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TIME-SERIES PHOTOMETRY OF THE SYMBIOTIC NOVA NSV 11749 AND NEW VARIABLE STARS IN AQUILA

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The ChaMPlane project (Grindlay *et al.* 2005) is a survey to detect and optically identify low-luminosity X-ray point sources in the Galactic plane, with the goal of characterizing the Galactic distribution of accretion-powered sources such as X-ray binaries and cataclysmic variable (CV) stars. X-ray data were collected from archival deep (> 20 ks) Galactic plane ($|b| < 12°$) fields, while photometric V, R, I, and $H\alpha$ data were obtained using CTIO and KPNO 4.0 m telescopes. Multi-fiber spectroscopy was obtained of stars with Hα excesses to separate CVs from other objects such as chromospherically active red dwarfs based on Doppler broadening of the Hα line (Rogel *et al.* 2006). A number of potential CV candidates were found, including a bright one with $R \approx 14$ mag which coincided with the emission object HBHA -0201-01 (Kohoutek & Wehmeyer 1997). Figure 1 shows the spectrum of this star taken with the WIYN 3.5 m telescope. The hydrogen and helium emission lines are overlaid on a very late-type stellar continuum, indicating a hot source in proximity to a cool star, suggestive of a CV or other accretion-powered system.

Meanwhile, Williams (2005) presented a significantly revised position of NSV 11749, a star discovered to be variable by Luyten (1937). This position corresponds to the CV candidate discussed above. Williams derived photometry from plates in the Harvard collection, showing an outburst *circa* 1903 reaching a photographic magnitude of 12.5, then slowly fading to go below the plate limit, $m_{pg} \approx 15$ mag, by 1912. It remained below this limit through 1988, the end of the plate sequence, though it was detected on a few deeper plates at ∼17 mag. Based on this outburst, Williams suggested that NSV 11749 is either a slow nova or a FU Orionis pre-main sequence star.

Miller Bertolami *et al.* (2011) compared the outburst light curve of NSV 11749 with the outbursts of V605 Aql and V4334 Sgr, two objects widely accepted as “born-again” asymptotic giant branch (AGB) stars. In these stars, a very late thermal pulse ignites helium burning in a star transitioning from the AGB to the top of the white dwarf sequence, causing the star to return temporarily to the tip of the AGB. Based on light curve similarities and fits of thermal pulse models to the observations, Miller Bertolami *et al.* (2011) suggested that NSV 11749 is also a born-again AGB star. Bond & Kasliwal (2012, hereafter “BK12”) presented optical and infrared spectra of NSV 11749 showing Balmer and helium emission lines on a continuous spectrum of a late type star (they estimated M1-M2 III spectral type), much like our Figure 1. These spectra contrast sharply with that of the born-again star V605 Aql by Clayton *et al.* (2006), which shows high excitation lines of helium, carbon and oxygen, indicative of a hot, compact, hydrogen-poor object. While both objects underwent outbursts about a century ago, these recent spectra show that the born-again AGB star has returned to its former state as a young white dwarf, albeit dust-enshrouded, while NSV 11749 has the spectral characteristics of an accreting compact binary. Thus, BK12 clearly showed that NSV 11749 is not a born-again AGB star.

BK12 argued that NSV 11749 is a symbiotic star, a compact object (likely a white dwarf) accreting matter from a giant star, rather than a dwarf star in a traditional cataclysmic variable.[1] They based this distinction on the presence of the broad emission feature at 6825 Å due to Raman scattering by neutral hydrogen, a feature only seen in symbiotic stars (hereafter "SSs"). Unfortunately, this feature is just off the red end of our spectrum, so we cannot confirm its presence. However, our spectrum has much higher signal-to-noise ratio than that of BK12, enabling us to see more clearly the bands of molecular titanium oxide in the stellar continuum. The lower panel of Figure 1 shows our spectrum divided by template spectra of M3, M4, and M5 III stars from Pickles (1998). A spectrum between M3 and M4 provides the best match, leaving little residual signature of the TiO bands. A smoothed version of the resulting curve is the inverse of the function needed to flux-calibrate our original spectrum, convolved with the interstellar reddening function.

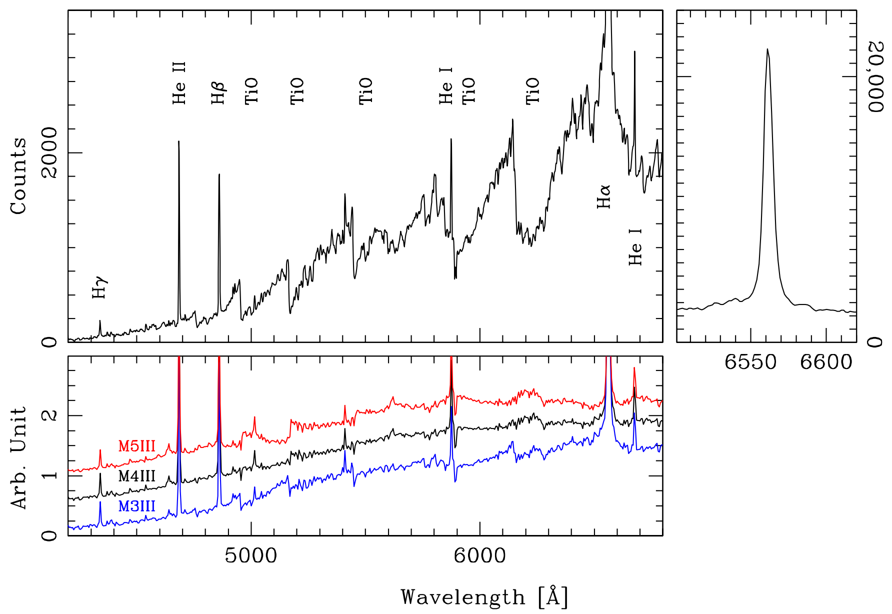

Figure 1. Top-left: the ChaMPlane spectrum of NSV 11749 (not flux calibrated). **Top-right:** a detail of the Hα line. **Bottom:** the NSV 11749 spectrum divided by template spectra of M3, M4, and M5 III stars (lower, middle, and upper curves, respectively).

BK12 matched their spectra with templates of M1 and M2 giants using a reddening function for $E(B-V) = 0.75$ mag. Had they used an M3 or M4 template, a lower reddening would be needed, trending toward the value of $E(B-V) = 0.67$ mag given by the dust maps of Schlegel, Finkbeiner & Davis (1998) at the location of NSV 11749,

[1]The powerful outburst of 1903 resembles the 1980 outburst of the symbiotic nova PU Vul shown in Figure 4 of Mikolajewska (2010), who provides a review of this rare subclass of symbiotic stars.

$(l, b) = (34^\circ\!.8313, -3^\circ\!.5974)$, or $E(B-V) = 0.57$ mag from the recalibration by Schlafly & Finkbeiner (2011). The spectral type difference may also reflect a change in the intrinsic color of the red giant if the star is a long period variable; our spectrum was taken on 2007 June 20 *versus* 2012 for BK12.

Reddenings from the dust maps are uncertain at low latitudes, so we compared the $R-I$ color of NSV 11749 (see below) with de-reddened $R-I$ colors of M3 and M4 giants in the Bright Star Catalog (Hoffleit & Jaschek 1991). This suggested an even lower reddening, $E(B-V) \approx 0.1$ mag, but the large range in intrinsic color at fixed spectral type and the effect of the hot companion star on the intrinsic $R-I$ of the red giant in NSV 11749 leave a very large uncertainty in this value. As usual, finding the reddening of a low latitude object is difficult.

The Williams (2005) photometry suggests NSV 11749 has been in a quiescent state since the nova outburst 110 years ago, but no time-series photometry is available since 1988, the last plate in Williams' sequence. We therefore undertook CCD photometry of NSV 11749 to provide a clearer understanding of its nature in quiescence, to confirm that its photometric behavior is consistent with its spectroscopic identification as a symbiotic nova, and to seek the orbital period as suggested by BK12. Here, we report the results of the first six months of photometric monitoring.

Images were acquired with the Bowling Green State University 0.5 m $f/8$ Cassegrain telescope and Apogee AP6e CCD camera from 2012 May 16 through July 11. The camera has a 21 × 21 arcmin field of view with 1.2 arcsec pixels. Images were taken in V (180 s) and I (120 s) and the star was visited at least twice each night, with each visit consisting of three images per filter, dithered to prevent stars from repeatedly landing on bad pixels. On one night, we visited the field ten times over an interval of 4.5 hours, and on two nights we visited continuously over 1-2 hours to search for short term variations. Preliminary photometry of the Bowling Green (BG) images indicated the star was variable, but exhibited a slow brightening over the 60 day interval with little short term variation.

We therefore initiated observations with the PROMPT #5 0.4 m telescope (P5; Reichart *et al.* 2005) located on Cerro Tololo in Chile, which we used from 2012 July 24 through November 17. We visited the field one night each week, taking three images each in V (60 s), R (30 s), and I (20 s). The darker skies in Chile yielded higher quality V images than we obtained from BG, though the camera field of view is smaller (10 × 10 arcmin). The images from BG and P5 were processed to remove the bias level and dark current, and to flatten sensitivity differences across the chip.

The images were analyzed using the DAOPHOT II point-spread function fitting photometry package (Stetson 1987). Combined use of DAOPHOT and ALLSTAR located all possible stars on each image. Because the seeing and sky background varied from one image to the next, the number of stars detected also varied. To create a more uniform object list, the best quality images in V, R and I were combined using MONTAGE to produce master images with high signal-to-noise. The DAOPHOT/ALLSTAR procedures were then applied to these master images, giving a master list of stars in the field. Stars were matched on each frame using DAOMASTER, and ALLFRAME (Stetson 1994) was run on all images using the master list from the respective MONTAGE images to produce both time-averaged and time series photometry for each star detected in the field.

Table 1. Photometric Calibration.

Date	Telescope	rms_V	rms_R	rms_I	N_{std}	N_{fld}	N_{SS}
2012 Jul 10	BG	0.027	...	0.031	76	13	12
2012 Jul 11	BG	0.043	...	0.041	41	6	12
2012 Nov 17	P5	0.022	0.021	0.023	60	8	3

On two photometric nights in BG and one at P5, images of standard stars (Landolt 1992) were taken over a range of airmass throughout the night. The instrumental aperture magnitudes of these standard stars, along with their $V-I$ color and airmass, X, were used to do least-squares fits,

$$m - M = c_0 + c_1 X + c_2(V - I), \quad (1)$$

where m is the instrumental magnitude and M is the standard magnitude. For July 11, a linear time dependent term was added. Table 1 shows the dates of each night, the rms scatter of each fit, the number of standard stars observed, the number of independent visits to standard fields, and the number of observations made of the SS field. We then used the "c_i" coefficients to standardize the instrumental magnitudes of 15 uncrowded, non-variable stars in the SS field to serve as comparison stars for differential photometry of the variable stars. Given the details of our calibration, we estimate the final photometric zero-points on the comparison stars to be accurate to 0.01-0.02 mag in V and I and to ~0.04 mag in R. The larger value for R reflects that data were taken on a single night at high airmass. The quality of our zero-points are demonstrated by comparing our V photometry to that in the APASS database.[2] We find a median difference of $V_{\rm BG} - V_{\rm APASS} = -0.012 \pm 0.011$ mag for 14 stars in common, with the uncertainties of the individual magnitudes being 3-5 times larger in APASS than in ours.

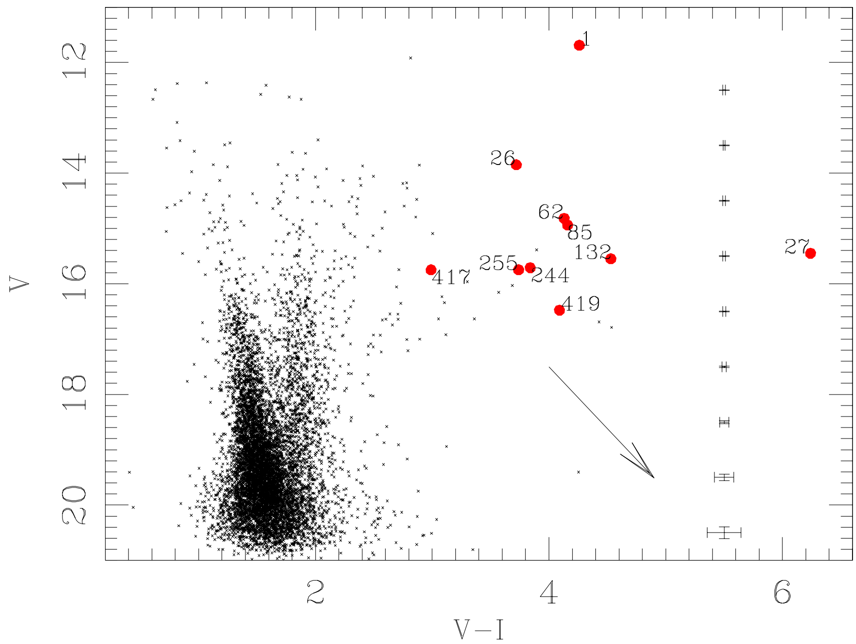

Figure 2. A color-magnitude diagram of the 10 × 10 arcmin P5 field around NSV 11749. The error bars and reddening vector are described in the text. The red circles and numbers mark the positions of the variable stars in Table 3; NSV 11749 is #417.

We also used these results to calibrate the time-averaged ALLFRAME photometry from P5 and produce a color-magnitude diagram of the field, which is shown in Figure 2. There are 7867 stars in total, of which 547 are brighter than $V = 17$ mag. The error bars along the right show mean errors in magnitude and color for stars binned by V

[2]Data Release 7, 2013 by the AAVSO, see http://www.aavso.org/apass.

magnitude. The pattern of bluer, main sequence disk stars and redder stars that include red giants is commonly seen in fields close to the Galactic plane (e.g., Ortolani, Bica & Barbuy 1993). The reddening vector is based on $E(B-V) = 0.67$ mag at the location of NSV 11749 (Schlegel, Finkbeiner & Davis 1998). There is no evidence for strong variations in reddening across our field, either from the dust maps, from inspection of our images, or from the the color-magnitude diagram.

When compiling photometry using DAOMASTER, each star is labeled with a variability index. Stars with the highest variability index were flagged in each of the five data sets (V and I from BG, and V, R, and I from P5), and these lists were compared to find stars in common. Through this method, we detected nine variable stars; NSV 11749 was below our initial detection threshold, but we extracted its photometry and found it to have low-level variations. Equatorial coordinates for each star were estimated from the Two-Micron All Sky Survey images (Skrutskie *et al.* 2006). These and the (x, y) coordinates on a master image[3] are shown in Table 2, along with a column indicating in which fields of view the star was visible. We searched the SIMBAD database at the equatorial coordinates of each star (see Table 2), and followed up named objects with the International Variable Star Index.[4] The results are discussed below, star by star.

Table 2. Variable Star Coordinates.

ID#	$X_{\rm pix}$	$Y_{\rm pix}$	RA (J2000)	Dec (J2000)	FOV	Name
417	485.1	547.1	19:07:42.4	+00:02:51	BG + P5	NSV 11749
1	460.8	331.4	19:07:44.3	+00:07:10	BG + P5	ASAS 190744+0007.1
26	325.9	414.7	19:07:55.1	+00:05:30	BG + P5	
27	546.4	381.8	19:07:37.5	+00:06:09	BG + P5	IRAS 19050+0001
62	485.0	571.2	19:07:42.4	+00:02:22	BG + P5	
85	637.9	832.3	19:07:30.2	–00:02:51	BG	
132	885.6	784.6	19:07:10.4	–00:01:55	BG	
244	700.9	640.0	19:07:25.1	+00:00:59	BG + P5	
255	407.9	412.6	19:07:48.5	+00:05:32	BG + P5	
419	800.6	655.5	19:07:17.2	+00:00:40	BG	

We paired each variable with as many of the comparison stars as possible ($N_{\rm comp}$), then calculated the differential photometry of each pair from the ALLFRAME time-series data, and transformed the result to the standard VRI system, taking the median magnitude of the $N_{\rm comp}$ measurements to represent the magnitude of that variable on that image. We adopted the standard error of the $N_{\rm comp}$ measurements as the random uncertainty in that magnitude. The calibrated time series photometry for each variable is available electronically. Figures 3–6 show the time series after multiple observations taken on a single night were medianed; the error bar on a given point shows the standard error of the $N_{\rm obs}$ magnitudes measured that night.

Table 3 shows the median, maximum (max) and minimum (min) brightness in V and I for each star, along with its median color. From Table 3 it is clear that all ten variables are extremely red, and the color-magnitude diagram shows that they are among the reddest stars in this field. As the bluest of the ten variables, NSV 11749, with its very late-type stellar continuum, sets a temperature upper limit on the other variables. Thus, they are likely to consist of, or contain, red giant or red dwarf stars. Unfortunately, only NSV 11749 was the target of a ChaMPlane spectrum, so no spectral information is available for the other variable stars.

[3]A FITS format image corresponding to these (x, y) coordinates is available at `http://physics.bgsu.edu/~layden/publ.htm` along with other data products from this research. The files are also available as 6071-d1.tar.gz from the IBVS website.

[4]The VSX is available at `http://www.aavso.org/vsx/`.

Inspection of the light curves provided approximate periods for most stars, and the ones with more regular periods were investigated using the phase dispersion minimization method. Also, for some stars we applied the template fitting program of Layden (1998) to fit ten standard light curve shapes to the data for each star to provide a best-fit amplitude and to provide an objective means for classifying the variability type based on light curve shape.

Table 3. Photometric Characteristics.

ID	$\langle V\rangle$	$V_{\max}$	$V_{\min}$	$\langle I\rangle$	$I_{\max}$	$I_{\min}$	$\langle V-I\rangle$	Period	Type
417	15.75	15.61	16.17	12.76	12.70	12.84	2.99	?	Z And
1	11.69	11.55	11.84	7.43	7.25	7.51	4.26	40-50	Lb
26	13.85	13.51	14.17	10.13	9.91	10.25	3.72	73 ± 2	SR
27	15.45	15.00	17.16	9.21	9.01	10.31	6.24	>200	M
62	14.82	14.48	15.32	10.69	10.57	10.97	4.13	58/116	SRa/EW?
85	14.94	14.84	15.09	10.78	10.76	10.88	4.15	?	Lb?
132	15.55	15.38	15.76	11.02	10.95	11.11	4.54	?	Lb?
244	15.71	15.32	16.03	11.87	11.70	12.02	3.84	61 ± 5	Lb
255	15.75	15.48	15.94	12.01	11.92	12.06	3.74	47 ± 3	Lb
419	16.48	16.26	16.77	12.39	12.36	12.71	4.10	?	?

In Figure 3, the symbiotic star, NSV 11749 (ID #417), shows a gradual increase in V and I over the course of the BG observations, and a gentle decline in VRI during the P5 interval. The scatter in the BG V data is mostly observational, as the star was quite faint relative to the background sky. However, the slight variability seen in the P5 data seems to be correlated between VRI, so is probably real, with a time scale of roughly 40 days. The star showed no evidence of short-term variability ($\sigma < 0.015$ mag) over the three nights of high-cadence I-band observing from BG. Flickering due to variable accretion rates cannot be ruled out completely, however, since the cool red giant may dominate any flux variations due to accretion onto the hot companion. We intend to obtain high cadence observations in UBV to seek evidence for a variable accretion rate.

These limits on variability over the 1-5 hour time scale support the claim of BK12 that NSV 11749 is a rare symbiotic star, rather than a more common cataclysmic variable. Brightness modulations due to orbital effects should be evident if the star were a CV, which typically have orbital periods of hours (e.g., Warner 1995). Also, the lack of outbursts over the 184 days of observation is unusual for typical dwarf nova systems (Sterken & Jaschek 1996).

The slow variation seen in Fig. 3 is consistent with the behavior of symbiotic stars (Z Andromedae type; Sterken & Jaschek, 1996), in which the hot spot or accretion disk contributes the H and He emission lines seen in Fig. 1, while our I photometry is dominated by the light of a red giant companion. The orbital periods of SSs are typically hundreds to thousands of days, with the very rare subclass of symbiotic novae having periods greater than 800 days (Mikolajewska 2010). It is not clear from the small fraction of a light cycle seen in our photometry whether the behavior is sinusoidal, and indicative of the orbital period of an tidally-distorted red giant, or asymmetric and indicative of Mira-type pulsations seen in the secondaries of many symbiotic novae (Mikolajewska 2010). However, the colors and spectral type of NSV 11749 indicate a star hotter than the Mira variable #27, so as we gather more data in the coming years, we anticipate seeing an elliptical light curve with a period of $\sim$3 years.

Figure 4 shows the light curves of star #1. Despite being the brightest star in the field and saturated on some images, the star is clearly variable with a low amplitude ($\Delta V \sim 0.3$) mag and irregular cycle (40-50 days between peaks). The All Sky Automated Survey (ASAS; Pojmański & Maciejewski 2005) also detected this star, labeled ASAS

190744+0007.1, as variable with a mean V of 11.41 mag and a V amplitude of 0.35 mag. The period given by ASAS is 57.9 days, but they were unable to ascribe a variable type to the star; it is listed as "MISC." A time-magnitude plot of the ASAS data shows no regular periodicity, and the time and amplitude scales of the variability come in and out of coherence over months to years. Our photometry is consistent with the behavior seen in the ASAS photometry. Given the irregular behavior seen in both data sets, the lack of variation over hours, and the extremely red color of the star, we believe this star is a low-amplitude irregular pulsating giant star, type "Lb" in the GCVS notation (Samus *et al.* 2012).

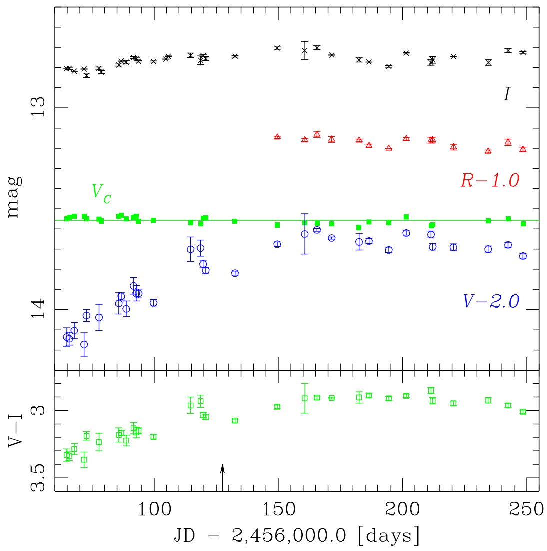

Figure 3. Light and color curves for NSV 11749 (ID#417) where the V and R data (◯ and △) have been shifted upward by 2.0 and 1.0 mag, respectively, for ease of display. The solid squares and line (V_C) show photometry of the non-variable star #127 for comparison. The arrow indicates the transition from BG to P5 data.

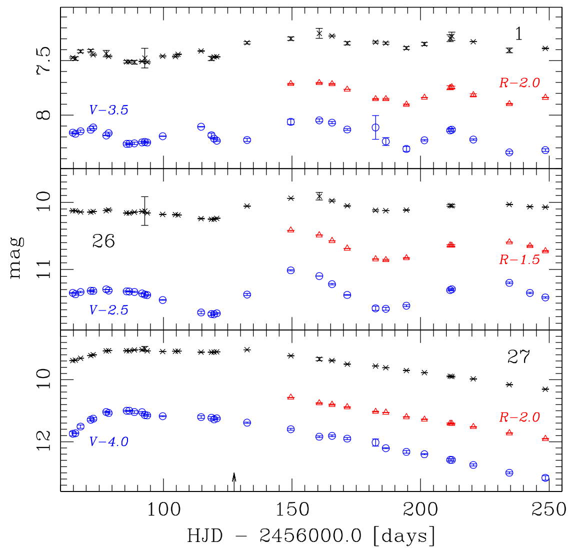

Figure 4. Light curves for stars #1, #26 and #27. Symbols are as in Fig. 3. Error bars in Figs. 3-6 are described in the text.

The light curves for star #26, shown in Fig. 4, indicate a more consistent periodicity of 73 ± 2 days over 2.5 light cycles, while the amplitude varies considerably from cycle to cycle. These and the star's red color suggest this star is a semi-regular (SR) long period variable. Our continuing observations will determine the level of periodicity and hence the sub-category SRa versus SRb.

The classification of star #27, also shown in Fig. 4, is clearer: it must be a Mira (M) type long period variable with a period longer than 200 days and an amplitude $\Delta V > 2.2$ mag. Continuing observations will refine these values. This very red star is 7.5 arcsec from the cataloged position of IRAS 19050+0001 and is almost certainly a match.

Star #62, shown in Fig. 5, has a regular periodicity superimposed on a linear decline over the 184 day observing interval. After fitting and removing the linear trend, we obtained a period of 58 ± 3 days. This could be interpreted as an SRa long period variable with a long secondary period (e.g., Kiss *et al.* 1999), or a contact binary (EW type) in which both components are giants and one has slow, low-level pulsation. Template fitting

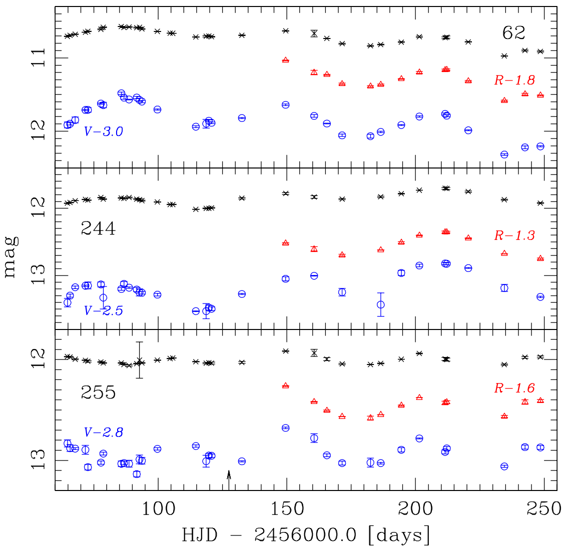

Figure 5. Light curves for stars #62, #244 and #255. Symbols are as in Fig. 3.

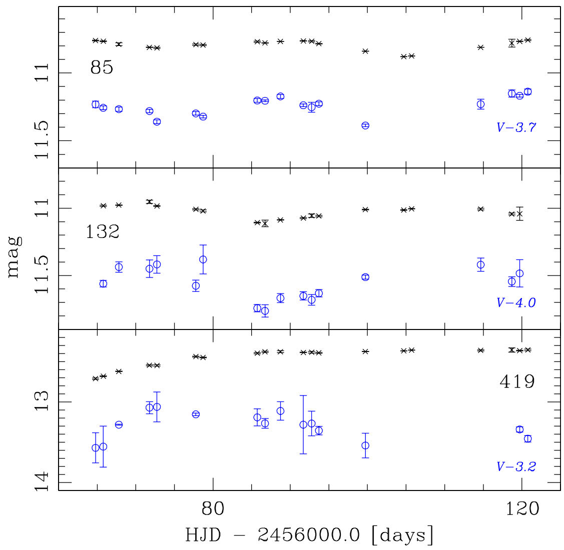

Figure 6. Light curves for the three stars viewed only from BG: #85, #132 and #419. Symbols are as in Fig. 3.

using the 58 day period resulted in a best fit using a sine curve template with an amplitude of 0.31 mag in V and 0.14 mag in I, while a 116 day period yielded an EW template with amplitudes of 0.34 and 0.14 mag, respectively. The rms scatter around the templates was comparable, giving us no reason to prefer one fit over the other. More photometric observations may clarify these two interpretations.

Stars #244 and #255 have similarly red colors and irregular light curves in terms of both period and amplitude (see Fig. 5). We classify them both as irregular long period variables of class Lb, with periods around 61 ± 5 days and 47 ± 3 days, respectively.

Stars #85, #132, and #419 were outside the P5 field of view, so we have only the 57 day time series obtained at BG to interpret their light curves (see Fig. 6). All three stars have $V - I \approx 4$ mag, and stars #85 and #132 have low amplitude variations. We tentatively classify these two stars as irregular long period variables of class Lb. Star #419 brightens and fades in V during our observations, while it remains bright in I. This deviation might indicate an epoch of dust formation, perhaps at maximum light of a Mira with a period much longer than 57 days. Longer time series data for all three of these stars is needed to clarify their behavior.

We note the similarities in the light curves of stars #1, 26, 62, 244, and 255. We reviewed our analysis and found no errors that could account for this behavior. Stars of similar brightness, color, and location (#417, 27, and a host of non-variable stars) behave differently, indicating that it cannot be due to systematic properties of the sky or CCD. These light curve similarities must be coincidental, and we expect to see them fall out of sync in future photometry.

In conclusion, we obtained six months of time series photometry on the emission line object NSV 11749 and confirmed its slow photometric variability, consistent with the determination of BK12 that this object is a symbiotic nova. We are continuing to monitor this field in $BVRI$ in order to find the orbital period of the binary. In the process of observing NSV 11749, we confirmed the variability of one known variable, and we detected eight new variable stars in the surrounding field. We classify the known variable, ASAS 190744+0007.1, as an irregular long period variable (Lb) and suspect the new variables are all red, long period variables (L). Our continuing observations of these stars will refine their periods and sub-categories within the L type.

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