attempted to measure the orbital period of LQ Peg by doing a radial velocity study, but obtained only an uncertain estimate of 2.9 hours (0.121 ± 0.001 days). This was uncertain because the time series was short, which gave problems with aliasing (see Thorstensen and Freed, 1985). Another reason this orbital period is suspect is due to the difficulty in measuring the Hα line. The Hα line was quite narrow and quite faint, relative to the continuum, during the observations. This resulted in the only orbital-period measurement done by a radial-velocity study of a CV by Ringwald (1993) in which there was a significant false-alarm probability, of 17.4%, as defined by Thorstensen and Freed (1985). This means that there was a non-negligible chance that the velocity measurements themselves showed a false signal, regardless of aliasing, which was determined by how they were sampled.

Misselt and Shafter (1995) obtained six hours of time-resolved, V-band photometry of LQ Peg. The only variability they noted was the flickering that is characteristic of all CVs while transferring mass. (See Chapter 10 of Hellier, 2001.) A photometric study by Papadaki et al. (2006) concluded that LQ Peg has an orbital period of 2.99 hours (0.124747 $\pm$ 0.000006 days), although, as we will show, we suspect this is not the orbital period.

Ak et al. (2008) assumed that the orbital period of 0.12475 days was correct, and used it and $JHKs$ magnitudes observed for LQ Peg by the 2MASS survey (Cutri et al., 2003) to estimate an absolute magnitude of $M_J = 4.76$, a distance of 809 pc, and $E(B-V) = 0.095$, estimated from the position in the Galaxy and the distance that Ak et al. (2008) found for LQ Peg. Even if this assumed orbital period is incorrect and these values are only approximate, they are still consistent with LQ Peg being a relatively luminous, nova-like CV.

LQ Peg goes into unpredictable low states, similar to those of VY Sculptoris and similar stars, which are sometimes called anti-dwarf novae (Kato and Uemura, 1999; Schmidtke et al., 2002; Honeycutt and Kafka, 2004; Kafka and Honeycutt, 2005; Shugarov et al., 2007). This further supports that LQ Peg is a nova-like CV. Honeycutt and Kafka (2004) give a light curve from 1993 to 2003. It shows that LQ Peg spends most of its time in the high state, as VY Scl stars do. For LQ Peg, this high state is near $V = 14.6$, but LQ Peg can drop to $V = 17.0$ during a low state.

Observations

Time-resolved CCD photometry of LQ Peg was collected on the nights of 2010 August 20-28 UT, with the exception of August 22 UT. We used the 0.41-m (16-inch) f/8 telescope by DFM Engineering at Fresno State's station at Sierra Remote Observatories and a Santa Barbara Instruments Group STL-11000M CCD camera. Frames were exposed for 23 seconds, with a dead time to read out the CCD between exposures of 7 seconds, making for a total time resolution of 30 seconds. All exposures were taken through a Clear luminance filter by Astrodon. Weather was clear and apparently photometric on all nights, although the third night (August 23 UT) may have had some haze. Table 1 is a journal of the observations.

The data were processed with AIP4WIN 2.0 software (Berry and Burnell, 2005). All exposures were dark-subtracted, but not divided by a flat field. The CCD temperature was −5°C for all exposures. Fifteen dark frames were collected every night. These frames were median combined to form a master dark frame, which was then subtracted from each of the target frames.

To measure the photometry, we used the same check stars as those used by Papadaki et al. (2006). Check stars S1 – S8 were used for ensemble photometry (Gilliland and Brown, 1988), with S4 being relabeled as C1 and S7 as C2. This telescope and camera have an image scale of 0.51 arcseconds/pixel. All our observations were done binned 3x3, making for an image scale of 1.53 arcseconds/pixel. The seeing ranged between 0.95 and 1.72 arcseconds on all nights. All photometry used an aperture of 6 pixels, or 3.06 arcseconds, in diameter, and

Table 2.1. Journal of observations

UTDate	*UTStart*	*Duration(hr)*	*Number of exposures*
2010 August 20	4:26	7.61	874
2010 August 21	3:40	8.3	947
2010 August 23	3:44	8.04	920
2010 August 24	3:25	8.36	962
2010 August 25	9:33	2.12	244
2010 August 26	8:54	2.34	270
2010 August 27	3:27	8.12	937
2010 August 28	3:37	7.88	897

used an annulus around between 9 and 12 pixels (4.59 and 6.12 arcseconds) in diameter around this, for sky subtraction. Figure 2.1 shows a typical nightly light

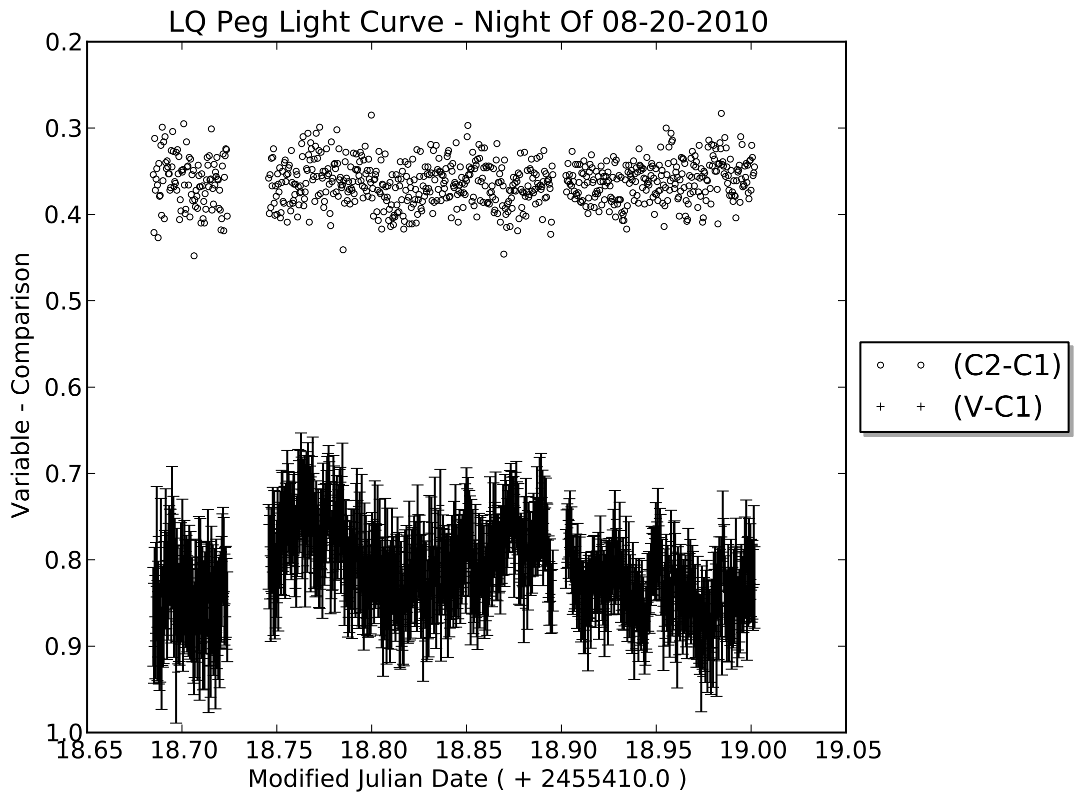

Figure 2.1. Differential Light Curve of LQ Peg for 2010 August 20 UT.

curve of our differential photometry of LQ Peg, comparison (C1), and check (C2) stars, from the first night (2010 August 20 UT).

Data Analysis

Figure 2.2 is a Lomb-Scargle periodogram (Lomb, 1976; Scargle, 1982; Press et al., 1992) of our time-resolved photometry that we calculated with the

PERANSO (PeRiod ANalysis SOftware) software package (Vanmunster, 2009) to search for periodicities.

Figure 2.2 shows that the low frequency signal at 0.4162 cycles/day is by far the most prominent signal. Other significant periods were observed at: 0.5809, 1.4252, 2.0180, 3.0150, 7.0390, and 8.0240 cycles/day.

We note four distinct periodicities, accompanied by aliases. The first periodicity has a frequency $f_1 = 0.4162$ cycles/day, corresponding to a period $P_1 = 56.8 \pm 0.01$ hours. The periodogram shows its one-cycle-per-day alias at a frequency of 1.42 cycles/day. The second periodicity has $f_2 = 7.039$ cycles/day, corresponding to a period $P_2 = 3.42 \pm 0.03$ hours. The periodogram shows its one-cycle-per-day aliases at frequencies of 6.06 and 8.02 cycles/day. The third periodicity has $f_3 = 0.5809$ cycles/day, corresponding to a period $P_3 = 41.3 \pm 0.01$ hours. The fourth periodicity has $f_4 = 3.0$ cycles/day, with aliases at 2.0 and 4.0 cycles/day.

Figure 2.3 shows the spectral window function for our observations. This plots the pattern caused by aliasing because of the convolution with the diurnal cycle (see the discussions of the convolution theorem and window functions by Press et al., 1992), and shows what signals could inadvertently be introduced to the data set because of the spacing of our observations. Signals found in our time series analysis, which coincide with signal peaks in the spectral window function, are regarded as suspect and ignored. We will therefore ignore the signal with $f_4 = 3.0$ cycle/day signal, as well as its aliases at 2.0 and 4.0 cycles/day.

Figure 2.4 is a log-log plot of Figure 2.2, the Lomb-Scargle periodogram. It shows that the maximum power is at frequencies less than one cycle/day. It also shows no obvious excess of power at high frequencies, as can be caused by Quasi-Periodic Oscillations (QPOs), or Dwarf Nova Oscillations (DNOs). (See Chapter 10 of Hellier, 2001.) There is a power spike at the Nyquist Frequency which may be the result of our sampling rate or unresolved higher frequency periodicity.

Figure 2.5 shows a fluctuation in the mean magnitude of LQ Peg. Phase folding the data over the 0.4162 cycles/day frequency (56.8-hour period), as shown by Figure 6, shows sinusoidal behavior.

Papadaki et al. (2006) normalized, or pre-whitened their time-resolved photometry, to eliminate night-to-night variations in the systems mean magnitude. Unsurprisingly, their time series analysis did not show the low-frequency signals we found.

Superhumps, both apsidal and nodal, can give rise to the periodicities observed in LQ Peg. As discussed in Chapter 6 of Hellier (2001), positive superhumps (also known as apsidal superhumps) are fluctuations in the light curve due to eccentricity in the accretion disk. When the precessional period of the elliptical disk and the orbital period of the star beat against one another, this periodic phenomenon can show in the light curve.

Interpreting the low-frequency signal of 0.4162 cycles/day ($P_1 = 56.8 \pm 0.01$ hours) to be associated with the precessional period Pprec, and the period associated with the signal at 7.039 cycles/day ($P_2 = 3.42 \pm 0.03$ hours) to be the apsidal superhump period Psh, we predict that the orbital period Porb = 3.22 0.03 hours, since (see page 77 of Hellier, 2001):

$$\frac{1}{P_{sh}} = \frac{1}{P_{orb}} - \frac{1}{P_{prec}} \tag{2.1}$$

Figure 6.19 of Hellier (2001) plots apsidal superhump period excess (ϵ_{sh}) versus orbital period in hours. Using our values for Porb and Psh, we find a period excess $\epsilon_{sh} = (P_{sh} P_{orb})/P_{orb} = 0.056$, which fits the upper trend line of Figure 6.19 of Hellier (2001).

The orbital period is not obvious in our data, but LQ Peg may be nearly face-on, which may explain the difficulty in obtaining a radial velocity curve. A thick disk (Ferguson et al., 1984), characteristic of a luminous nova-like CV, is expected to be bright everywhere, not just where the gas stream from the mass-losing secondary star strikes the edge of the disk.

Taking the 0.5809 cycle/day signal (corresponding to $P_3 = 41.3 \pm 0.01$ hours) to be the nodal precessional frequency ($1/P_{nodal}$), and the orbital period to be 3.22 ± 0.03 hours, we arrive at a nodal superhump period $P_{ns} = 2.99 \pm 0.03$ hours. Harvey et al. (1995) called these negative superhumps; Hellier (2001) called them infrahumps, and wrote their period as P_{ih}. They are thought to be from bending waves in the accretion disk, perpendicular to the disks plane. This matches the signal observed by Papadaki et al. (2006), though they interpreted this as the orbital period. In our interpretation,

$$\frac{1}{P_{ns}} = \frac{1}{P_{orb}} + \frac{1}{P_{nodal}} \tag{2.2}$$

$$\epsilon_{nodal} = -\frac{1}{2}\epsilon_{sh} = -0.031 \tag{2.3}$$

The nodal superhump excess nodal fits the lower trend line in Figure 6.19 of Hellier, 2001. This interpretation may explain why there is so much power in the peak at 8.02 cycles/day: this frequency is a one-cycle-per-day alias of the 3.22-hour apsidal superhump period, and it is also the nodal superhump period.

Conclusion

We carried out a photometric study of LQ Pegasi. Time series analysis was performed and a low-frequency signal of period 56.8 hours, not discussed by the previous literature on the star, was discovered. Our analysis indicates that the low frequency periodicity appears to be the precessional period of both an elliptical accretion disk, and nodal precession of the disk. Based on this analysis, we predict that the true orbital period of LQ Peg is 3.22 hours, that the 3.42-hour period we have observed and reported in this paper is the apsidal superhump period, and that the 2.99-hour periodicity observed by Papadaki et al. (2006) is the nodal superhump period of the accretion disk.

To confirm our prediction, it will be necessary to carry out an improved radial velocity study of LQ Peg. We recommend tht the spectra of LQ Peg of Papadaki et al. (2006) and of Rodrguez-Gil et al. (2007) be re-phased over the 3.22-hour orbital period we have predicted. If this orbital period is correct, the time-resolved behavior and Doppler tomogram of LQ Peg may become clearer.

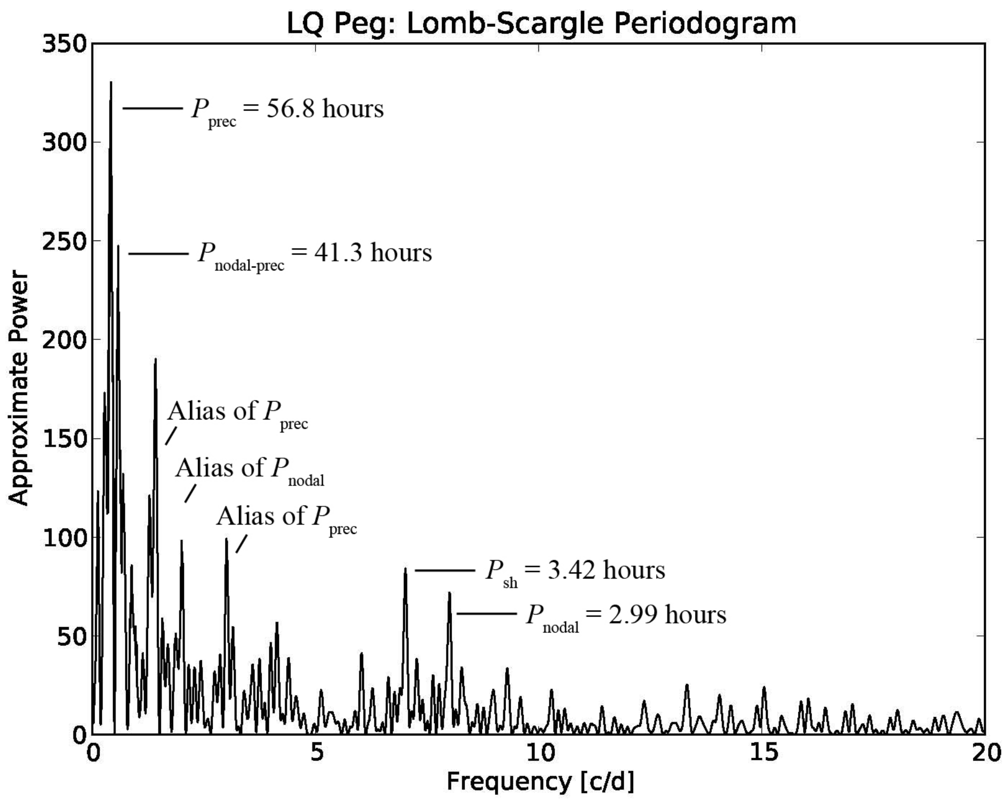

Figure 2.2. Lomb-Scargle periodogram showing the periods of note.

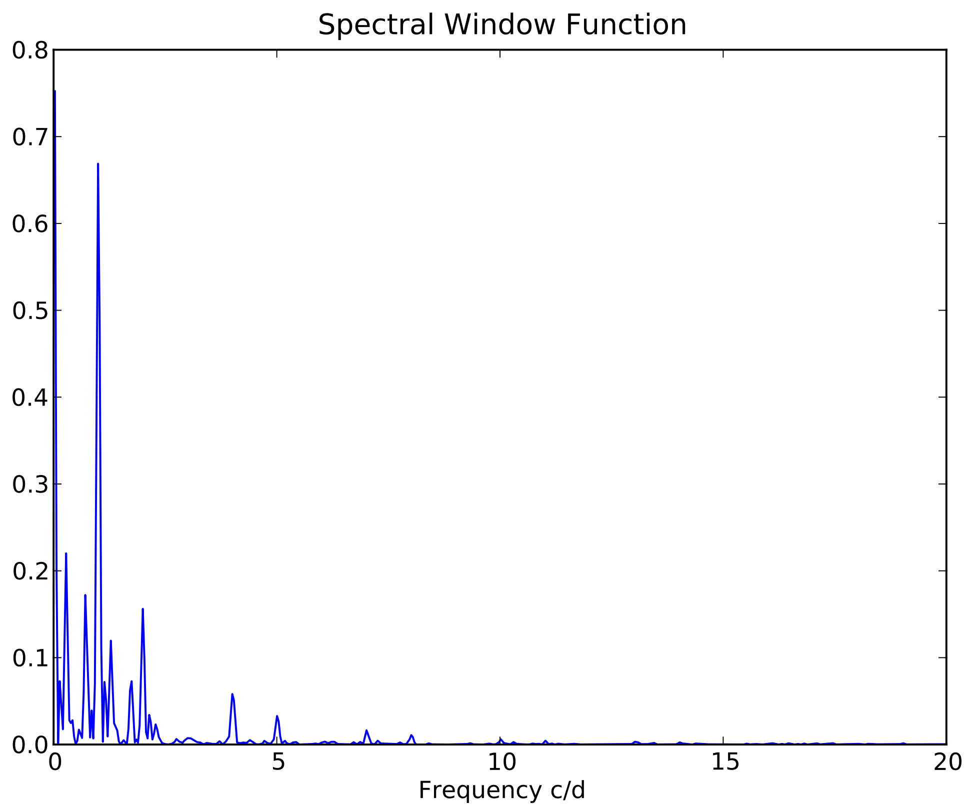

Figure 2.3. Spectral Window Function of LQ Peg.

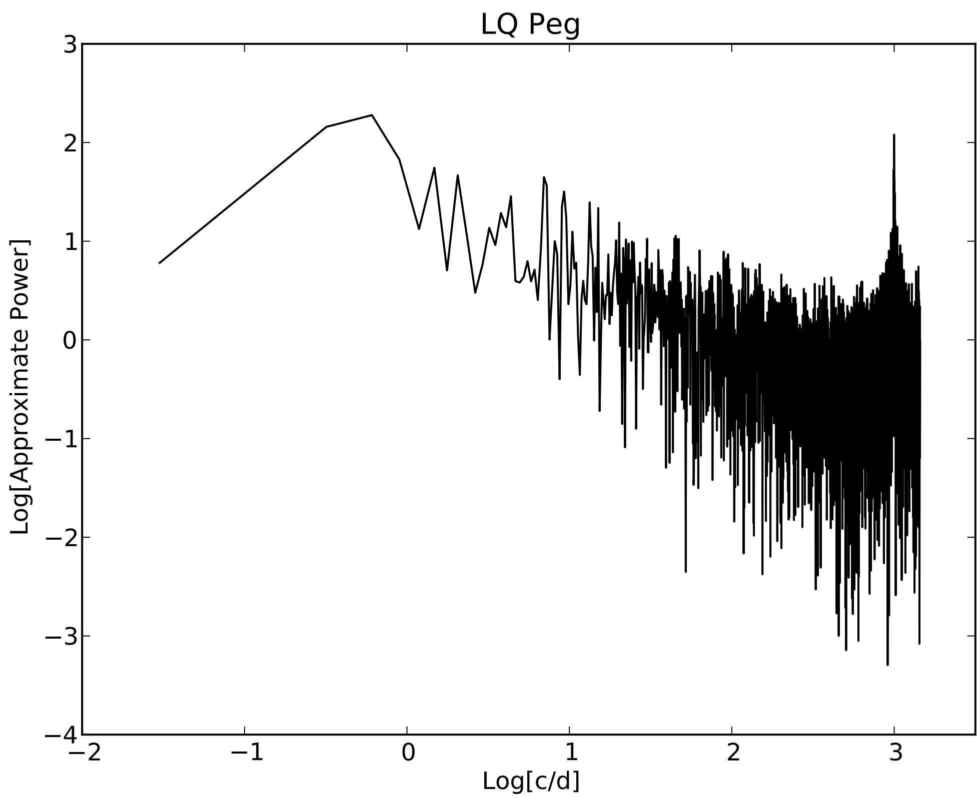

Figure 2.4. A log-log plot of the Lomb-Scargle periodogram shown in Figure 2.2. The signal at the tail end of this plot is an artifact of our sampling rate at the Nyquist frequency f, where $\log{(f \text{ cycles/day})} = 3.16$.

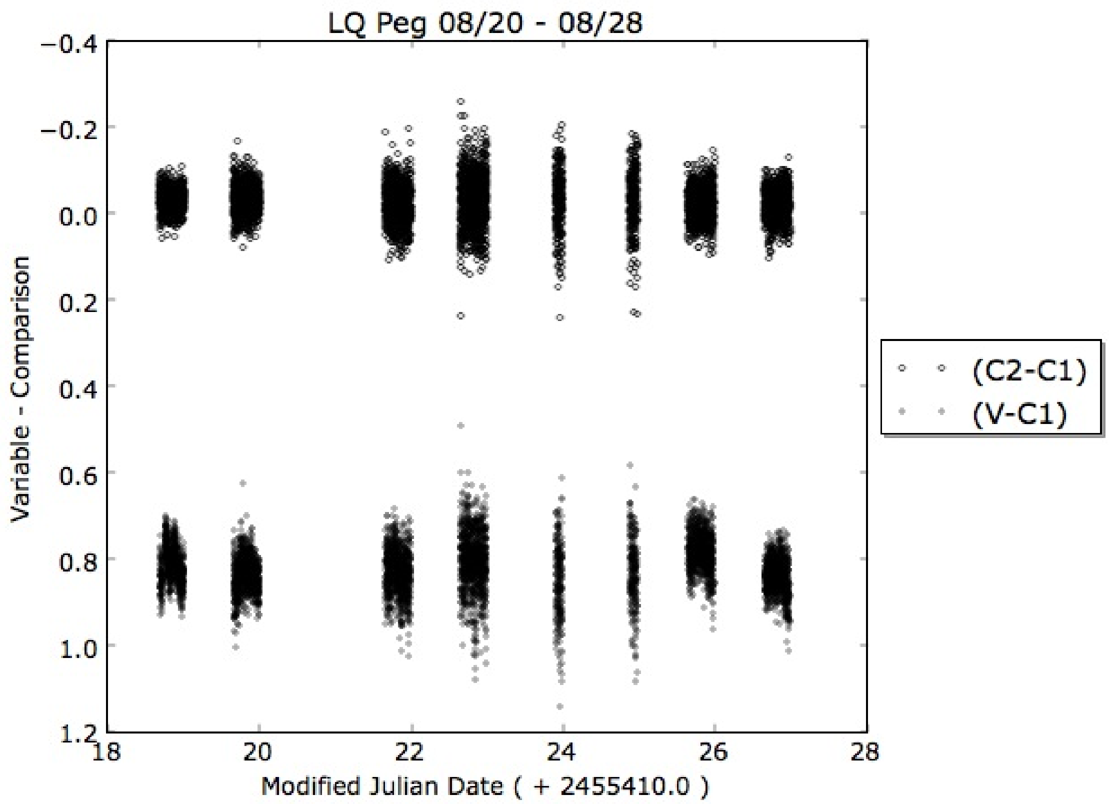

Figure 2.5. Differential Light Curve of LQ Peg

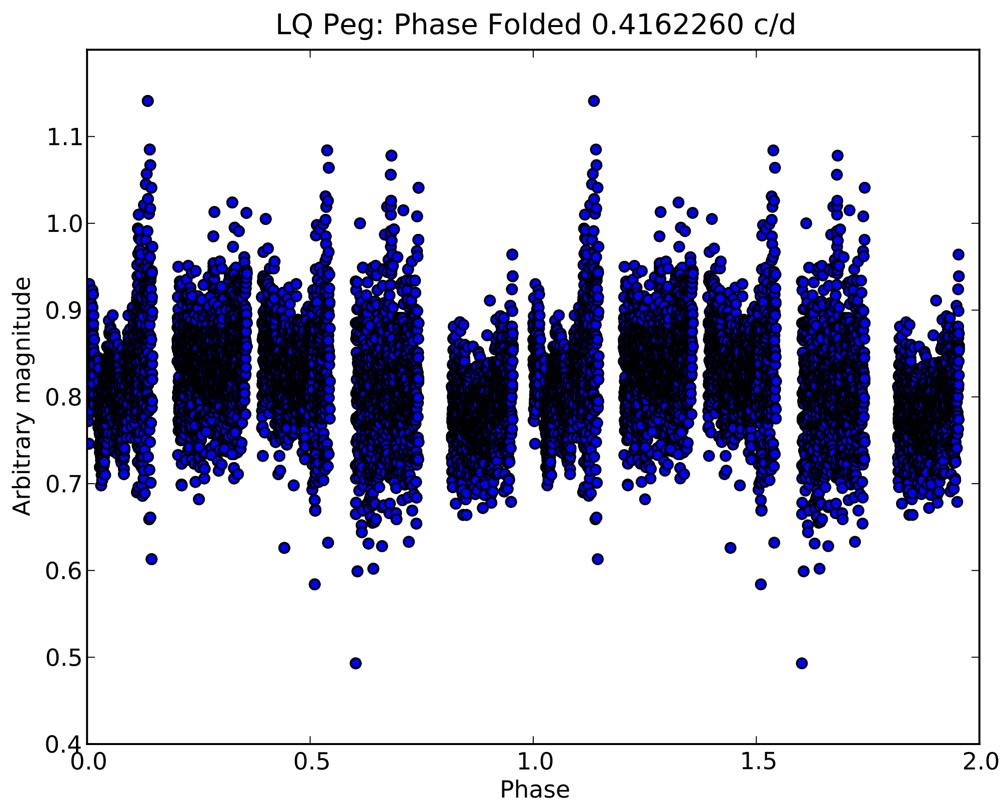

Figure 2.6. Phase folded light curve over the low-frequency (56.8-hour) signal.

HV ANDROMEDAE

Introduction

The cataclysmic variable star HV And was first identified as an irregular variable star by Meinunger (1975). It was later classified by Meinunger (1980) as a probable AM Her star. The AM Her stars are CVs in which the magnetic field of the white dwarf is so dominant that an accretion disk does not form. Instead, the mass transferred by the donor star threads onto the magnetic field lines of the whitedwarf and slams into the surface of the white dwarf on one or both of its magnetic poles (Hellier, 2001). Due to the material being directed onto the magnetic poles of the primary star, the literature also refers to these stars as polars.

Photometry of HV And was reported by Andronov and Banny (1985). Despite the data being noisy, they found a period of 80.63 ± 0.026 minutes. They admitted, however, that their time series was not conclusive. Andronov and Meinunger (1987) used archive plates from the Sonneberg Observatory to augment their time series analysis, but were unable to arrive at a conclusive period.

Schwope and Reinsch (1992) carried out a polarimetric study of HV And in 1988. This conclusively refuted the classification of HV And as an AM Her star, by showing that HV And has none of the extreme circular polarization that characterizes AM Her stars.

Schwope and Reinsch (1992) also presented two spectra of HV And, including a high-resolution spectrum taken in 1988 November, and a lowresolution spectrum taken in 1991 July. These spectra were also unlike those of an AM Her star, with weak He II 468.6nm emission, weak or absent other He II lines, weak CIII/NIII 464.0nm emission, weak He I emission lines, and weak Balmer emission lines in broad, absorption cores. Schwope and Reinsch (1992) noted that their spectra are similar to those of a CV with an optically thick disk, such as a nonmagnetic nova like variable, or a dwarf nova in outburst.

Over 140 photometric estimates were made by Meinunger (1975), Andronov and Banny (1985), and Andronov and Meinunger (1987). They showed that HV And varies erratically between $m_{pg} \approx 15.5$ and 16.0 over days, and that HV And has never clearly shown dwarf nova outbursts. We still cannot rule out the possibility of stunted outbursts, similar to those discovered by Honeycutt et al. (1998) and discussed by Honeycutt (2001).

Nonmagnetic novalike variables with orbital periods shorter than two hours are rare. BK Lyn (PG 0917+342) is the only definite case listed in the catalogue of Ritter and Kolb (2003). Its short orbital period was measured spectroscopically (Dobrzycka and Howell, 1992; Ringwald et al. 1996), and by the period of its superhumps. The superhumps in BK Lyn are not surprising. One would expect strong tides in the accretion disk as a result of the short orbital period (see Chapter 6 of Hellier, 2001).

We therefore undertook the following exploratory study of HV And, to check whether it is an anomalous, shortperiod novalike like BK Lyn. It is not: although we did find photometric variability that may be superhumps, we find that the 80.6 minute period reported by Andronov and Banny (1985) is likely to be incorrect. HV And likely has an orbital period greater than three hours, above the 2-to-3-hour CV period gap (see section 4.3.2. on page 51 of Hellier, 2001).

Observations

We collected four consecutive nights of timeresolved differential CCD photometry of HV And. We used the 0.41m (16-inch) f/8 telescope by DFM Engineering at Fresno State's station at Sierra Remote Observatories, and a Santa Barbara Instruments Group STL11000M CCD camera. Frames were exposed for

120 seconds with a dead time between each frame of 8 seconds, making for a total time resolution of 128 seconds. All observations were made through a Clear filter by Astrodon, which admits nearly all near ultraviolet, visible, and nearinfrared wavelengths, from the atmospheric cutoff at 350 nm to the cutoff wavelength for the silicon CCD detector near 1000 nm. Weather was clear and apparently photometric.

The data were processed using AIP4WIN 2.0 software (Berry and Burnell, 2005). Dark frames with the same exposure times as the target images were mediancombined to produce a master dark that was scaled and subtracted from each target image. Bias frames were similarly processed, and a master bias frame was subtracted from the target images. We then mediancombined the flat fields together, and divided the target exposures by this darksubtracted master flat. We also mediancombined dark frames taken with the same exposure time as the flat-field frames, and subtracted this master flatdark from the flats. The CCD was kept at $-5°$C for all exposures.

To measure the photometry (see Chapter 10 of Berry and Burnell, 2005), we used the star designated HV And-10 by Henden and Honeycutt (1995) as a comparison star. We also used the star designated HV And-5 by Henden and Honeycutt (1995) as a check star. This telescope and camera have an image scale of 0.51 arcseconds/pixel. All our observations were done binned 3x3, making for an

Table 3.1. Journal of observations

UTDate	*UTStart*	*Duration(hr)*	*Number of exposures*
2010 October 13	2:15	10.28	289
2010 October 14	2:20	7.89	222
2010 October 15	2:12	10.31	290
2010 October 16	3:01	9.53	268

image scale of 1.53 arcseconds/pixel. The seeing ranged between 1.20 and 1.43 arcseconds on all nights. All photometry used an aperture with a diameter of 6 pixels, or 3.06 arcseconds, and used an annulus around between 9 and 12 pixels (4.59 and 6.12 arcseconds) in diameter around this, for sky subtraction.

Data Analysis

Figure 3.1 shows the light curves for all four nights. It is apparent in Figure 1 that a sawtooth periodicity is present, which is generally considered indicative of superhumps in the accretion disk (Harvey et al., 1995).

We looked for further periodicity in the data with the Lomb-Scargle periodogram (Press et al., 1992) routine found in the PERANSO analysis software (Vanmunster, 2009). The periodogram and spectral window function can be seen in Figure 3.2. The spectral window function shows how the sampling rate would affect our periodogram. It is clear that the 3.368-hour periodicity is not the result of our sampling rate. We can also see that our sampling does not coincide with the entire low-frequency signal shown in Figure 3.2. Finally, we tested the 3.368-hour signal with a false-alarm probability algorithm for the Lomb-Scargle periodogram (see Press et al., 1992). The algorithm gives us a 99.999% confidence that the 3.368-hour signal we see in the periodogram is present in the data.

The periodogram in Figure 3.2 shows a strong signal at 3.368 ± 0.060 hours. It is flanked by one cycle/day aliases, because we cannot observe in the daytime (see pages 9192 of Hellier, 2001). The light curves, with their sawtooth shape, do not appear to correspond to the expected light curve of an eclipsing CV. The sawtooth waves coupled with the low-frequency power seen in the periodogram appear to indicate we are seeing waves in the accretion disk.

Taking the periodogram, we plotted the logarithm of approximate power versus the logarithm of frequency in order to search for quasiperiodic oscillations

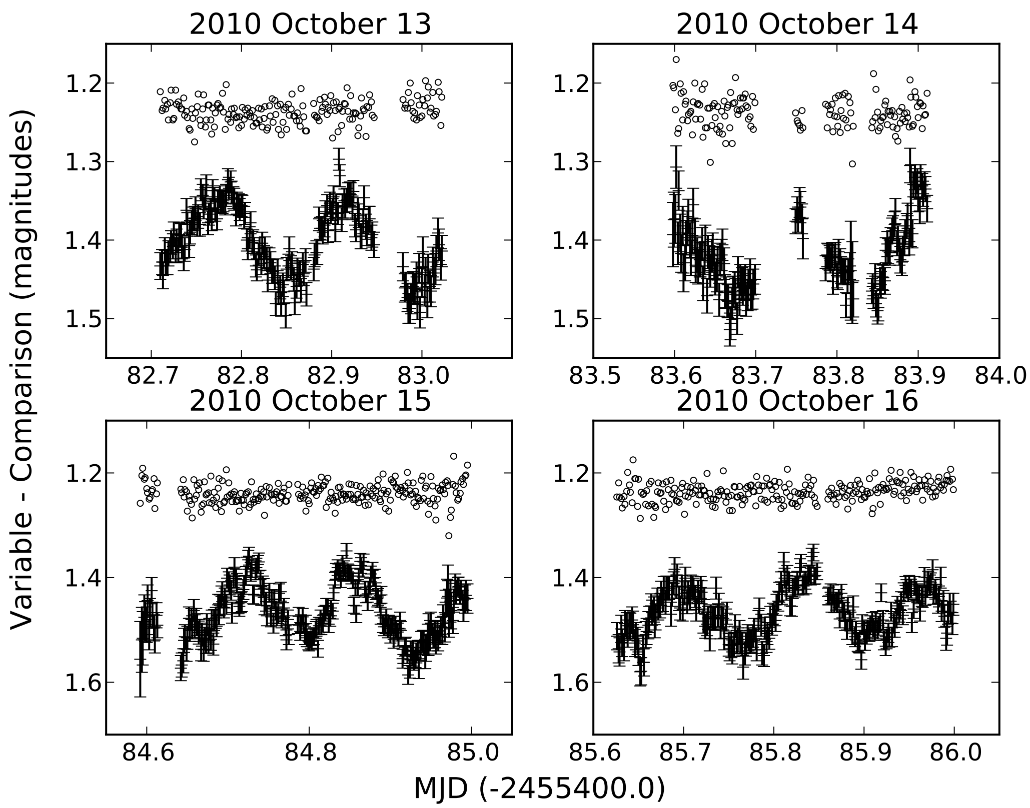

Figure 3.1. Light curve of HV And from 2010 October 13 to 17.

(QPOs). This plot can be seen in Figure 3. There is an indication that there may be some highfrequency power near the Nyquist frequency (which is 675 cycles/day), but the signal is not strong enough to confirm the presence of QPOs.

The lowfrequency peaks in Figure 2 have frequencies of 0.198 ± 0.184 cycles/day (corresponding to periods of 5.04 ± 5.43 days), 0.80 ± 0.12 cycles/day (corresponding to periods of 1.24 ± 0.19 days), and 1.20 ± 0.11 cycles/day (corresponding to periods of 0.84 ± 0.07 days). With only four nights of

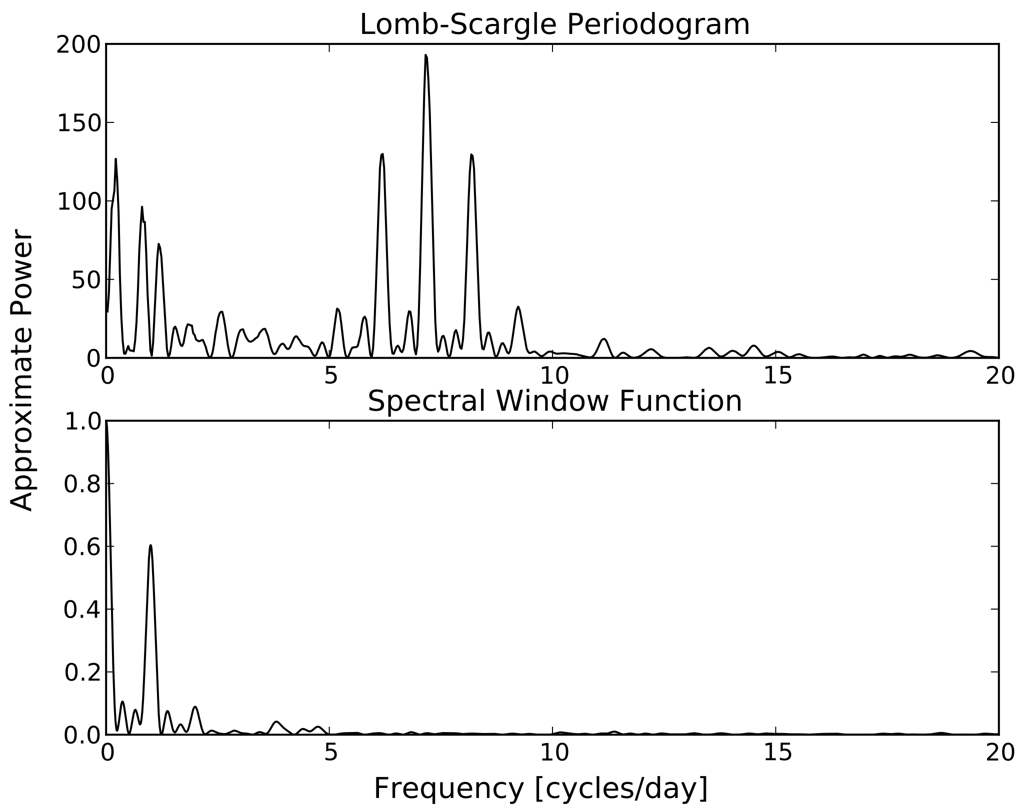

Figure 3.2. The LombScargle periodogram for HV And for 2010 October 13–17 (top) and the spectral window function of the dataset (bottom).

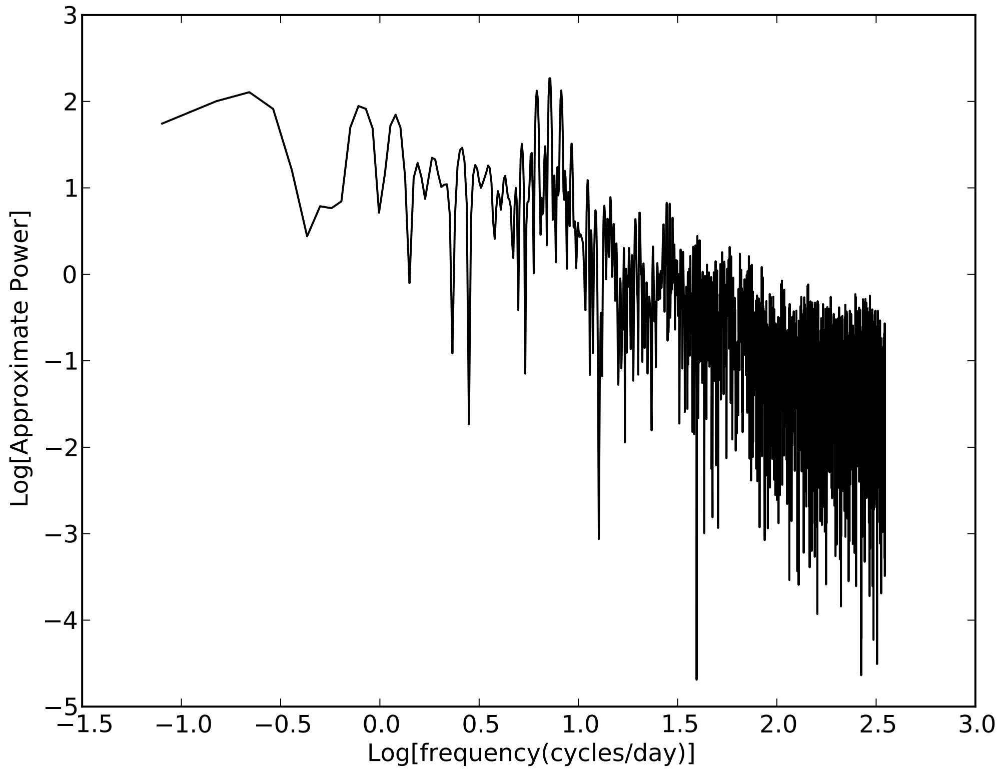

Figure 3.3. A log-log plot of the HV And periodogram showing little indication of QPOs

observations we cannot reliably resolve the low frequency power into specific periodicities and discern the precession of the accretion disk, which would be expected if the 3.368-hour periodicity is from superhumps. Despite this, one would expect lowfrequency power like this, if the 3.368-hour periodicity is from superhumps, and not from eclipses or variability on the orbital period.

Conclusion

The four nights of timeresolved differential photometry have revealed a sawtooth periodicity typical for superhumps. A timeseries analysis of the data revealed some low-frequency power coupled with a clear 3.368 ± 0.060hour signal in the light curve. While this signal may be the orbital period, the shape of the light curve suggests that we are detecting the superhump period. We predict that with a proper radial velocity study we will find the orbital period to be within a few percent of 3.368 hours just as the accepted model predicts. If the 3.368-hour signal is from apsidal, or positive superhumps, we predict that the orbital period should be near 3.11 hours (see Box 6.1 of Hellier, 2001, and Patterson, 1998). If it is from nodal, or negative superhumps, we predict that the orbital period should be near 3.67 hours (see Figure 6.19 of Hellier, 2001, and Patterson, 1998).

SW SEXTANTIS

Introduction

SW Sextantis is a novalike cataclysmic variable (CV). A CV is a binary star system composed of a white dwarf, hereafter referred to as the primary star, and a red dwarf or subgiant, hereafter referred to as the secondary star, in close orbit with one another. Due to the close orbit of the system, material is stripped off the secondary star and onto the primary star. The conservation of angular momentum prevents the material from falling directly onto the white dwarf. As a result, a thin accretion disk is formed. The study of CVs is largely a study of this accretion disk.

SW Sex has an orbital period of 0.1349384411(10) days, or 3.238522586(24) hours, and has deep eclipses from an orbital inclination $i = 79$ (Groot et al., 2001). SW Sex is the prototype of a class of CVs known as the SW Sex stars. These stars exhibit a suite of mysterious, but consistent behaviors that set them apart from other CVs.

These characteristics of the SW Sex stars were first discussed by Thorstensen et al. (1991). The SW Sex stars show no accretion-powered outbursts similar to those of dwarf novae. They usually have orbital periods of 3 to 4 hours. Another characteristic is single-peaked emission lines. Yet another is absorption features in these emission lines that recur at phase 0.4 – 0.7. Another is eclipse profiles in the lines and continuum that have a V-shape. Another is eclipses in the lines that are much shallower than in the continuum. Another is high-velocity S-waves in the emission lines. Another is Doppler tomograms that are bright in the lower-left quadrant. A particularly puzzling characteristic of the SW Sex stars is that radial velocity curves that are measured from emission lines clearly do not trace the motion of the white dwarf. This is because the phase of the emission lines lag behind where eclipses show the white dwarf should be by 70o or more (Thorstensen et al., 1991; Hellier, 2000; Hoard, 2007).

Not all SW Sex stars have all of these characteristics, however, so how exactly the class is defined is still debatable. Hellier (2000) and Hoard (2007) consider superhumps as a possible observational characteristic of the SW Sex stars, because they are common among CVs with periods shorter than 4 hours (Patterson et al. 2005). This paper, however, will show that not all the SW Sex stars have obvious superhumps.

Our goal was to search for evidence of superhumps in the accretion disk of SW Sex. Positive superhumps are waves in the light curve of the accretion disk, due to the ellipticity of the disk. They have periods a few percent longer than the orbital periods, in a predictable, linear manner (see Figure 6.6 of Hellier, 2001). Negative superhumps are waves in the light curve due to the tilt of the accretion disk. They have periods a few percent shorter than the orbital periods, in a predictable, linear manner (see Figure 6.19 of Hellier, 2001). We therefore collected time-resolved photometry of SW Sex and performed a time series analysis on the data.

Observations

Using the DFM 16-inch telescope at Fresno State's station at Sierra Remote Observatories and an SBIG STL-11000M camera, we collected time resolved photometry of SW Sex. The data were collected on HJD 2,455,271 + (0.69-0.91), 2,455,276 + (0.67-0.94), and 2,455,277 + (0.66-0.94), or 2010 March 17, 22, and 23 UT, respectively. The dataset is composed of 929 one-minute exposures with a six-second readout time between exposures. All exposures were taken through a clear filter by Astrodon, for luminance exposures in astrophotography, which passes nearly all wavelengths of visible light.

We processed the photometry using AIP4Win 2.0 (Berry and Burnell, 2005).

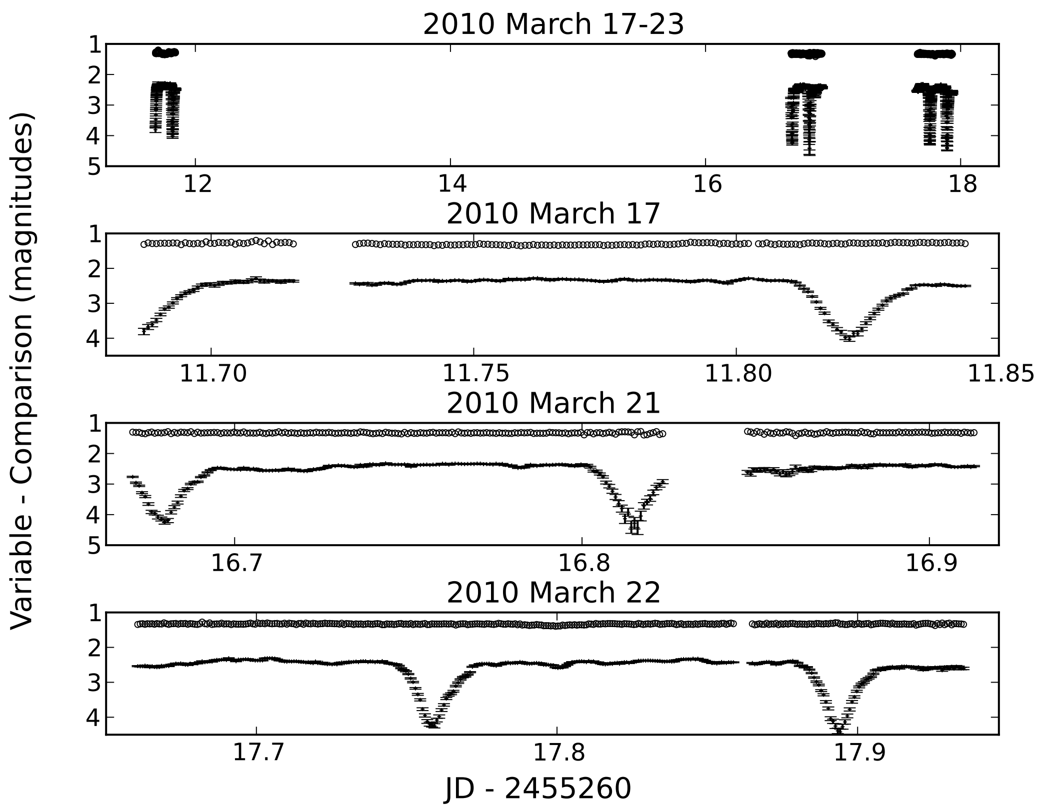

Figure 4.1. Differential light curves of SW Sex (V) minus the comparison (C_1) star; at the top of each panel

Calibration was done with the automated photometry package in AIP4Win 2.0 where a master dark frame is constructed, through the process of median combining a series of dark frames, and subtracted from all the images. The photometry was measured for SW Sex and two other stars in the field, a comparison star and a check star, to check that the comparison and check stars were not fluctuating in time. We used the star designated SW-Sex-2 by Henden and Honeycutt (1995) as the comparison star. We also used the star designated SW-Sex-3 by Henden and Honeycutt (1995) as a check star.

The telescope and camera have an image scale of 0.51 arcseconds/pixel. All our observations were done binned 3x3, making for an image scale of 1.53 arcseconds/pixel. The seeing ranged between 0.88 and 1.57 arcseconds on all nights. All photometry used an aperture of 6 pixels, or 3.06 arcseconds, in diameter, and used an annulus around between 9 and 12 pixels (4.59 and 6.12 arcseconds) in diameter around this, for sky subtraction. The light curve for all three nights can be seen in Figure 4.1 along with check star subtracted from comparison star (C1-C2). Light curves for the individual nights can also be seen in Figure 4.1.

Data Analysis

We then searched for periodicities in the light curve of SW Sex. The dataset contains gaps in observations which make a conventional Discrete Fourier Transform impossible to calculate accurately. We therefore used the Lomb-Scargle algorithm, which enables us to perform an approximate power spectrum for data that are unequally spaced in time (Lomb, 1976; Scargle, 1982; Press et al., 1992). We used the PERANSO (PEriod ANalysis SOftware) data analysis package (Vanmunster, 2009) to calculate the Lomb- Scargle periodogram, as well as for subsequent prewhitening of the light curve.

The Lomb-Scargle periodogram for all three nights (Figure 4.2) shows three

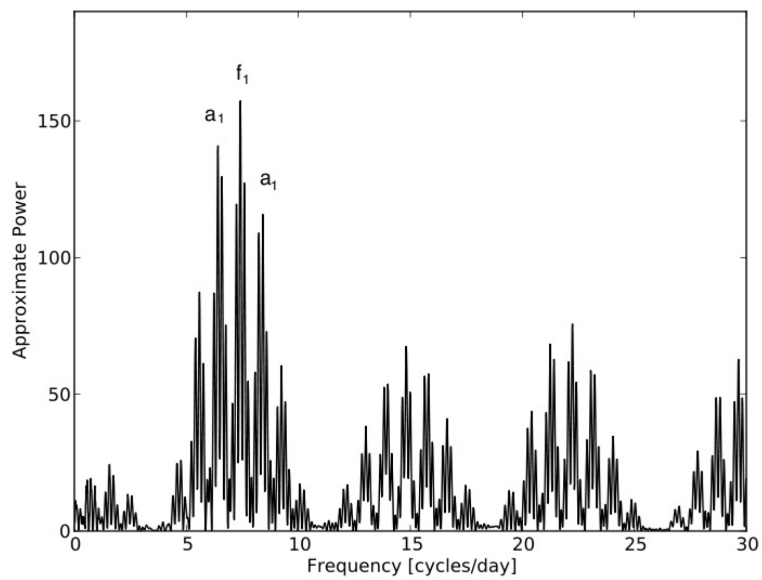

Figure 4.2. The Lomb-Scargle periodogram for all three nights.

large peaks. The large peak, f_1, has a value of 7.410 ± 0.045 cycles/day. This corresponds to a period of 0.1349 ± 0.0008 days, which is within 0.0085% of the orbital period. The frequencies labeled a_1 are the one cycle-per-day aliases of the orbital frequency (see pages 130-131 of Hellier, 2001). The other peaks on this periodogram are integer multiples, or harmonics, of these features. There appears to be no additional periodicity.

Figure 4.3 is a Lomb-Scargle periodogram of the data from all nights, with the eclipses cut out of the time series. The most prominent peak is at a frequency of

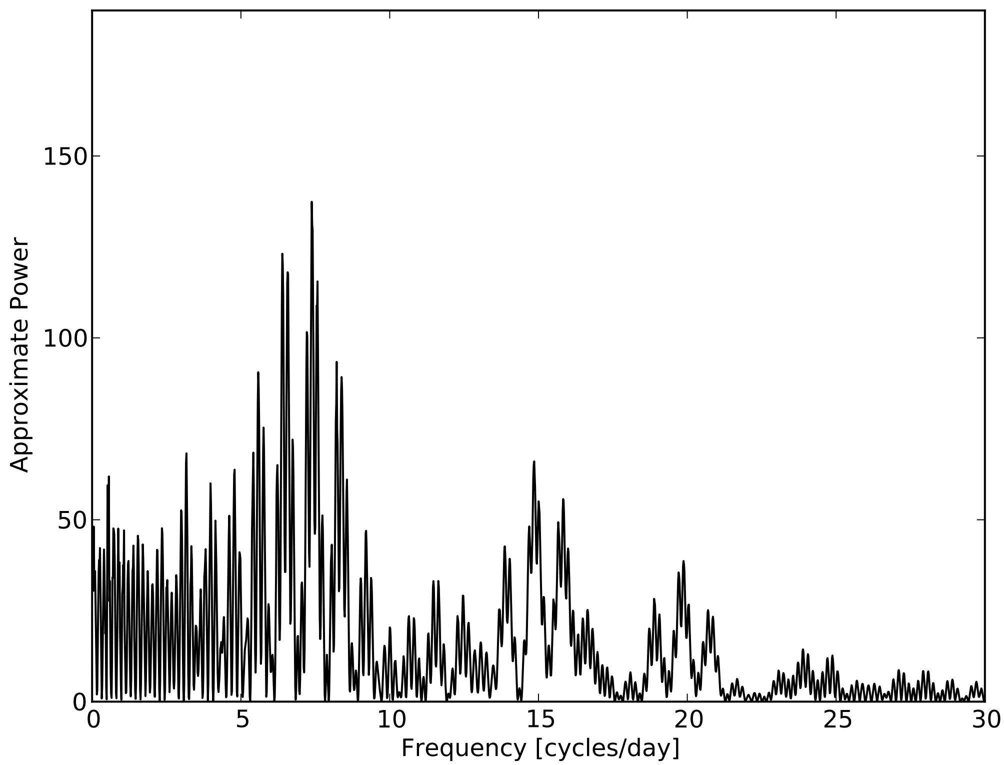

Figure 4.3. The Lomb-Scargle periodogram for data from all nights with the eclipses cut out

7.380 ± 0.045 cycles/day, which corresponds to a period of 0.1350 days (3.24 hours), which is 0.41% longer than the orbital period of 0.1349384411(10) days. We folded the data, with the eclipses cut out, over the frequency of 7.38020 cycles/day (Figure 4.4.) Figure 4.4 shows only the erratic flickering all CV accretion disks have and no obvious periodicity.

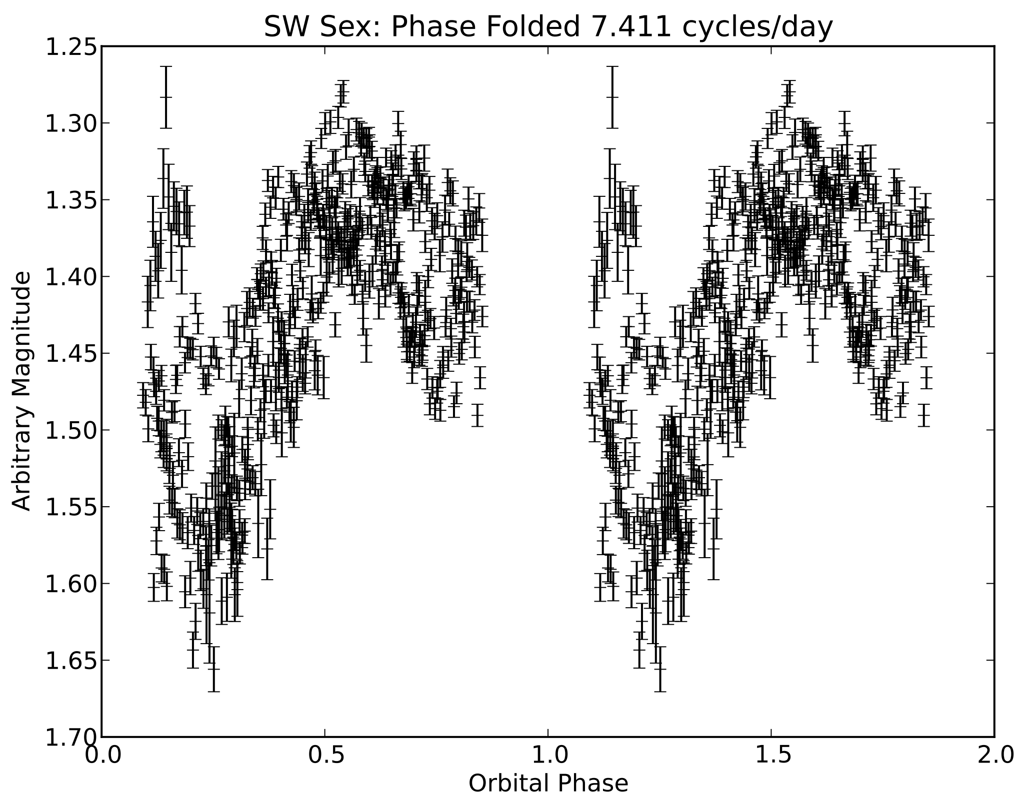

Figure 4.4. Our time-resolved photometry with the eclipses cut out folded over the orbital cycle.

Positive superhumps in a CV with this orbital period should have a period of 0.147 ± 0.082 days, however (Stolz and Shoembs, 1984; see also Figure 6.6 of

Hellier, 2001). We can exclude the possibility that these are negative superhumps, because these should have a photometric period shorter than the orbital period.

We then cut out the eclipses from the light curve, prewhitened the remaining data, and calculated a periodogram. It showed no residual signal associated with superhumps. By calculating the standard deviation of the noise level from the light curve with the eclipses cut out, we can show that the upper limit for the amplitude of any superhumps that may be present can at most be 0.0779 magnitudes. We therefore conclude that we have not detected any superhumps, positive or negative, in SW Sex.

Conclusion

The Lomb-Scargle periodogram does not show any periodicity other than the frequency associated with the orbital period. It shows a peak frequency within 0.0085% of the orbital frequency for the complete dataset (Figure 4.2). We also cut out the eclipses from the time series, and subsequently used prewhitening to remove any residual signal at the orbital period. Neither procedure revealed any additional periodicity, other than harmonics of the orbital frequency. SW Sex does not have superhumps with amplitudes greater than 0.0779 magnitudes.

Ever since the first paper about the mysterious, but consistent behavior of the SW Sex stars (Thorstensen et al., 1991), a debate has swirled about how precisely to define the class. What properties does a CV need to have, in order to be an SW Sex star? Hoard (2003) includes superhumps in his big list of all properties that have been suggested in the literature to define the SW Sex stars. This paper, however, shows that the obvious presence of superhumps is not one of these properties.

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