V478 Lyrae Revisited: A Current Look at Eclipses and Star Spots

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Presented at the 94th Annual Meeting of the AAVSO, October 14, 2005; received January 9, 2006; revised August 1, 2006; accepted November 14, 2006

Abstract Differential photometry of V478 Lyr from the 2005 observing season, spanning eighteen orbital cycles, is presented and analyzed. The resulting analyses are compared to previously published data. This study analyzed multiple eclipse cycles and obtained photometry demonstrating additional fluctuations in the light curve of the system. *V* and *I* band photometric observations were fit to a two-spot model using several commercially available binary star modeling programs. Spot distributions, relative size, longitudinal separation, and effective temperature have been determined.

1. Introduction

V478 Lyr (HD 178450) is a chromospherically active star, an eclipsing binary-type RS CVn. Its variability was first described by Henry (1981). Since then, other studies, most notably Fekel (1988) and Hall *et al.* (1990) have suggested that active star spots are present on its surface, and have shown that these spots can change significantly in as little as a few weeks or seem to last almost ten years or more. A search of the literature shows the orbital period of V478 Lyr to be 2.130514 days (Hall *et al.* 1990; Fekel 1998). Although in this type of binary system the stars are presumed to be tidally locked in synchronous rotation with the orbital period, the periodicity of the photometric variability due to spots has shown both a slower and faster rate, from –0.4% to 0.5% of the orbital period (Hall *et al.* 1990). Table 1 summarizes the orbital parameters and other major properties of the V478 Lyr system.

2. Observations

In the summer of 2005, V478 Lyr was observed almost nightly for 40 days from JD 2453550.703 to JD 2453589.693 (29 June 2005–9 August 2005), encompassing 18 orbital cycles. The observations were made using a Meade LX200 10-inch (0.25m) telescope with a Starlight Xpress MX 716 CCD camera, which has a 550 × 720 pixel array. Both fifteen- and eight- second exposures were taken at an *f*-ratio of 6.3 (for an effective field of view of approximately 11 × 14 arcminutes) with Johnson *V* filters for all observation dates, and additionally using a Johnson *I* filter for the latter half of the observational period. Typical seeing conditions for this low-altitude site were between 4.5 and 5.5 arcseconds FWHM for V478 Lyr in each image. The fifteen- second exposures were utilized for *V* band light curve development and the eight-second exposures were utilized for *V–I* color index results, with the shorter exposure time required not to saturate the CCD for *I* band exposures.

Additionally, eight-second exposures in both *V* and *I* band were taken of the nearby comparison star HD 177878 ($V = 7.72$, $V–I = 0.99$, from SIMBAD). Because HD 177878 is approximately two fields of view away from V478 Lyr for this CCD setup, all exposures were taken at high elevations (air mass < 1.27), and, coupled with the relatively small angular separation between V478 Lyr and HD 177878, resulted in the air mass differences between the two objects being less than 0.015, and in-turn, any magnitude differences due to differences in atmospheric extinction well below the accuracy of this study. All exposures were dark current-and-bias subtracted, and also flat-fielded (using twilight sky flats) according to established procedures.

To minimize the effects of scintillation, twenty images were averaged for each photometric measurement. Images were obtained by taking ten exposures of one of the objects (V478 Lyr or HD177878), then moving the telescope to the other object for another ten exposures, then repeating, so that altogether twenty exposures were obtained for each star. The averaging of exposures and use of the comparison star HD 177878, together with other field stars (GSC 22640 250 and GSC 2690 1550), yielded a photometric accuracy of 0.01 magnitude in *V*. The software tool AIP4WIN (Berry and Burnell 2000) was utilized for photometric measurements. The *V* and *I* photometric data on HD 177878 were normalized with measurements taken from the SIMBAD Hipparcos data, corrected to the Johnson system. Zero points were then determined from the HD 177878 photometry and applied to the V478 Lyr photometry using AIP4WIN, to produce standardized *V–I* measurements of V478 Lyr.

3. V478 Lyr photometry

Light curves of the photometric variation of V478 Lyr tended to group into three approximately 14-day segments. The first segment, JD 2453550.703 to JD 2453562.680, is shown in Figure 1. This first segment shows a total variation of approximately 0.08 *V* magnitude and is quite regular in shape. The second segment, JD 2453563.889 to 2453575.756, is shown in Figure 2 and illustrates a significant change that occurred in the light curve from the first data segment: in the second segment, the light curve at the earlier phase is significantly shallower than the later phases. The third segment, JD 2453576.680 to JD 2453589.693, shown in Figure 3, shows a shallow light curve with a total variation of only 0.04 *V* magnitude. The error bars shown in each figure are ± 0.005 *V* magnitude.

The software tool PERANSO (Vanmunster 2005) was used to determine the period of photometric variation. The tool produced a period of 2.15 ± 0.01 days for each segment, which is approximately 1% longer than the orbital period of the binary system.

4. Eclipse photometry

Because of the inclination of the orbit to our line of sight, the secondary star produces only a partial eclipse. During the observations of V478 Lyr, primary eclipses of this binary system were observed in each of the three data segments, although complete eclipse light curves were gathered only during the last two segments. As the photometric variation of the star changes due to surface spots, typical photometric observations of this system and subsequent period analysis cannot be used to determine the orbital period (Percy *et al.* 2001). Therefore midpoint eclipse timing is the only accurate method. Determination of the midpoints of the eclipses was accomplished by utilizing the extremum tool of Kwee and van Worden (1956) in PERANSO (Vanmunster 2005). The Geocentric epochs for the midpoint of these eclipses are JD 2453569.700359 ± 0.000039, JD 2453571.84526 ± 0.000033, and JD 2453586.761459 ± 0.000054. The reported uncertainly is chiefly caused by scintillation and scatter effects. The eclipse for JD 2453569.700359 is shown in Figure 4. It can be seen that these eclipses are quite shallow, with the variation being only 0.035 visual magnitude. The corresponding secondary eclipse was not seen, since the amount of light variation is quite small and is below the photometric accuracy of this study.

A new calculation of the period can be accomplished by using the second, and most accurate, eclipse epoch from this study, JD 2453571.84526, and the one utilized by Hall *et al.* (1990) as input to their binary star model. Between the HJD epoch of 2445940.334 from Hall *et al.* (1990) and the second epoch, converted to a HJD 2453571.84883, there are 3,582 orbital cycles. Correspondingly, the period can be calculated as 2.13051782 ± 0.00000028 days, which is slightly longer than Hall *et al.* (1990) and which implies the period of V478 Lyr has increased in the past twenty years.

5. Fit to a two-spot model

It is generally assumed that the (non-eclipse) light variation of RS CVn stars is due to large spots on the surface of the active component. The specific shape of the light curve, in turn, depends on the distribution, size, and number of these spots. If the observed light curve can be matched to a model of an eclipsing binary star system, the probable number and nature of these spots can be characterized. Additionally, a change in the light curve implies a change in the character and distribution of the spots (Raveendran and Mohin 1995).

Two software tools, NIGHTFALL (Wichmann 1999) and PHOEBE (Prsa 2005), were used to model the V478 Lyr system and assumed surface features. Both software tools produced similar results, within a few percent, with some obvious differences in phase angles, coordinate origins, and parameter names.

The parameters from Table 1 for the V478 Lyr system were entered into the binary star software, together with initial assumptions about the surface star spots on the primary. A review of the literature, principally Hall *et al.* (1990), Fekel (1988), and Strassmeier and Bopp (1992), shows surface modeling of RS CVn binaries typically presumes a two- or three-spot model to characterize the photometric variation. Two surface spots on the larger primary star, with an assumed radius of 15°, were initially used in this analysis. The photometric period being slightly longer than the orbital period (2.15 days as opposed to 2.13 days) could indicate that any surface spots might be at higher latitudes due to differential rotation of the primary star (Strassmeier *et al.* 1994; Mekkaden and Raveendran 1998), but it might simply be reflection of uncertainty in the data and the period analysis software. Based primarily on the review of the literature, it was initially assumed that these two spots were positioned at 30° of latitude to begin the data fitting routine. Additionally, the linear cosine relationship was utilized in the model for limb darkening.

The binary star modeling software requires an additional parameter, a "dimming factor," A_p (Djurasevic 1992), which is the ratio of the spot effective temperature versus the surrounding unspotted star surface. Previous modeling techniques for surface spots on RS CVn binaries (Strassmeier *et al.* 1994; Olah *et al.* 2001) have tended to assume spot differential effective temperatures of between 800 and 1,200 K from the surrounding, unspotted stellar surface. For our spot analysis, this value was assumed to be 800 K and, assuming the effective temperature of a G8 V star to be 5,490 K (Guinn *et al.* 1998), this makes the initial dimming factor:

$$A_p = (4690\,K / 5490\,K) = 0.854.$$

A data file for each observational segment was created using both the photometric "spot" variation and the eclipse data. The data fitting routine of the software was utilized and, for the first segment processing, the values for latitude, longitude, spot radius, and dimming factor were allowed to vary. After multiple iterations, the best match for the data (i.e., the smallest χ^2 value) was found. The NIGHTFALL software model output for *V*-band photometry, together with the observational data for the each segment, is shown in Figures 5, 6, and 7. It should be noted that the output of the NIGHTFALL program positions the primary eclipse at the 0.5 phase point and the light curve is drawn from –0.25 to 0.75 phase. The observational data are then shifted to match this eclipse point, approximately –0.33 phase from that shown in Figures 1, 2, and 3.

The best fit for the three data segments produced the values shown in Table 2.

For the second and third segments, the results of the first segments analysis was used as a starting point for subsequent data fitting. The data fitting routine was run as before, with the exception of not allowing the latitude to vary, since latitudinal drift of spots should be quite small for the 40-day observational period.

6. Star and spot effective temperature

McWilliam (1990) and Amado and Byrne (1996) have provided empirical relationships for Effective Temperature versus Color Indices (e.g., *B–V* or *V–I*) for stars of spectral type G, K, and M. Since the primary component of the V478 Lyr system is a G-type star, it should be possible to verify that the unspotted surface effective temperature of the primary star used in the software model software is consistent with the observed *V–I* data. The *V–I* data for segment three are shown in Figure 8. Note that a greater *V–I* index indicates a cooler effective temperature for the star. The error bars on the *V–I* data are ±0.01 magnitude.

For the third segment, although there is considerable scatter in the data, the minimum *V–I* value appears to be 0.95, which is corresponds to the unspotted surface of the primary. Using the *V–I* relationship from McWilliam (1990), we get

$$T_{eff} = \Sigma A_i C^i,$$

where A_i are empirical constants and C is the Color Index. For *V–I*, this equation becomes:

$$T_{eff} = (9853) + [(-6733) \times (V\text{–}I)] + [(2564) \times (V\text{–}I)^2] + [(-335) \times (V\text{–}I)^3].$$

For $V\text{–}I = 0.95$, this corresponds to an effective surface temperature of 5475 K ± 80 K, which is consistent for a G8 star, and very close to the effective temperature of 5490 ± 80K given by Guinn *et al.* (1998), 5490 K ± 80 for V478 Lyr, and the effective temperature used to model the primary of this system.

Additionally, it should be possible to determine whether the differential effective temperature of the spots that was used to model the system is consistent with the observed data. Since the amplitude and shape of the *V–I* color curve indicate a change in effective temperature of the stellar disk (Poe and Eaton 1985), the actual observed *V–I* color curve compared to a modeled *V–I* color curve would provide a qualitative measure of the accuracy of the differential temperature assumptions. While neither software program can produce a color curve outright, PHOEBE can produce a light curve of the total flux for a given wavelength. This makes it possible to use the data from these flux curves to produce a synthetic *V–I* color curve. Such a curve was created for the third segment, where the resultant dimming factor from the model was 0.901, corresponding to a differential effective temperature of approximately 550 K. This synthetic *V–I* color curve is shown, together with the observed *V–I* data, in Figure 9. Within the margin of error and the scatter of the data, the synthetic *V–I* curve is a reasonable match to the actual data.

7. Conclusions

This paper has presented new *V*- and *I*-band photometry of V478 Lyr, demonstrating the photometric variation of the system, in addition to the primary eclipses. From the observations, it has been possible to determine the orbital period of V478 Lyr that is in excellent agreement with previous studies. Using two binary star software modeling programs, it has been possible to deduce the presence of two dark spots on the surface of the primary star. In the first data segment, both spots were 15° in radius. In the second and third data segments, spot 1 remained nearly the same size while spot 2 decreased to 10° in radius.

While the apparent movement of both spots (approximately 15° in longitude) during the observation period is significantly greater than sunspot drift rates, it is consistent with longitudinal drift rates for other RS CVn binaries, such as HR 7275 or HD 17433 (Strassmeier and Bopp 1992; Strassmeier *et al.* 1994).

An effective surface temperature of 5490 K of the primary and a spot differential temperature of approximately 500 K, used in the software model in the third segment, is consistent with the *V–I* observational data for that same segment. This implies that both spots cooled approximately 300 K from the first to the third segment.

While the determination of surface spots on the primary component of V478 Lyr has seemingly been straightforward, a note of caution must be given. Because of limitations in the accuracy of the photometry and the inherent limitations of the binary models, the analysis offered here is simply one solution, consistent the observational data, not necessarily a unique solution. Multiple smaller spots, in close proximity to the two-spot solution offered here, could present similar light curves, as could more complex arrangements of spots at much different latitudes. Still, within the accuracy involved, the analysis offered here is a reasonable interpretation of the current status of the V478 Lyr system.

8. Acknowledgement

This research has made use of the SIMBAD database, operated at Centre de Données astronomiques de Strasbourg. I also wish thank an anonymous referee for many detailed comments and for suggesting additional analyses that have improved the paper substantially.

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Table 1. V478 Lyr system properties, from Hall *et al.* (1990).

Property	*Value*
Primary Star Type	G8V
Primary Star Mass	0.93 $M_\odot$
Primary Star Radius	0.98 $R_\odot$
Secondary Star Type	M3
Secondary Star Mass	0.25 $M_\odot$
Secondary Star Radius	0.3 $R_\odot$
Orbital Inclination (i)	82.8°
Semi Major Axis	7.33 $R_\odot$
Orbital Period	2.130514 days
Duration of Primary Eclipse	2.0 hours

Table 2. Values of the best fit for the data segments of V478 Lyr.

Segment	*Spot* °	*Radius* °	*longitude* °	*latitude*	A_p
1	1	15	16	32	0.860
1	2	15	85	48	0.853
2	1	16	24	32	0.902
2	2	10	100	48	0.891
3	1	17	30	32	0.911
3	2	10	106	48	0.901

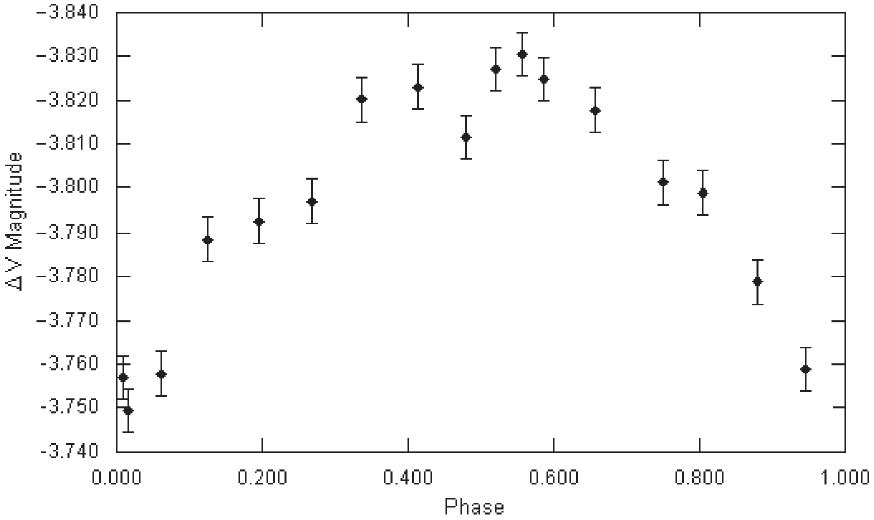

Figure 1. Photometric variation of V478 Lyr for the first data segment, 29 June 2005–11 July 2005. From observations by the author in 2005. Error bars are ± 0.005 magnitude.

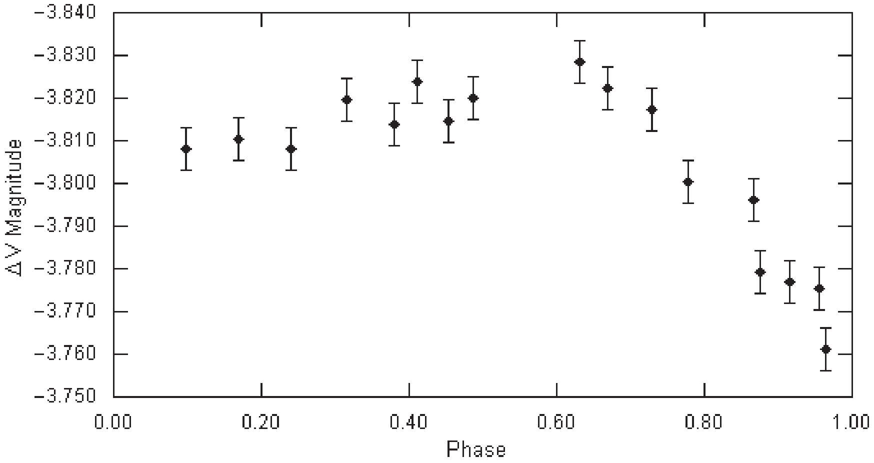

Figure 2. Photometric variation of V478 Lyr for the second data segment, 12 July 2005–25 July 2005. From observations by the author in 2005. Error bars are ± 0.005 magnitude.

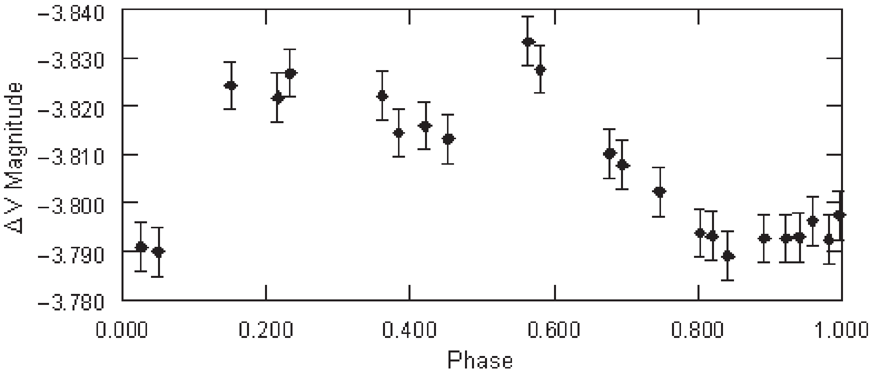

Figure 3. Photometric variation of V478 Lyr for the third data segment, 26 July 2005–9 August 2005. From observations by the author in 2005. Error bars are ± 0.005 magnitude.

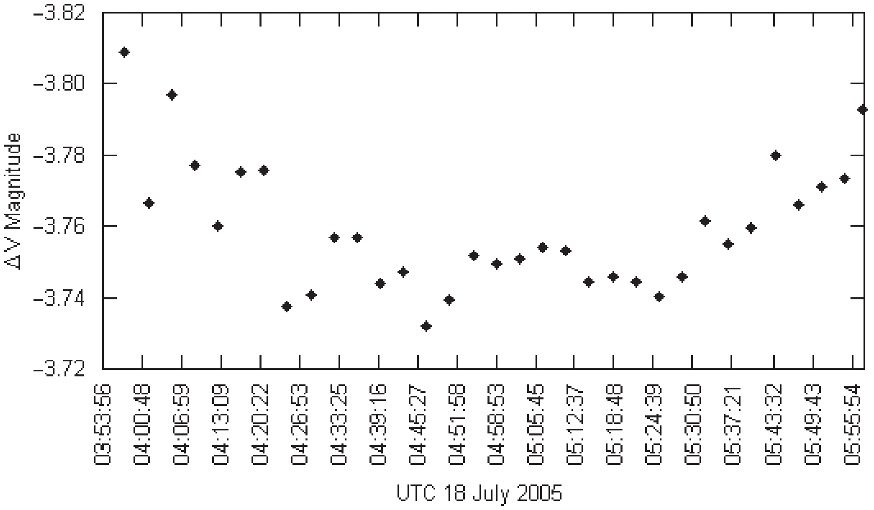

Figure 4. The primary eclipse of V478 Lyr, epoch JD 2453569.700359, UTC 18 July 2005. From observations by the author in 2005.

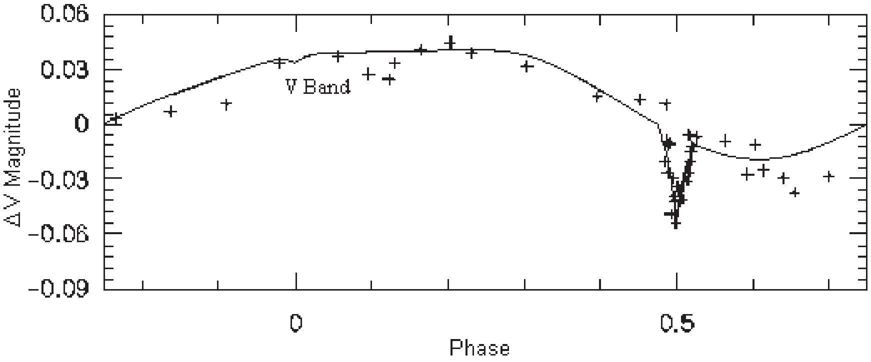

Figure 5. Data fit for a two-spot model for V478 Lyr, for the first data segment. From observations by the author in 2005. Spot 1: Longitude, 16; Latitude, 32; Radius, 15; Dimming, 0.860. Spot 2: Longitude, 85; Latitude, 48; Radius, 15; Dimming, 0.853. χ-square = 1.07.

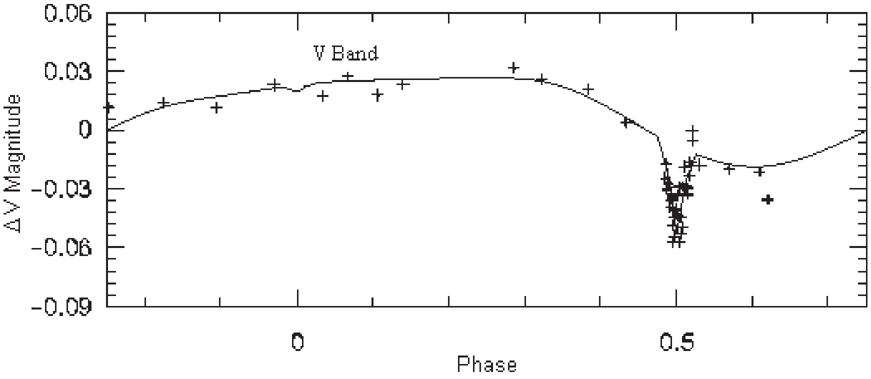

Figure 6. Data fit for a two-spot model for V478 Lyr, for the second data segment. From observations by the author in 2005. Spot 1: Longitude, 24; Latitude, 32; Radius, 16; Dimming, 0.901. Spot 2: Longitude, 100; Latitude, 48; Radius, 10; Dimming, 0.891. χ-square = 1.07.

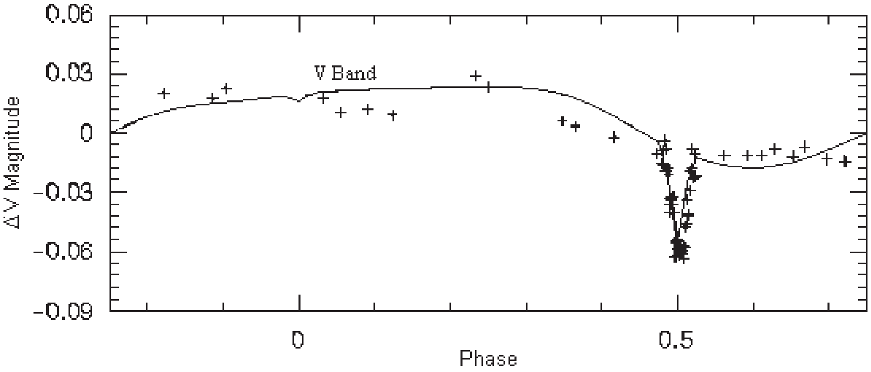

Figure 7. Data fit for a two-spot model for V478 Lyr, for the third data segment. From observations by the author in 2005. Spot 1: Longitude, 30; Latitude, 32; Radius, 17; Dimming, 0.911. Spot 2: Longitude, 107; Latitude, 48; Radius, 10; Dimming, 0.901. χ-square = 0.893.

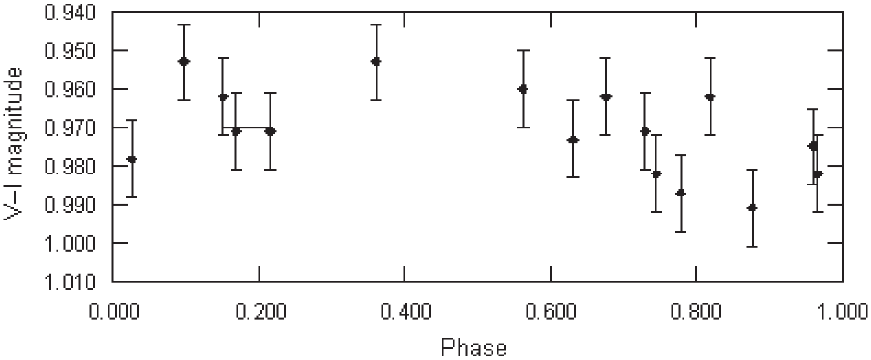

Figure 8. *V–I* data for V478 Lyr, for the third data segment. From observations by the author in 2005. Error bars are ± 0.01 magnitude.

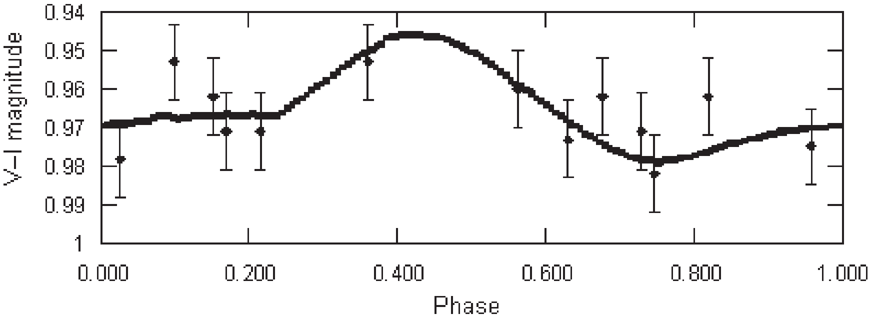

Figure 9. V–I data versus binary software model for V478 Lyr, for the third data segment. From observations by the author in 2005. Error bars are ± 0.01 magnitude.