ABSTRACT

WAVES IN AN ACCRETION DISK: NEGATIVE SUPERHUMPS
IN V378 PEGASI

We present the results obtained from the unfiltered photometric observations of the cataclysmic variable V378 Pegasi during 2001, 2008, and 2009. From the photometry we found a negative superhump period of 3.23 ± 0.01 hours. In addition we calculated the nodal precessional period to be 4.96 days.

Estimates of the distance of V378 Pegasi were also calculated. The methods of Beuermann (2006) and At et al. (2007) gave 536 ± 66 pc and 703 ± 92 pc, respectively. We also calculated an absolute magnitude of 5.2 using the method of Beuermann (2009). Furthermore it is determined that V378 Pegasi is a nova-like.

Kenia Velasco
03/15/2010

# WAVES IN AN ACCRETION DISK: NEGATIVE SUPERHUMPS IN V378 PEGASI

by

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APPROVED

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## ACKNOWLEDGMENTS

The 2008-2009 photometric observations used in this study were taken from Fresno State's facility at the Sierra Remote Observatories, operated by Professor Frederick A. Ringwald.

The 2001 August photometry was taken by Paul Etzel and Lee Clark at Mount Laguna Observatory, which is operated by the Department of Astronomy at San Diego State University.

This research has made use of the Simbad database, operated at CDS, Strasbourg, France. All of the period analyses in this research were made with the Peranso (PEriod ANalysis SOftware) package by Tonny Vanmunster. Furthermore we used observational data from the AAVSO International Database.

I would like to thank my advisor/professor F. A. Ringwald for making this research possible. His guidance, expertise, enthusiasm, and support always motivated me. I would also like to thank my physics professors, G. Munoz, D. Singleton, J. Van der Noorda, and K. Runde for motivating and encouraging me. I would like to thank my boyfriend Manuel Pimentel for supporting and believing in me for the last 9 years. Finally, I would like to thank my mother for believing.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

# INTRODUCTION

## Cataclysmic Variables

A cataclysmic variable is a close binary star system that is composed of a white dwarf primary accreting from a low-mass secondary star. The mass-losing secondary star is approximately on the main sequence. These two stars orbit about their center of mass so closely that the white dwarf's gravity pulls at the outer layers of its companion until is distorted into a tear drop shape (Hellier 2001). Eventually the secondary reaches the critical point at which it is just possible for mass to transfer onto the white dwarf; at this stage, the outline of the tear drop shape is called the Roche lobe (Hellier 2001). If the white dwarf is devoid of any significant magnetism, the mass transferred to it will form an accretion disk, as shown in Fig. 1.

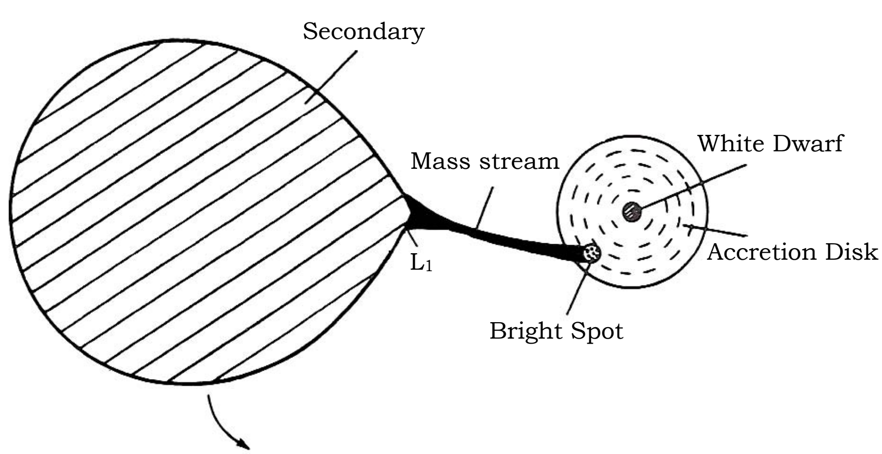



Figure 1. Schematic drawing of a cataclysmic variable, from Warner (1995), page 63.

The apex of the Roche lobe is called the inner Lagrangian point ($L_1$). It is the point of gravitational equilibrium between the two stars through which matter can flow from one star to the other. The inner Lagrangian point is the easiest path by which mass transfer can occur (Hellier 2001). The bright spot, shown in Fig. 1, is created when the mass stream from the secondary strikes the outer edge of the already formed accretion disk (Warner 1995).

Cataclysmic variable stars exhibit such a myriad of characteristics that they have been organized into classes. Initially they are divided into two classes, magnetic and non-magnetic (our focus here will be the non-magnetic cataclysmic variables). Non-magnetic variables are then classified into one of the following 5 subclasses: classical novae, recurrent novae, dwarf novae, nova-likes, and AM Canum Venaticorum stars (AM CVn). Classical novae have only one observed eruption (outburst); recurrent novae are previously recognized classical novae that are found to repeat their eruption; dwarf novae have multiple observed eruptions of typically 2-5 magnitudes (measure of brightness);and nova-likes are non-eruptive cataclysmic variables (Warner 1995). AM CVn variables are systems composed of a white dwarf primary and a secondary composed mostly of helium instead of hydrogen like normal stars (Hellier 2001). These types of cataclysmic variables have very short orbital periods, ~ 78 minutes or less.

## Superoutbursts and Permanent Superhumps

Dwarf novae have outbursts that occur when thermal instabilities in the accretion disk trigger the intensity to jump by several magnitudes in the space of a day or so (Hellier 2001). Outbursts are known to occur because the light curve of a dwarf novae show them, see Fig. 2. A dwarf nova will be in outburst for a few days before it declines in brightness to a quiescent state for some months until the next outburst. In addition to normal outbursts that last 2 to 3 days, there are superoutbursts that last about 14 days (Hellier 2001). Superoutbursts are brighter than normal outbursts and are not as frequent. Light curves of superoutbursts reveal hump-shaped modulations called superhumps, shown in Fig. 3. The period of the superhumps is a few percent longer than the orbital period. Dwarf novae that show superhumps during outbursts are called SU UMa stars (Hellier 2001).

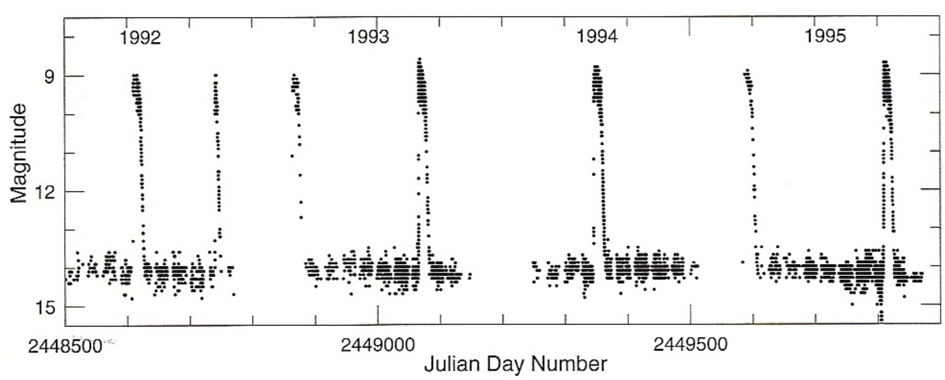



Figure 2. A 3-yr section of a dwarf nova showing 5 magnitude outbursts, from Hellier (2001) pg 56.

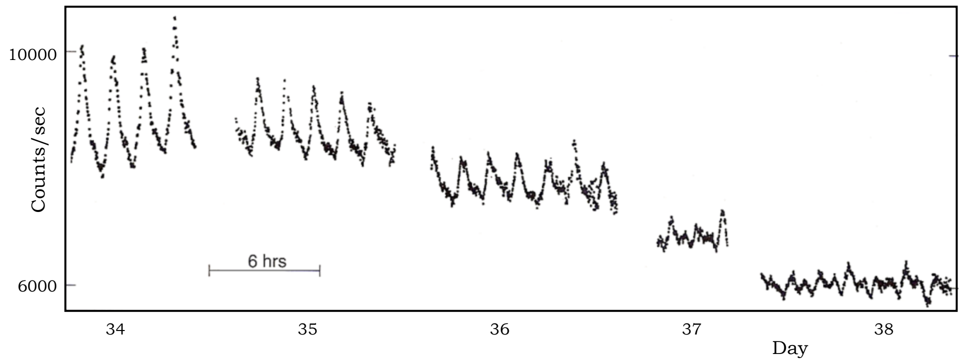



Figure 3. The light curve of V1159 Ori shows the evolution of superhump modulations over five nights, from Hellier (2001) pg 83.

Osaki (1989) proposed that superoutbursts are a consequence of the combined mechanism of thermal instability and tidal instability in accretion disks. He suggested that normal outbursts are caused by thermal instabilities in the accretion disk and superoutbursts are caused by normal outbursts that are accompanied by tidal instabilities (Osaki 1989). The occurrence of superhumps results from the disk becoming elliptical during superoutburst (Whitehurst 1988). Furthermore, the elliptical disk has an apsidal precession, i.e., a precession along its axis of elongation. The precessional period and the orbital period interact creating a beat period, which is the superhump period (Hellier 2001).

Superhumps do not appear exclusively during superoutbursts of SU UMa stars. They also appear in other subclasses of cataclysmic variables during their normal brightness state if there is a sufficiently small mass ratio ($M_{secondary}/M_{primary}$) and a sufficiently large accretion disk (Hellier 2001). These two conditions are satisfied when a short orbital period exists and they are sustained by a high mass transfer (Hellier

2001). Permanent superhumps with periods a few percent longer then the orbital period are called permanent positive superhumps.

There are also some superhumps that have a period a few percent shorter than the orbital period. These superhumps are called negative superhumps. They occur when the accretion disk that is tilted out of the plane precesses; this is referred to as nodal precession, see Fig. 4 (Hellier 2001).

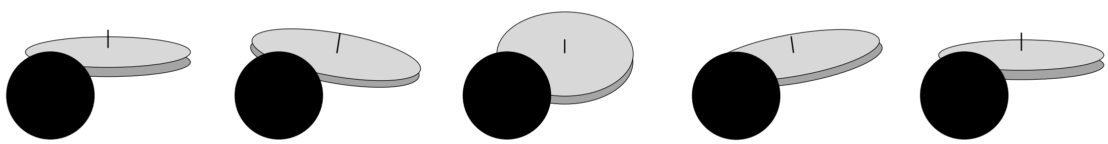


Figure 4. Illustration of a tilted disc precessing, from Hellier (2001) pg 92.

In other words, they arise from bending waves in the accretion disk. The motion of the nodal procession is retrograde, i.e., in the opposite direction to the orbital motion. The negative superhump period is the beat period between the orbital and the nodal precession periods. Negative superhumps have only been observed in nova-likes. Because of this, they are sometimes called permanent negative superhumps.

## V378 Pegasi

The cataclysmic variable V378 Pegasi is a much understudied system, thus there is hardly any published information about it. The existence of this star was first discovered by the Palomar-Green Survey (Green, Schmidt & Liebert 1986) in the constellation Pegasus. It was believed to be a hot subdwarf. However, further observations of V378

Pegasi indicated that it was actually a cataclysmic variable star (Koen & Orosz 1997). Since little more than this is known, it was decided to make observations of V378 Pegasi. From these observations, photometric data were extracted in order to find any periodicities of the binary system.

Cataclysmic variables are not the only stellar objects that have accretion disks. Black holes, protostars, quasars, and newly forming stars are just a few examples of objects that have disks. By observing cataclysmic variables we can gain knowledge of accretion disks which can then be applied to other stellar objects.

## PROCEDURE

### Observations

Observations of V378 Pegasi were made on the nights of 2009 September 17-19, 2009 September 23-26, 2009 November 23-25 and 2009 November 28-30 from Fresno State's station at the Sierra Remote Observatories, located in the Sierra Nevada Mountains of central California. The equipment utilized for these observations were the DFM Engineering 16-inch f/8 telescope with an SBIG STL-11000M camera. The observations consisted of taking a series of images of V378 Pegasi through a clear filter. Each image was exposed for 60 seconds, with 6 seconds of dead-time—the amount of time the camera spends reading out between exposures. Fig. 5 shows the image of V378 Pegasi as seen from the 16-inch telescope in the Sierra Remote Observatory. The two stars in the binary cannot be distinguished because current technology limits the resolution of telescopes.

### Photometric Data

Photometry is the science of measuring the brightness (magnitudes) of celestial objects. Photometric data are used to create light curves. The Multiple-Image Photometry tool from the *Astronomical Image Processing* software (Berry & Burnell 2000) was used to extract the brightness data from the observation sets. The way the tool works is that it takes measurements of a variable star and a star of constant brightness, called the comparison star—denoted by $C_1$ (Berry & Burnell 2000). Then by comparing their values, tiny changes in the brightness of

Figure 5. Image of V378 Pegasi. The arrow is pointing at the variable.

the variable can be detected (Berry & Burnell 2000). In addition a second comparison star (denoted by $C_2$), of similar brightness to the variable, is measured and the magnitude difference of the two comparison stars is computed to create a second light curve. This second light curve is used as a check.

## Light Curves and Lomb-Scargle Periodograms

Once the photometric data are obtained they are used to create light curves and Lomb-Scargle periodograms. A light curve is a graph of the variation of brightness of a celestial object as a function of time. A Lomb-Scargle periodogram is a discrete Fourier transform that is modified to find sinusoids in unevenly spaced data, which is the case for most astronomical datasets. It is basically a graph of power (in arbitrary units) as a function of frequency and it is used to find periodicities of celestial objects. In this study, *Peranso* (PEriod ANalysis SOftware) (Vanmunster 2009) was used to analyze the data. This included the production of Lomb-Scargle periodograms and spectral window functions.

DATA ANAYLSIS

Light Curves

The light curves of V378 Pegasi for the nights of 2009 September 17-19 and 2009 September 23-26 are presented in Fig. 6 and Fig. 7 respectively. These figures show sections of the light curve; each section accounts for one night of observation and the gaps in between are due to the lack of images during daylight. The light curve for all the observational nights of 2009 September is shown in Fig. 8. This figure shows the magnitude difference between V378 Pegasi (denoted by V) and comparison star $C_1$ and the magnitude difference between the two comparison stars, $C_1$ and $C_2$. Fig. 8 shows that comparison star $C_1$ certainly has a constant magnitude, whereas the magnitude of V378 Pegasi is varying. From Figs. 6, 7, and 8 it can be seen that V378 Pegasi has a constant saw-tooth shaped light curve which shows periodic variability in the magnitude.

The light curves of the observational nights of 2009 November 23-25 and 2009 November 28-30 are presented in Fig. 9 and Fig. 10, respectively. Again, these figures show saw-toothed shaped light curves with periodic variability. These characteristics are present in light curves from observations dating back to 2008 and 2001, shown in Figs 11-13. The light curves shown in Figs. 11 and 12 were generated from the photometric data extracted from the observations made from the Sierra

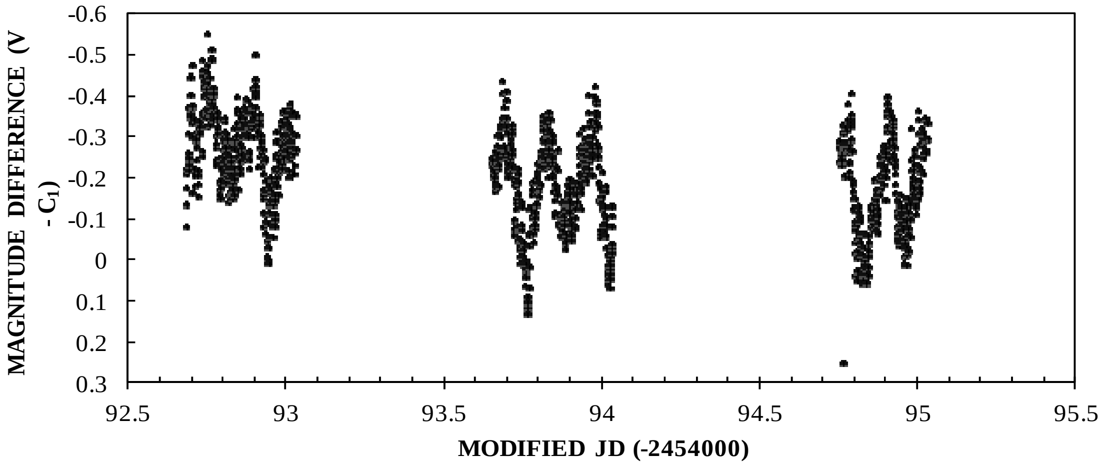



Figure 6. Light curve of the 2009 September 17-19 observations (clear filter).

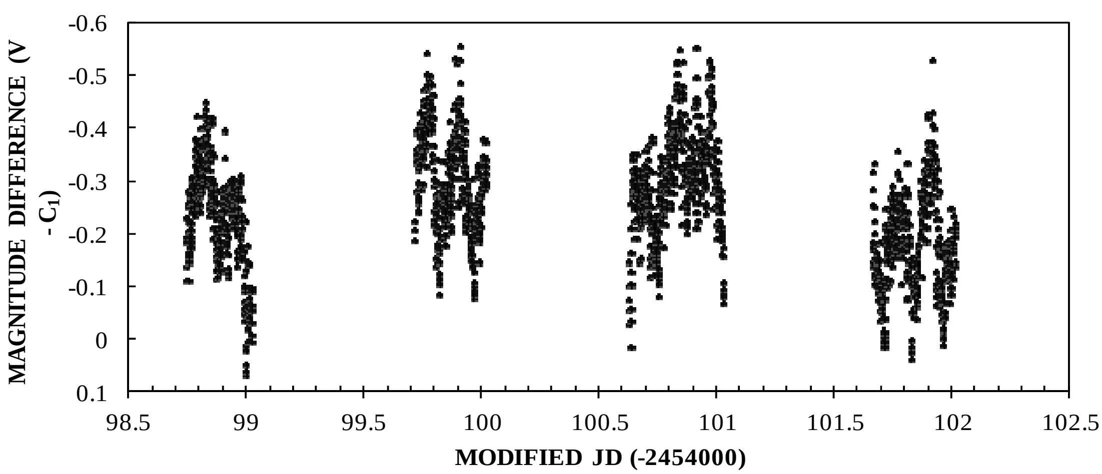



Figure 7. Light curve of the 2009 September 23-26 observations (clear filter).

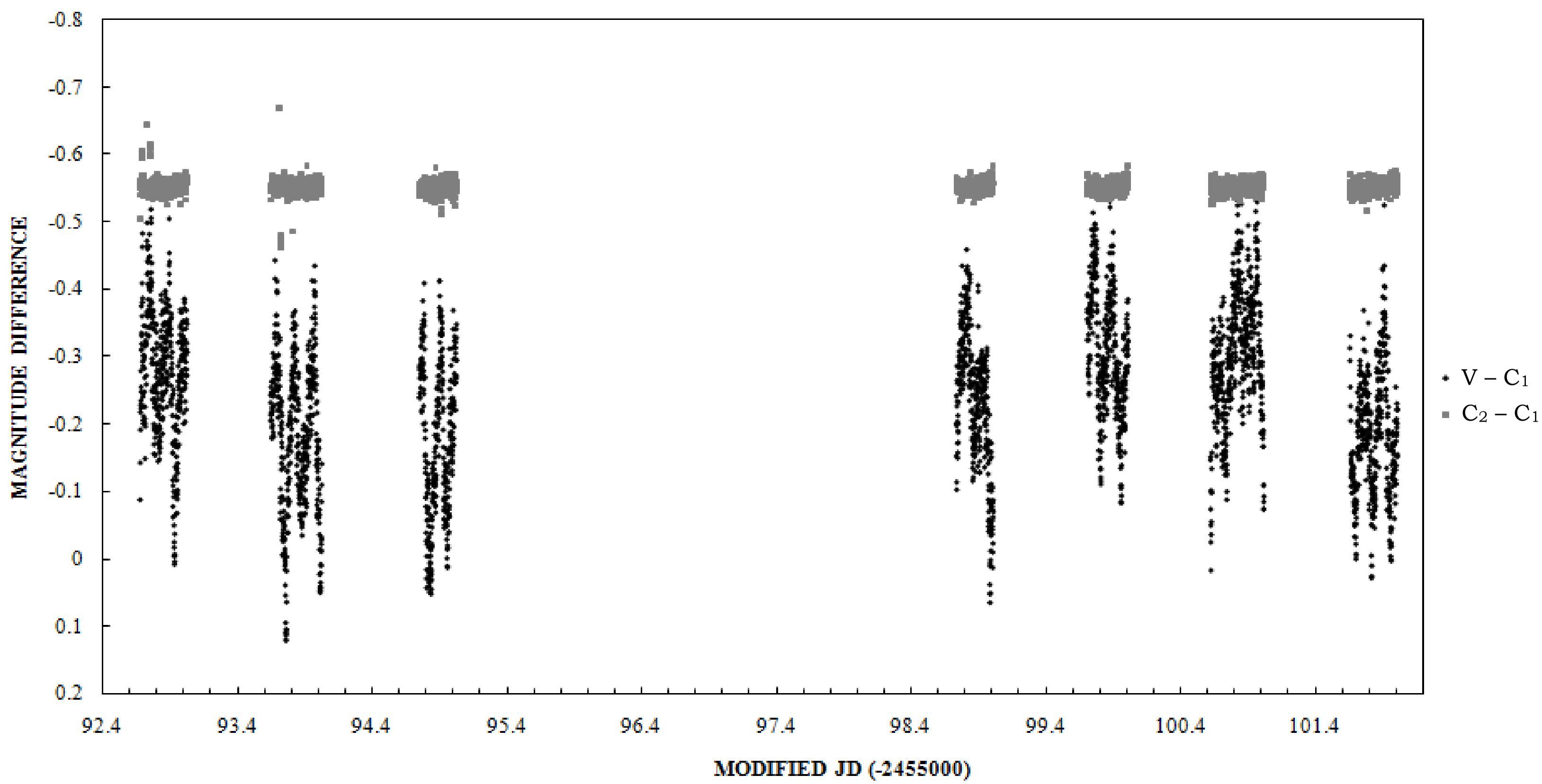



Figure 8. Light curves of the magnitude difference between V378 Pegasi (denoted as V) and comparison star $C_1$ and of the magnitude difference of the two comparison stars, $C_1$ and $C_2$.

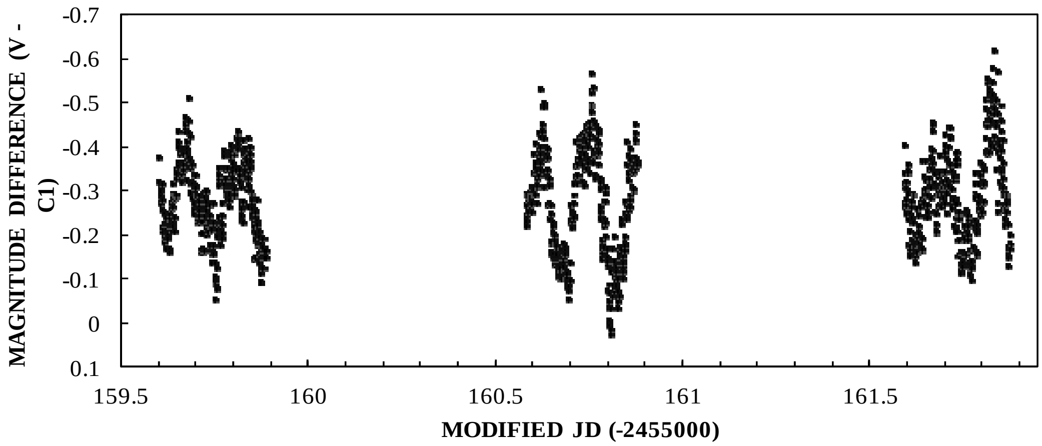



Figure 9. Light curve of the 2009 November 23-25 observations (clear filter).

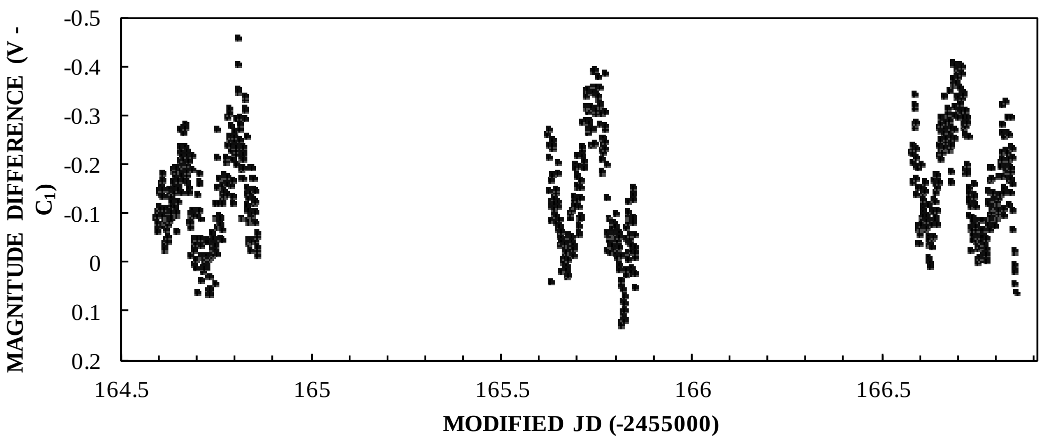



Figure 10. Light curve of the 2009 November 28-30 observations (clear filter).

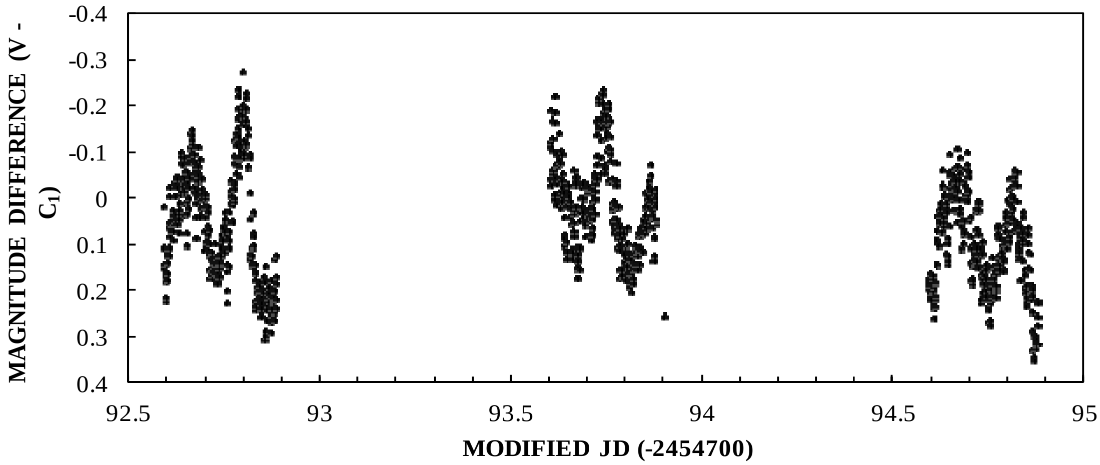



Figure 11. Light curve of 2008 November 21-23 observations.

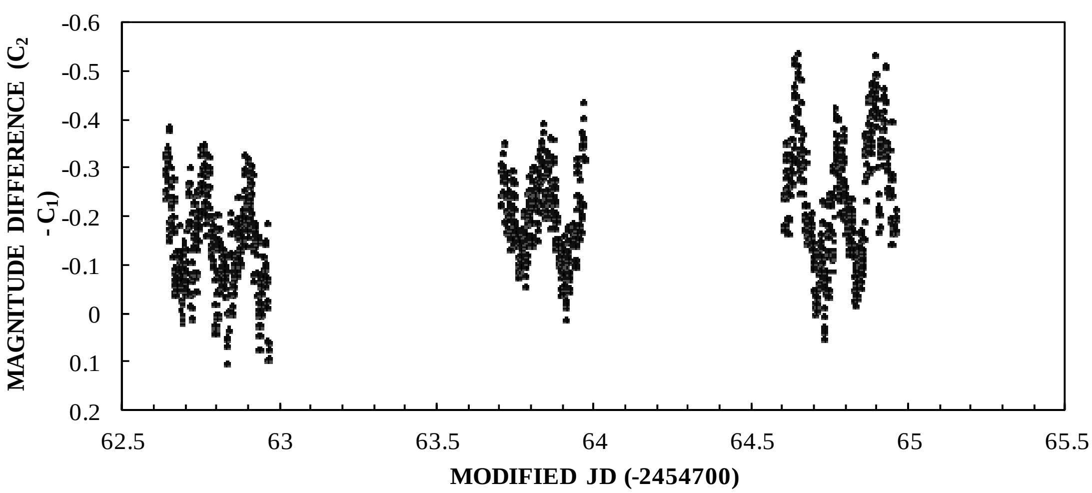



Figure 12. Light curve of 2008 October 22-24 observations.

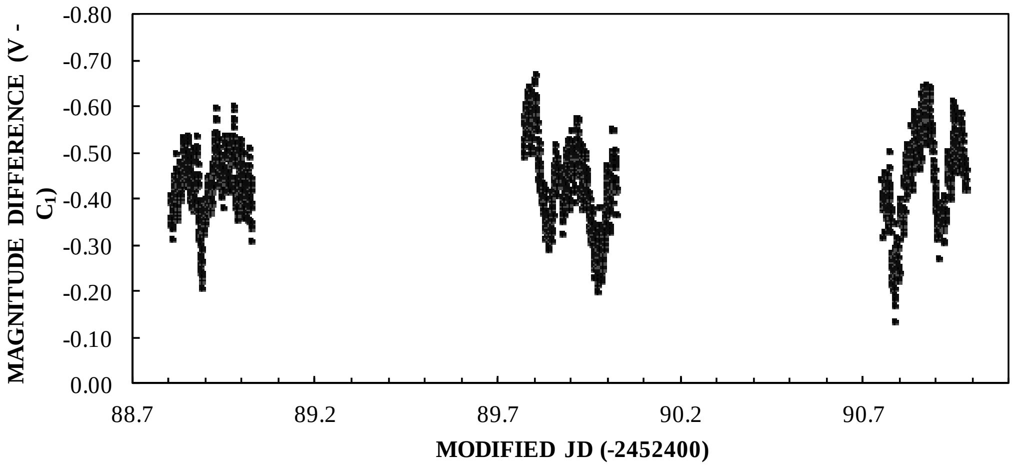



Figure 13. Light curve of 2001 August 1-3 observations.

Remote Observatory by F. A. Ringwald on 2008 November 21-23 and 2008 October 22-24. The light curve shown in Fig. 13 was generated from the photometric observations made with the 1-m telescope, CCD Zod camera, and no filter from the Mount Laguna Observatory located in Cleveland National Park, California by Paul Etzel and Lee Clark.

## Lomb-Scargle Periodograms

The photometric data were further used to produce Lomb-Scargle periodograms. The graph in Fig. 14 shows the periodogram of the seven observational nights of 2009 September. The strongest peak in the power spectrum is labeled $f_1$ and is at a frequency of $7.41919 \pm 0.01709$ cycles/day, or a period of $3.23496 \pm 0.00744$ h. The peaks labeled $a_1$ on either side of peak $f_1$ are simply the cycle/day aliases—false peaks that are produced due to the gaps in the light curve because of daylight.

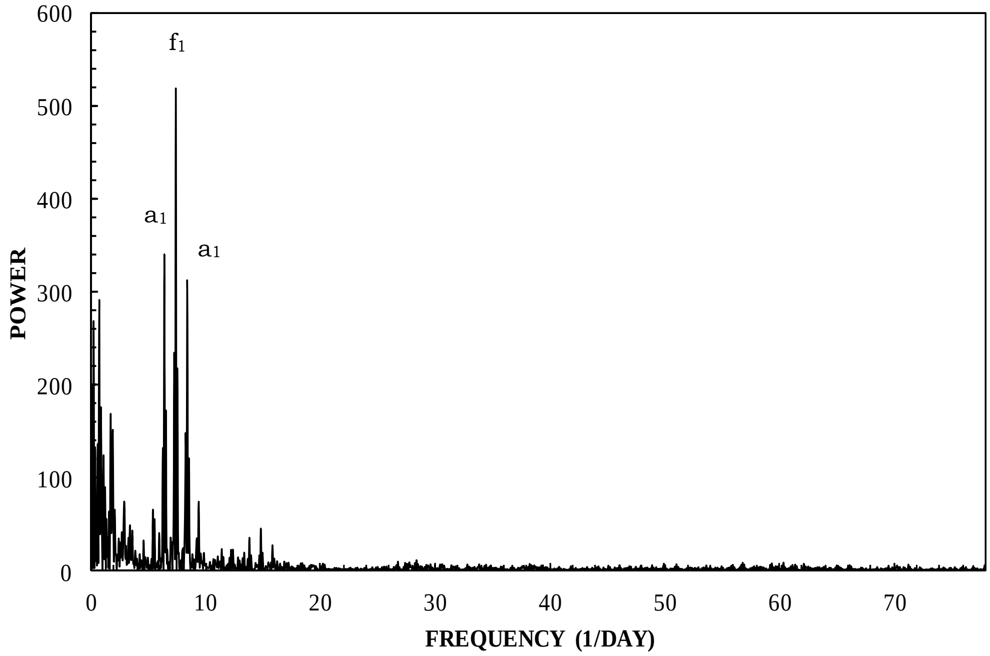



Figure 14. Lomb-Scargle periodogram of the photometric data from 2009 September 17-19 and 23-26.

Ringwald et al. (2009) determined that the orbital period of V378 Pegasi is 3.32592 ± 0.00096 h from a radial velocity study. From this it was determined that the period found in the 2009 September observations is 2.71% shorter than the orbital period. As mentioned before, superhumps have periods that are a few percent different from the orbital period; thus we have discovered negative superhumps. This discovery leads us to believe that V378 Pegasi is a nova-like (recall that negative superhumps have, so far, only appeared in nova-likes).

If Fig. 14 is investigated closer, it can be seen that there are more significant peaks before $f_1$ and its aliases, see Fig. 15. These peaks were examined by creating a spectral window function from the light curve of

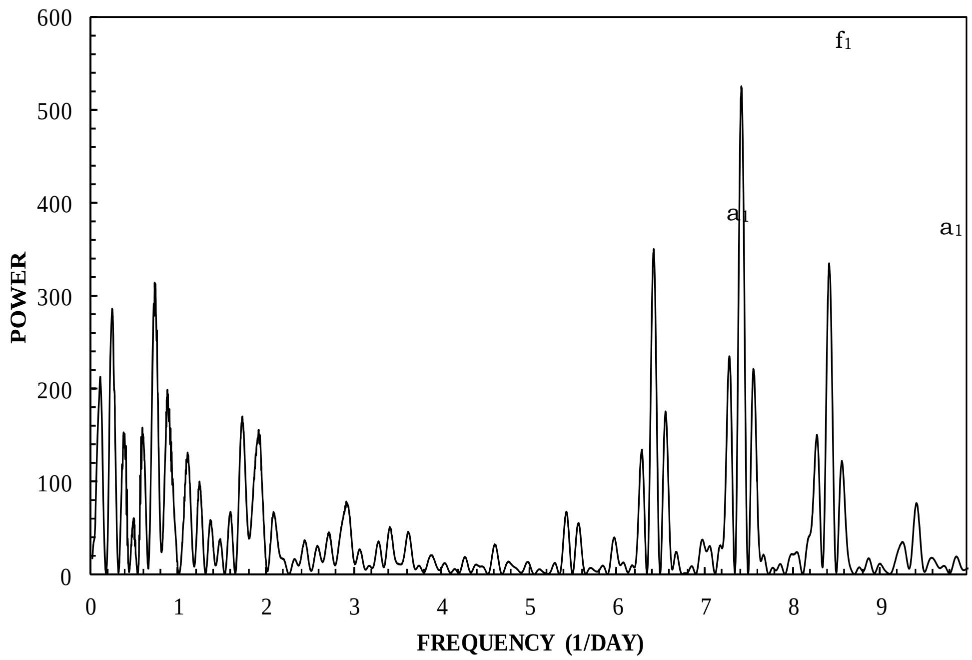



Figure 15. A closer look of Fig. 13.

the 2009 September observations. The purpose of a spectral window function is to indicate which peaks in a periodogram are the result of the data sampling. In *Perasno* the spectral window function calculates the pattern caused by the structure of gaps in the observations. The spectral window function of the 2009 September light curve is shown in Fig. 16. As can be seen from this figure there is no peak at a frequency of 7.41919 $d^{-1}$, thus it is a genuine period. Figs. 15 and 16 were compared to determine if any peaks in the range of 0-2 $d^{-1}$ matched, but they did not; so these peaks might not be due to aliasing. Subsequently CLEANest, a period analysis method used to find multiple periods, was employed to attempt to determine if these peaks were real. Unfortunately conclusive evidence that theses peaks, ranging from 0-2 $d^{-1}$, were real

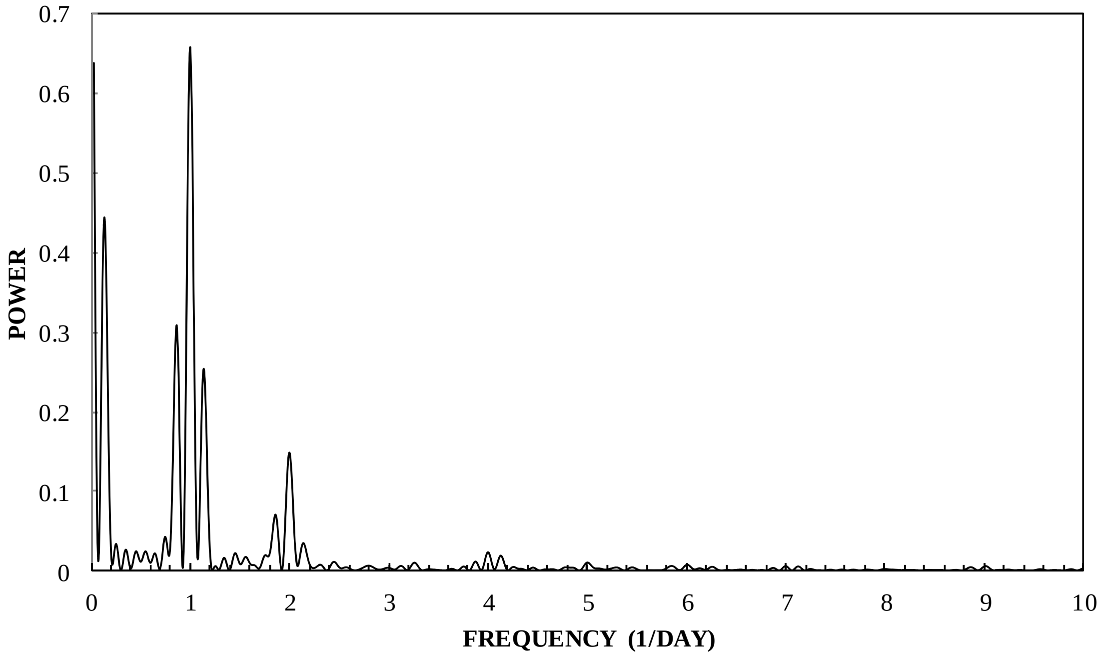



Figure 16. Spectral window function of the observations of 2009 September.

was not obtainable from these photometric observations. Determined to conclude whether these peaks were real are due to aliasing, it was decided that more observations of V378 Pegasi were necessary. Accordingly observations were made from the Sierra Remote Observatory on the nights of 2009 December 3-4. The exposure time was only 5 seconds with 7-8 seconds of dead time. The photometric data from these observations were used to generate the periodogram shown in Fig. 17. Upon inspection of this periodogram peaks were found about a frequency of 1000 $d^{-1}$. To test the validity of these peaks a spectral window function of the light curve of the 2009 December 3-4 observations was generated, see Fig. 18. From this spectral window function it was

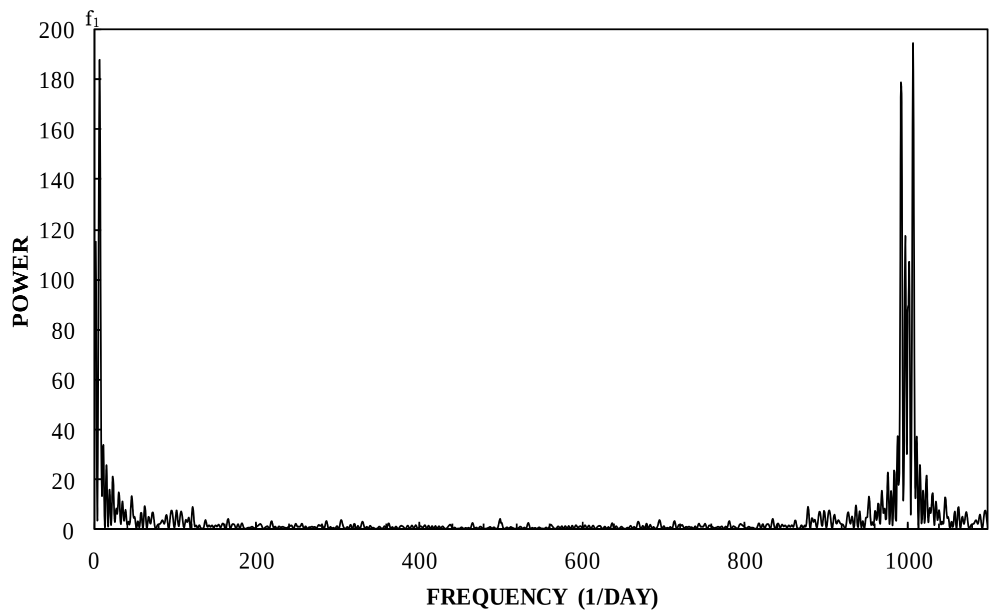



Figure 17. Lomb-Scargle periodogram of the 2009 December 3-4 observations.

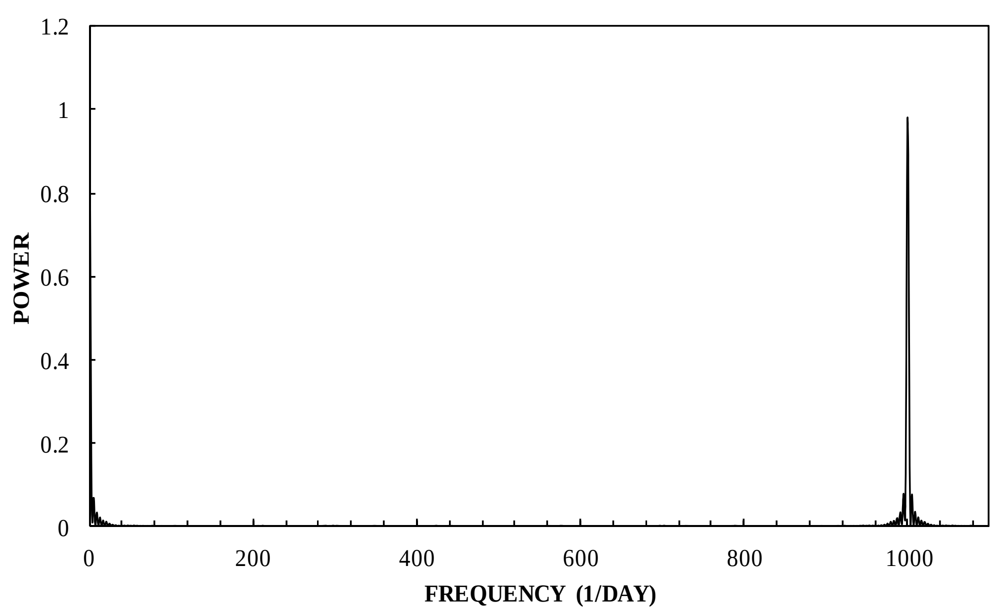



Figure 18. Spectral window function of the 2009 December 3-4 light curve.

determined that the peaks at 1000 $d^{-1}$ were due to aliasing. There were also two other powerful peaks in Fig. 17; the one labeled $f_1$ is the negative superhump period, while the peak before it, is false as shown in Fig. 18. Regrettably we did not find other periods in the light curve.

In addition to checking for multiple periods, we also checked the consistency of the negative superhump period. Figs. 19-22 present the Lomb-Scargle periodograms of the 2009 November, 2008 November, 2008 October and 2001 August datasets. The period for each observation set is shown in Table 1. It is verified that the negative superhump period has not varied much in eight years; from 2001 to 2009 it has been practically consistent.

If a closer look of Fig. 22 is taken, it can be seen that the most powerful peak in this Lomb-Scargle periodogram is actually at a frequency of 8.42749 ± 0.11868 (1/day) and that the second most powerful peak is at 7.41871 ± 0.00108. So which is the true period?

Table 1. The negative superhump period of V378 Pegasi.

| Observation Set | Frequency (1/day) | Period (hour) |
|---|---|---|
| 2009 December | 7.11668 ± 0.73140 | 3.37224 ± 0.34656 |
| 2009 November | 7.40700 ± 0.02500 | 3.24240 ± 0.01140 |
| 2009 September | 7.41919 ± 0.01709 | 3.23496 ± 0.00744 |
| 2008 November | 7.44113 ± 0.06904 | 3.22536 ± 0.03000 |
| 2008 October | 7.42335 ± 0.06705 | 3.23304 ± 0.02928 |
| 2001 August | 7.41386 ± 0.11576 | 3.23712 ± 0.05064 |

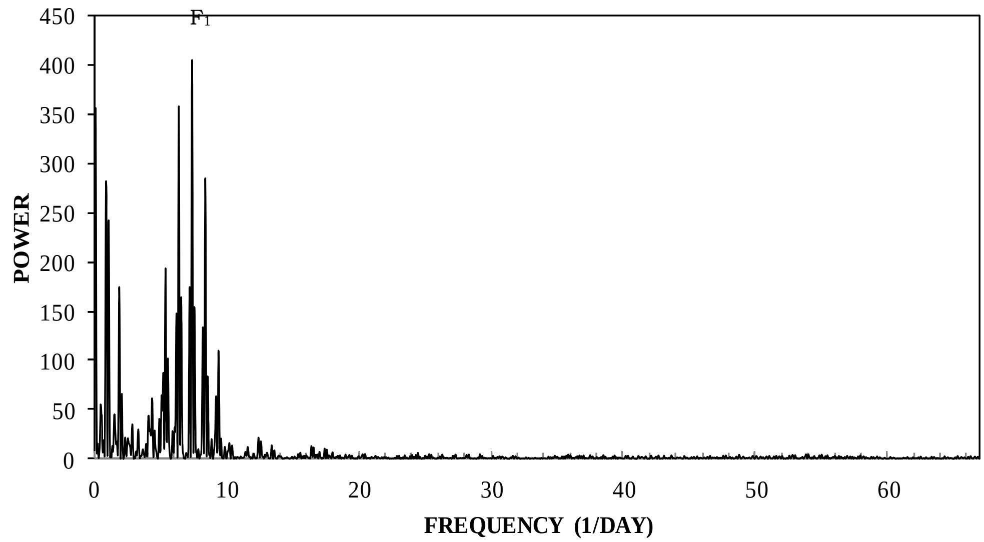



Figure 19. Lomb-Scargle periodogram of the light curve of the 2009 November 23-25 and 2009 November 28-30 observations.

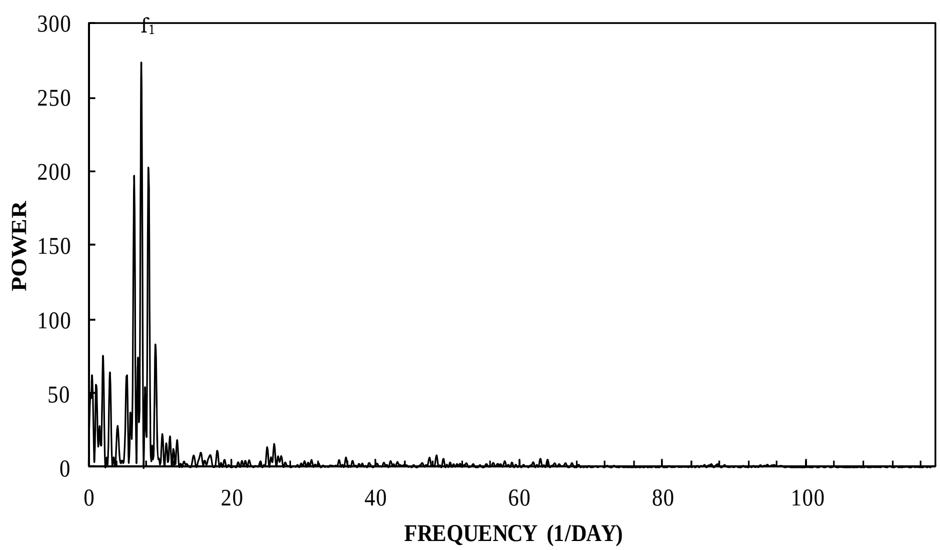



Figure 20. Lomb-Scargle periodogram of the light curve of the 2008 November 21-23 observations.

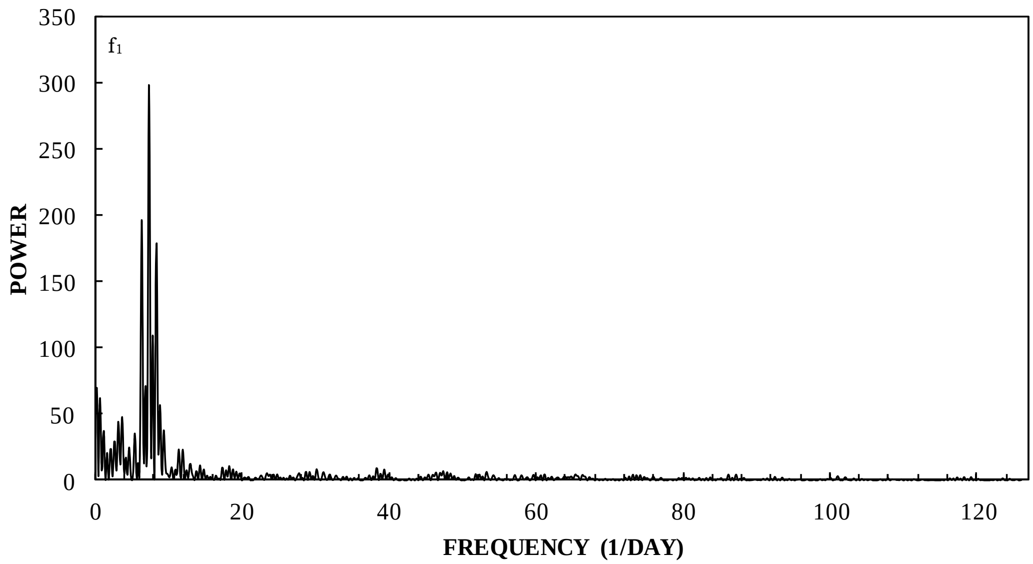



Figure 21. Periodogram of the light curve of the 2008 October 22-24 observations.

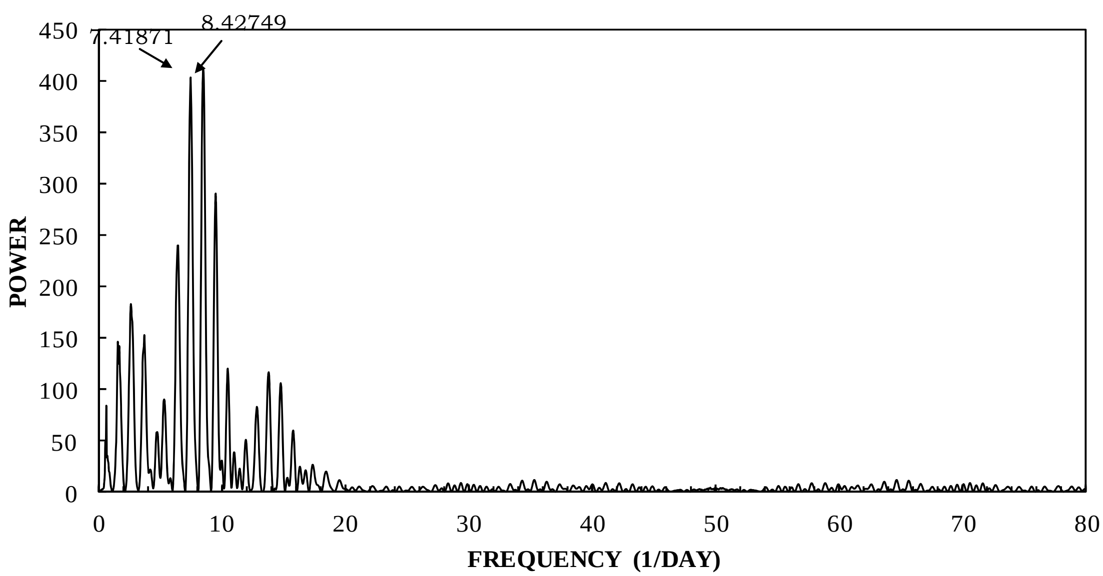



Figure 22. Periodogram of the light curve of the 2001 August 1-3.

From the light curve and the photometric data of 2001 August it was found that the observations were only about 5-6 hours long per night when they needed to be 7 hours or more (Thorstensen & Freed 1985). V378 Pegasi needs to be observed for 7 or more hours in order to avoid the ambiguity of the aliasing. Consequently we conclude that the peak at the frequency of 8.42749 $\pm$ 0.11868 (1/day) is a peak due to aliasing and that the peak at a frequency 7.41871 (1/day) is the true one.

## Precessional Period

The nodal precession period of the disk was calculated using the equation (Hellier 2001),

$$\frac{1}{P_{nsh}} = \frac{1}{P_{orb}} + \frac{1}{P_{nodal}} \qquad (1)$$

where $P_{nsp}$ is the negative superhump period, $P_{orb}$ is the orbital period and $P_{nodal}$ is the nodal precession period. The above equation yielded $P_{nodal}$ = 4.96 days.

## DISCUSSION

### Distance Determination

The distance of V378 Pegasi from Earth is not well known, however rough estimates of the distance can be calculated. In this study two methods were used to determine the distance. In the first method the following formula was used,

$$\log d = \frac{1}{5}(m_{\lambda} - A_{\lambda} - S_{\lambda}) + 1 + \log\left(\frac{R_{eff}}{R_{\odot}}\right), \qquad (2)$$

where $d$ is the distance, $m_{\lambda}$ is the observed magnitude, $A_{\lambda}$ is the extinction, $S_{\lambda}$ is the surface brightness, and the subscript $\lambda$ denotes the spectral band type (Beuermann 2006). The variable $R_{eff}$ is the effective radius and R  is the radius of the sun.

For these calculations it is assumed that $A_{\lambda} = 0$ and $R_{eff} \approx R_2$, where $R_2$ is the radius of the secondary. The formula $R_2 = 0.094\, P_{orb}^{\frac{13}{12}} R_{\odot}$ is used to calculate the radius. The values of the observed magnitude and the surface brightness in the K band are used to deduce the distance. The surface brightness was calculated by using the formula given by Warner (1995),

$$S_K = 2.56 + 0.508(V - K) \qquad (V - K) < 3.5\,. \qquad (3)$$

The magnitudes of $V$, $K$, and $m_K$ for V378 Pegasi were obtained from the SIMBAD database. The errors were calculated by using $P_{orb} = 2.944$ hours—this is the period of one of the aliases of the orbital period (F.

Ringwald 2009, private comm.). Finally all the values were plugged into equation (2) and the distance was determined to be 536 ± 66 pc.

In the second method the formula,

$$\log d = \frac{1}{5}(J - M_J) + 1 \,, \tag{4}$$

was used (Ak et al. 2007), where $M_J$ is the absolute magnitude in the J band. The absolute magnitude was determined by using the formula,

$$M_J = a + b \log P_{orb}\,(day) + c(J - H)_0 + d(H - K_S)_0 \,, \tag{5}$$

(Ak et al. 2007), where a, b, c and d are constants. The subscript *0* indicates that the terms are de-reddened values.

For these calculations it was assumed that there was a minimal amount of reddening, thus $(J - H)_0 = (J - H)$ and $(H - K_S)_0 = (H - K_S)$. Once again the magnitudes in the spectral bands *J*, *H*, and $K_S$ from were obtained from the SIMBAD database and it was determined that the distance was 703 ± 92 pc.

<u>Absolute Magnitude</u>

From Beuermann (2009) we can use the equation,

$$S_\lambda = M_\lambda + 5\log\left(\frac{R}{R_\odot}\right) = m_\lambda + 5\log\left(\frac{R}{R_\odot}\right) - 5\log\left(\frac{d}{10}pc\right), \tag{6}$$

to obtain the absolute magnitude; where $M_\lambda$ is the absolute magnitude and $R$ is the radius of the secondary. We let $\lambda = V$ and use eq. (6) to obtain the absolute magnitude in the visible spectral band of

$M_V = 5.26418$.

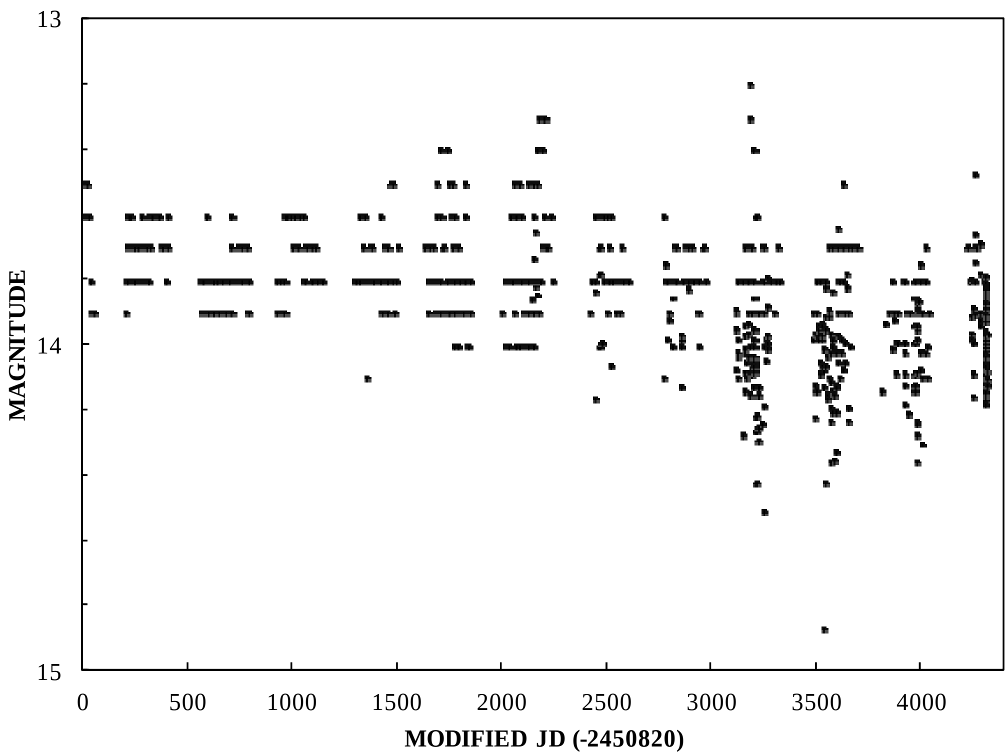
Nova-likes typically have absolute magnitudes of about 4-5. Dwarf novae, on the other hand, have absolute magnitudes less than 11 during rare outbursts. Thus, this gives us further evidence that V378 Pegasi is a nova-like.

## Long Term Light Curve

We have obtained data from the AAVSO database (Henden 2009) to produce the long term light curve shown in Fig. 23.

Figure 23. Long term light curve of V378 Pegasi, from 1998 January 06 to 2009 October 25. (Data compilation by the AAVSO.)

This light curve contains observational data from 1998 January 06 to 2009 October 25. Comparing Fig. 23 to Fig. 2, we notice that there are no outbursts present in the long term light curve, thus indicating that V378 Pegasi is a nova-like.



## SUMMARY AND CONCLUSION

A period of 3.23 ± 0.01 h has been found in the light curve of V378 Pegasi. It is 2.71% shorter than the orbital period, thus it is determined to be the negative superhump period. Also it is believed that V378 Pegasi is a nova-like. Besides exhibiting a powerful peak at a frequency of

7.4 $d^{-1}$, the Lomb-Scargle periodograms also exhibit significant peaks at lower frequencies. Although different methods were employed to determine the validity of these peaks it was not possible to conclude if they were genuine periods. The nodal precession period was found to be 4.96 days.

The distance of V378 Pegasi from Earth was calculated using the methods given in Beuermann (2006) and in Ak et al. (2007). The former method gave 536 ± 66 pc and the latter method gave 703 ± 92 pc. These two values are quite different and are only rough estimates of the distance. The absolute magnitude of V378 Pegasi was determined to be about 5.2.

We determined that V378 Pegasi is a nova-like cataclysmic variable. There are three reasons to suppose this: 1) negative superhump periods occur only in nova-likes, 2) the absolute magnitude of V378 Pegasi corresponds to values typical of nova-likes, and 3) the long term light curve shows no outbursts.

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