Binaries in the Young Globular Cluster NGC 1850

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ABSTRACT

The overturning of the conventional wisdom that globular clusters (GCs) do not include primordial binaries has been a subject of recent excitement. Both theory and observation have changed from a time when GC binaries were neither observed nor expected, except for the possibility of a small number of binaries collisionally created since the formation of the GCs. Around 1990, theorists found that that if GCs contained "primoridial" binaries (binaries formed during GC formation), their presence could improve explanations of GC dynamics. Theorists shifted away from from their long-held belief that GCs would contain no "primordial" binaries, and observers began finding significant numbers of binaries in GCs, where before 1990 few binaries were found (but few were searched for).

The observation part of this revolution in GC understanding has largely come from detection of Milky Way globulars, which are of roughly similar age of the galaxy itself. The Magellanic Clouds (MCs) possess Globular-like Clusters (GLCs) that are relatively "young," with ages of the orders of 10^6 and 10^7 years, and thus present an opportunity to compare the binary star fractions over a longer period of GC lifetime. But only a limited amount of study of MC GLC's binary fractions has been done, and this largely by Color Magnitude Diagram (CMD) analysis. How GLCs relate to definitively true GCs is a still unanswered question that studies of their binary fraction may help answer. Fewer observational studies of MC GLCs by the more direct determination of binary fraction by observing MC clusters stars for transit signals have been done, especially surveys that have found GC eclipsing binaries.

This paper presents the detection of two detached eclipsing binary stars in the region of NGC 1850. One is a newly detected binary in the region of the

subcluster NGC 1850A. Due to the young age of NGC 1850A this binary will be of particular interest if confirmed to be a member of NGC 1850A. Its eclipsing binary status has been confirmed by the OGLE group; the other eclipsing binary had already been found by OGLE.

Subject headings: clusters: globular —stars: binaries

1. Introduction

Binary stars influence globular cluster evolution to a far greater degree than had long been believed (Meylan & Heggie 1997; Hut, McMillan, & Romani 1992). Once thought not to exist in numbers significant to the evolution of globular clusters (GCs), binary stars are now being seen as providing energy to GC single stars that influence events as important as halting core collapse. Not only has the importance of binary stars increased to theoretical studies, observers are now detecting globular cluster binaries, overturning earlier observational reports of GCs not containing binary stars (Meylan & Heggie 1997).

The question that arises is whether the binary fraction in GCs changes with age. While young globular clusters have been studied theoretically, it is well known that Milky Way GCs were all formed in the first few Gyr of the history of the universe, but such is apparently not the case in the Magellanic Clouds, with LMC globular-like clusters (GLCs) such as NGC 1850 and NGC 1818 having ages on the orders of 10^7 or even 10^6 years. Preliminary observational work has led to the discovery of some binaries in the field near these clusters (Sebo & Wood 1995), but surveys within the GC range are needed in order to compare the binary fraction of these "young" GCs with that of the better studied but older Milky Way GCs.

Observations have been taken in response to this central question: "How do binaries affect the dynamical evolution of *young* globular-like clusters?" The detection reported here of two photometric binary stars in the region of the young GLC NGC 1850 does not yet answer this question, but shows that the use of moderate sized (0.9 m) telescopes can be brought to bear on constraining the answer. Future work by both moderate and larger telescopes can then be used to evaluate CMD (Color Magnitude Diagram) studies of young GCs, and results from both can be compared with results from the relatively better studied "old" GCs of the Milky Way.

It is still a matter of debate whether MC GLCs are true globular clusters. The dense MC clusters under discussion have been referred to up to this point as GLCs to distinguish them from definitively open clusters, which are not being discussed, but for the remainder of the current discussion, the term "cluster" will refer to these dense potential GC candidates and not open clusters. It is acknowledged that the references to the theory of GC evolution do not constitute an assertion that the debate of the status of these clusters has been settled. This discussion does not yet seek to answer this important question of whether these MC dense clusters truly belong in the class of GCs (or GCs in formation), other than to point out that further work to establish their binary fractions may shed important light on this question.

Theoretical studies of GC evolution emphasize the process of "core collapse" (or "gravothermal collapse") through "mass segregation," where heavier stars migrate towards the center of the cluster and lighter stars evolve outward, perhaps even being ejected from the cluster (Meylan & Heggie 1997; and references therein). In this scenario, a binary system would be considered a "heavier star" for the purposes of mass segregation. Binaries were not considered to be likely constituents of globulars when this theory was first worked out, but now that binaries are a part of the standard GC model a higher fraction of binaries has in fact been found, even including one young LMC globular-like cluster observed by CMD analysis (Elson et al. 1998). A major theoretical puzzle had been what has prevented runaway core collapse, but the existence of binaries in globulars has provided a source of kinetic energy to the core that has been shown to be sufficient to halt gravothermal collapse.

A parameter important to the effect of binaries on globular cluster evolution is the fraction of binaries ("hard" binaries) that have sufficient binding energy to be dynamically important to the evolution of the star cluster. Wilkinson et al. (2003) find in their simulations that the boundary between hard and soft binaries occurs at a separation

of about 120 AU for binaries containing stars of the mean stellar mass in the clusters; they denote the fraction of hard binaries by f_b. In the language of globular evolution theory that characterizes these star clusters in thermodynamic terms, Wilkinson et al. state, "Hard binaries act as heat sources because they become more tightly bound as a result of interactions with single stars and thereby impart kinetic energy to the stars they encounter." Models by Heggie & Aarseth (1992) show a shallower contraction of the density radii of GCs containing primordial hard binaries during core collapse, giving these globulars larger volumes after their evolution than if the binaries were not present.

It is acknowledged that the debate over whether MC GLCs are true GCs has not been resolved. We will simply state that comparative studies of cluster binary fractions may contribute to this debate as well, by either finding Milky Way and MC GLCs to be of related or separate nature; beyond this statement, we present our work with the belief that MC GLCs are sufficiently similar to globular clusters to be referred to as such in this work.

The LMC also has intermediate age GLCs that will also need to be studied to answer the questions presented here. This work, however, chooses the youngest GLCs for our current attention because the differences between the youngest GLCs and MW GCs are likely to be the most dramatic, but further work will necessarily include study of older MC GLCs to provide a complete picture of GLC evolution.

Previously surveyed GCs for photometric binaries include 47 Tuc (Albrow et al. 2001; Kaluzny et al. 1997a, 1998; Edmonds et al. 1997), NGC 6934 (Kaluzny, Olech, & Stanek 2001), M22 (Kaluzny and Thompson 2001), ω Centauri (Kaluzny et al.1997b, 1996), M5 (Yan & Reid 1996), M71 (Yan & Mateo 1994), NGC 6397 (Rubenstein & Bailyn 1996; Kaluzny 1997), M4 (Kaluzny, Thompson, & Krzeminski 1997), NGC 3201 (von Braun 2002), and NGC 4372 (Kaluzny & Krzeminsky 1993), with a compilation of W UMa-type (contact or semi-detached) binary stars compiled and discussed by Rucinski (2000). Most of this

work was done by the conventional technique of first determining the numerical magnitudes and after that looking for periods in the photometric time series, however, Kaluzny, Olech, & Stanek (2001) and Albrow et al. (2001) were able to use image subtraction, after initially starting their analysis with conventional techniques, but after using image subtraction were able to find 6 additional variable stars not found with their previous procedures. The work by Kaluzny, Olech, & Stanek is of particular interest because it was done with a modest sized ground-based telescope (1.2 m).

In addition to seeking binary stars, other variable stars, especially RR Lyr stars, are found in all surveys for cluster binary stars, which, along with the CMDs that are produced, reveal much about GCs. This obvious point must be noted, and analysis of new observations of other variables and CMDs is proposed, but these are such well covered topics that this discussion will focus here on photometric binaries. Nevertheless, it is clear that image subtraction is more effective in finding variables of all types (Kaluzny, Olech, & Stanek 2001), and comparative studies of variable stars in young GCs are lacking compared to the studies of Milky Way GCs such as listed above.

This discussion presents the finding of a second detached eclipsing binary in the region of NGC 1850 (refered to here as "Variable 6" or "V6"); V6 is the first eclisping binary found in the region of the subcluster NGC 1850A. The first eclipsing binary ("Variable 1" or "V1") in the larger region of NGC 1850 was found by in the Optical Gravitational Lens Experiment (OGLE) collaboration's online catalog of LMC eclisping binaries (Udalski 2003). The OGLE group has graciously confirmed that their data show V6 to be an eclipsing binary that was originally missed in their large, comprehensive catalog of MC eclipsing binaries (Udalski 2003; Udalski et al. 1999) (publicly available from the OGLE project website), and data from the much longer-term OGLE project provided a better determination of the period than the current dataset alone (A. Udalski, private communication). Light curves of

the two known NGC 1850 region eclisping binaries, V6 and V1, are presented.

2. Observations and Pre-Processing

Seven nights of observations of a field roughly centered on NGC 1850 were taken during February and March, 2002, with the 0.9 m Cerro Tololo Inter-American Observatory (CTIO) telescope. This analysis is based on 77 300-second exposure frames and 99 100-second I frames obtained through the I_C filter; 16 300-second and seven 100-second V frames through the V_J filter were also taken. These observations are summarized in Table 1. This telescope was equipped with a 2048 $\times$ 2048 Tektronix CCD camera with 0."401 pixel^{-1} plate scale (as measured by Jao et al. 2003).

Bias frames and dome flats were taken at the beginning of each night. All frames were read through four amplifilers, one for each quarter of the frames. The raw data were reduced using the standard Image Reduction and Analysis Facility (IRAF) tasks ZEROCOMBINE and FLATCOMBINE, but in order to combine the four subframes produced by the four amplifiers, the task XCCDPROC, which was then a supplementary IRAF task, was used instead of CCDPROC.

3. Data Reduction and Analysis: Image-Subtraction and Light Curves

Relative photometric light curves for photometric binary stars were extracted using the image-subtraction package ISIS (Alard 2000, 1999; Alard & Lupton 1998), from the I-band data. Image-subtraction was chosen to deal with the highly crowded fields. The use of image-subtraction has allowed previous detections of greater numbers of variable stars over analysis by traditional crowded-field photometry (Bonanos & Stanek 2003), and works especially well in highly crowded fields (Zebrun et al. 2001; Wozniak 2000).

Other authors who have improved their results using image subtraction include Mochejska et al. (2001a,b); Bruntt et al. (2003); Kaluzny, Olech, & Stanek (2001); and Kaluzny & Thompson (2001). Because traditional crowded-field photometry (PSF or aperture fitting) works poorest in crowded fields, finding photometric binaries in dense GCs is well suited for image-subtraction.

Use of the "optimal image-subtraction" method of Alard (1999) and Alard & Lupton (1998) with Alard's ISIS image-subtraction reduction packages requires going through the following steps:

1) Image alignment: A new version of each image is produced that is aligned to one of the images that has been chosen as the grid "reference" image. The alignment is done by matching locations of stars, and can actually work better for moderately crowded field. The matching is done to a fraction of a pixel by interpolation, with the new images not only shifted and rotated but also adjusted (at 2nd, 3rd, or higher order as set by the user) for spatial variation within the image.

2) Reference image creation: From a user-selected list of the best images, one combined reference image is created by stacking the best images but removing inconsistent signals that are likely to be cosmic rays and other defects.

3) Formation of an optimum convolution kernel and image subtraction: For each image, a PSF matching "kernel" image is produced that minimizes least squares differences between each image and the reference image. This is a big improvement over previous methods because it is not necessary to know either the PSF or the backgrounds of individual images. Also, this only requires artificially degrading the seeing of the best images to that of each individual image, rather than as in earlier image subtraction efforts where all images were degraded to the seeing of the worst image. ISIS had difficulty processing the full 13.6 deg $\times$ 13.6 deg frames (only garbled images were output during this step), but ran

successfully when the frames were cropped to 12 deg × 12 deg. On the subtracted images, the constant stars ideally will cancel out, with only signal from variable stars remaining; in practice, residual signal from brighter stars remain, complicating identification of varying stars. Fortunately, true variable stars have smooth difference signals with PSFs resembling that of stars, but in the individual differenced frames, the noise signals have a characteristic wave pattern (as can be seen in Figures 8 and 9). This generally allows truly varying stars to be identified, but the high amount of residual noise in the densely crowded region towards the center of the cluster may be obscuring variable stars that might otherwise be identifiable. The presence of noise from brighter stars can be explained from the brighter stars having a larger noise variation from frame to frame than the background; hence, while the difference between PSFs of faint stars are low enough that the fainter stars' differenced signals fade into the background, the brighter stars' differenced signals still stand above the background. However, this should produce a fairly stellar-like difference signal, not the observed patterned one. Further work is planned to improve the input parameters that ISIS is set to in order to see if this noise can be reduced in ISIS. Examination of ISIS's code has found computer variable usage that may allow introduction of junk data when the program is run on machines with longer variable lengths than the machines for which ISIS was originally programmed. Future examination of this potential problem is planned. While such difficulties have been noted by others, (best described by Bruntt 2003), it is emphasized that ISIS is a powerful tool that has enabled important improvement in variable star detection.

4) Variable star identification: The subtracted images are stacked, from which variable stars stand out well, but defects from a single image also show up. An ISIS routine stacks a second image containing the absolute values of the subtracted images, and the two are correlated. This routine seeks variations that have more than a single increase in an individual image to accept a PSF-fitted region as a candidate variable star, thus rejecting

the majority of cosmic rays. The routine does not do as well at rejecting variation in bad columns, which are recognizable in the numerical output by eye and edited out by hand.

5) Light curve photometry: Lists of the differences photometric light curves as a function of time are produced from the image subtracted images, using both conventional photometric methods of PSF-fitting and aperture photometry. However, because these are created from image subtracted images rather than the original, the differential signal is output, and because the images are relative to a reference image, the values are negative as well as positive. While the disadvantage is that the absolute magnitude of each star is left to be determined after the image subtraction analysis is completed, the advantage is that smaller relative differences from image to image stand out more strongly.

6) Period Finding and light curve fitting: The algorithm of Schwarzenberg-Czerny (1996), optimized for searching for a periodicity in uneven sampled observations employing periodic orthogonal polynomials to fit the light curves is used first to obtain values for the periods, though the periods must be plotted and checked by eye. Subsequently, the Analysis of Variance code written and provided by A. Udalski (Udalski 2003) was found to yield better-fitting periods (both as measured against previously found periods and as measured by eye).

4. Photometric Variable Stars in NGC 1850 Field of View Region

Relative photometric light curves are presented for four stars in the NGC 1850 region, including two cluster eclipsing binary stars, and two cluster Cepheid variables; a nearby LMC field star is presented in the next section. These variables are summarized in Tables 2, 4, and 5, and photometric data on these variables from the OGLE project is listed in Table 3. Among the cluster region stars, two are confirmed detached eclipsing binaries, two

are Cepheid variables

The most significant find is Variable 6 (V6), a detached eclipsing binary with a period of 3.13 days that, unless it is a very coincidentally positioned foreground star, can be expected to be a member of the young subcluster NGC 1850A. Confirming its cluster membership would give V6 an age in the range of the 4 Myr to 6 Myr age of the subcluster reported by Sebo & Wood (1995); Gilmozzi et al. (1994), though Caloi & Cassatella (1998) report an age spread of about 10 Myr. However, it is of current interest that Caloi & Cassatella point out that if massive cluster stars are often members of binary systems, that this larger age spread may not be valid. The light curve of V6 is shown in Figure 10, and the position of V6 is shown in Figure 5. V6 can also be seen in the standard type image used as the reference image, Figure 7. Image subtracted frames for the same region as Figure 7 are shown in Figures 8 and 9. Examination of the image subtracted images at the position of V6 clearly show the stellar-like PSF pattern indicative of a change in magnitude between frames indicative of a variable star. V6 is in a group of a small number of young high luminosity stars that make NGC 1850A's core stand out brightly from the rest of NGC 1850. The strong blending between V6 and the other bright subcluster stars is the likely reason its binary nature was missed by previous surveys. The second eclipsing binary in the cluster region, variable 1 (V1), was previously in the OGLE collaboration's LMC eclipsing binary stars catalog (Udalski 2003), and is also a detached eclisping binary with a 1.48 day period. Its position is shown in Figure 2. Its light curve is shown in Figure 11. Though within the cluster radius, the NGC 1850 region's location in the fairly crowded LMC field will require confirmation of V1's cluster membership.

The luminosities of V6 in B, V, and I magnitudes give partial confirmation that V6 is a member of the NGC 1850 group, though it still could be an LMC foreground star. Using OGLE photometry for V6 listed in Table 3 and the redening value for NGC 1850 from

Gilmozzi et al. (1994) of $E(B-V) = -0.18 \pm 0.12$, the resulting $(B-V)$ value of -0.35 according to Wegner (1994) corresponds to V6 being an O5 (or perhaps earlier) spectral type, for which M_V = -4.88 (Hanson 1997), and the distance modulus is 18.9. This is in reasonable agreement with the LMC mean distance modulus of 18.5 and the NGC 1850 distance modulus of 18.2 (Gilmozzi et al. 1994).

Definitive confirmation of V6 and V1 as cluster members would put the currently known NGC 1850 binary star census at two (both detached). Assuming membership confirmation, obtaining a spectroscopic orbit along with a light curve that can provide a sufficiently accurate orbital solution for these detached eclipsing binaries can provide direct distances to NGC 1850 (Fitzpatrick et al. 2003; Andersen 1991), independent of the Cepheid *P-L* relationship, and V6 has the potential of providing a separate distance measurement to NGC 1850A.

Several previously known Cepheid variables were also clearly seen in the image subtracted current dataset, but this dataset's phase coverage was only sufficient to produce two clear Cepheid light curves, labeled here Variables 2 and 4 (V2 and V4).

V2 is a cluster Cepheid variable with an 8.56 day period, was known to Sebo & Wood and earlier authors (Sebo & Wood 1995), and is listed as SW 58. It is identified in the OGLE internet catalog of LMC Cepheid variables (Udalski et al. 1999) and is in the MACHO LMC survey internet database. The difficulty of getting the magnitude of such core region stars is illustrated by the MACHO data where only 141 of the 1215 B band and 120 of the 530 R band measurements of V2 had errors low enough to use the measurements. (OGLE data obtained over the internet reported few bad measurements but the data's number of "good measurements" varied, and an explanation of the OGLE criteria for good and bad measurements was not found.) Variables 1 and 4 are in similarly difficult to measure crowded regions.

V2 shows brightly in many image subtracted frames such as Figures 8 and 9, where in Figure 8 it is the southwest of the two strongest image subtracted signals in the frame. The other prominent nearby signal is "SW 17" (Sebo & Wood Variable 58), which has a period longer than covered by the current data. Despite being in the cluster core region line-of-sight, Sebo & Wood found SW 17's period-derived luminosity inconsistent with other NGC 1850 Cepheids, particularly V2 (SW 58), indicating that SW 17 is a foreground star (Sebo & Wood 1995).

V4 is another Cepheid variable discovery of OGLE, having a period of 5.57 days (Udalski et al. 1999), and can bee seen in Figure 3, which has had the contrast adjusted to more easily see the bright stars such as V4. The light curve for V4 is shown in Figure 13.

5. LMC Field Eclisping Binary

The light curve of an LMC field eclipsing binary star, variable 3, is shown in Figure 14. It is presented as an excellent example of an eclipsing binary which shows up clearly in image subtracted frames. The three images shown in Figure 6 include two standard light finder images in which V3 can be seen by eye to be of different magnitude, and one image subtracted frame in which the variable signal is apparent. The MACHO project, using traditional photometry, has V3 catalogued on their website but does not identify it as an eclipsing binary. The OGLE project, using image subtraction, was able to identify V3 as an eclipsing binary even though it is on the edge of their frame. The power of image subtraction became apparent when in the very early stages of the image subtraction analysis, this star stood out strongly despite its being significantly fainter than the two or three nearby stars with significant blending; at that time the OGLE finding was not known to the author but the lower level of brightness was apparent to the eye on the MACHO website's light curve of V3. The current data's light curve produced the same 3.1 day period and greater

than 1 magnitude change in brightness, but does not cover the secondary minimum. A nearby LMC field eclipsing binary which has sufficient dimming to be apparent to the eye in printed images is shown in Figure 6, along with its image subtracted image in which a clearly stellar-like PSF can be seen at its position in a field where most other stars are subtracted out, except for residual noise at the positions of brighter stars. Its light curve phased for a 3.11 day period, confirmed by the OGLE catalog, is shown in Figure 14.

6. Binary Fraction

It is difficult to estimate the fraction of eclipsing binary stars that would be found with the current data set's limited phase coverage. If cluster membership is confirmed for the detached eclipsing binary in the cluster region, then it would indicate a binary fraction greater than zero. In addition to the two stars deep within the cluster region presented here, additional varying stars were found whose periods could not be determined from the current data.

The fraction of stars that are eclipsing binary stars in the neighboring region of the LMC could also be determined if the current data were extended with more observations, to allow for a comparison of the density of binary stars in the cluster region and outside the cluster region. A higher density of binary stars within the cluster region would be evidence that some of them would be members, even without conclusively determining cluster membership.

7. Future Work: Binary Fraction

The limited phase coverage needs to be filled in by additional observations, for which the current procedure with a similar 1-m class telescope would allow a beginning

determination of the binary fraction of NGC 1850. In addition to the two stars of uncertain status presented here, additional variable stars were found for which the phase coverage was too incomplete to determine periods and phased light curves. Additional observations would allow definitive identification of these additional variable stars. The phase coverage of the current data has missed the large fraction of eclipsing binaries that did not eclipse during observed times. Longer observational runs would extend the period range for which eclipsing binaries could be found. This direct detection of eclipsing binaries needs to be accompanied by a CMD analysis for binaries. With larger telescopes, the image-subtraction procedure would be better able to separate more stars, especially in the crowded cluster center, from the larger telescopes' better defined PSFs. Also, the current survey is limited to the cluster's brightest stars; larger telescopes would obtain a more representative sampling of stellar types. For the best resolution of this crowded regions, space-based observation would greatly improve the ability to determine the binary fraction among a fuller range of spectral types.

Determinations of binary fraction of clusters are all magnitude limited and thus may be a function of stellar luminosities. To adequately compare Milky Way and LMC GLC's binary fractions, it will need to be determined if the binary fractions of the more nearby clusters change when only the brighter stars are considered. Of particular concern is the question of cluster membership, which is a significant difficulty in the generally crowded MC regions, as illustrated by the bright Cepheid variable's probable status as a foreground star (Sebo & Wood 1995). Other properties of clusters such as how crowded each cluster is may add additional biases, along with the ever-present observational biases. While the time evolution of GLC binary fraction is presented as a crucial astrophysical question, the effects of other cluster properties on binary fraction will likely need to be studied first. The question of the effect of GLC properties other than age on binary fraction are, however, of interest to cluster dynamical evolution in their own right. Because of the strong influence

binaries play in cluster evolution, binary fraction measurements in clusters will be valuable for improving and constraining models of cluster origin and evolution.

The current discussion has focused on the youngest LMC clusters, which are the most different from MW GCs and larger differences can be expected between young objects, but it will also be important to include study of the intermediate age MC clusters to best evaluate the connection between these MC clusters and the more familiar old GCs.

The current work shows that the binary fraction of a GC much younger than Milky Way GCs can be directly addressed with current techniques, in addition to CMD analysis. Extension of binary fraction measurements to young clusters, even in regions of crowded stellar fields, is now possible.

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Table 1: Number of observations used in analysis from observation period of 20-23 February and 03-05 March 2002, according to exposure time (seconds) and I or V band filter.

Filter	Exposure	Frames
I	100	99
I	300	73
V	100	7
V	300	16

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Table 2: Variables' Properties, using preliminary OGLE III data (Udalski 2003; Udalski et al. 1999), (personal communication). The amplitudes of the eclipsing binaries without given error values may be larger as not enough data points were available to definitively measure the minima (see figures).

Variable	Period (d)	I Magnitude	Amplitude(s) (I)	ID
1	1.48	16.2	0.7, 0.6	...
2	8.86	13.7	0.5	SW 58
3	3.11	16.7	1.7, 1.1	...
4	5.57	13.4	0.2	...
6	3.13	14.2	$0.35, 0.25$	...

Table 3: Variables' OGLE II photometry (Udalski 2003; Wyrzykowski et al. 2003; Udalski et al. 1999), (from OGLE ftp site linked from OGLE website, file lmc_sc11.map). OGLE II photometry has been more rigorously calibrated than the current preliminarily OGLE III photometry, hence the values differ some from the previous table.

Variable	V	$B-V$	$V-I$	B	I
1	18.1	0.07	-0.07	18.2	18.2
2	14.7	0.70	0.74	15.3	13.9
3					18.27
4	14.5	0.47	0.61	15.0	13.9
6	14.4	-0.17	-0.16	14.2	14.6

Table 4: OGLE, MACHO, and previous identifiers of Variables

Variable	ID	MACHO ID	OGLE ID
1	...	...	OGLE050842.01-684456.1
2	SW 58	MACHO 1.4540.17	LMC118.2 18259
3	...	...	LMC110.7 1437
4	...	...	OGLE050846.31-684539.7
6	...	...	LMC_SC11 162262

Table 5: Positions of Variables, JD 2000

Variable	Frame X Y	R.A. (2000.0) Decl.
1	1149 706	05 08 42.01 -68 44 56.1
2	1132 797	05 08 43.25 -68 45 31.76
3	93 628	05 09 59.80 -68 44 25.3
4	1090 812	05 08 46.31 -68 45 39.7
6	1189 827	05 08 42.01 -68 44 56.1

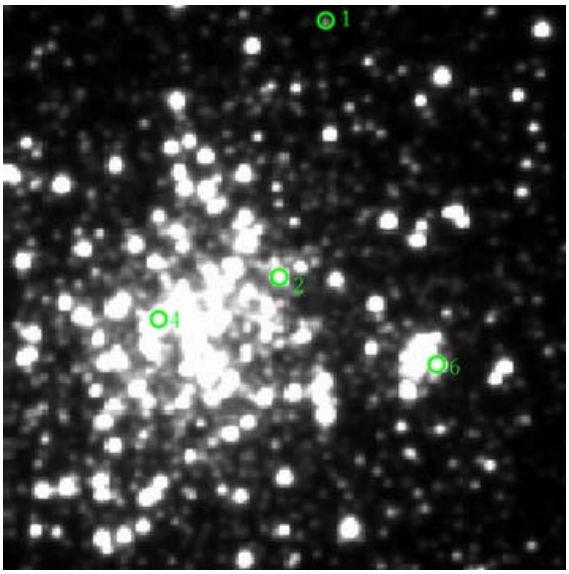

Fig. 1.— Finder chart for the variables discussed in the region of NGC 1850, Variables 1,2,4, and 6, with North up and East left.

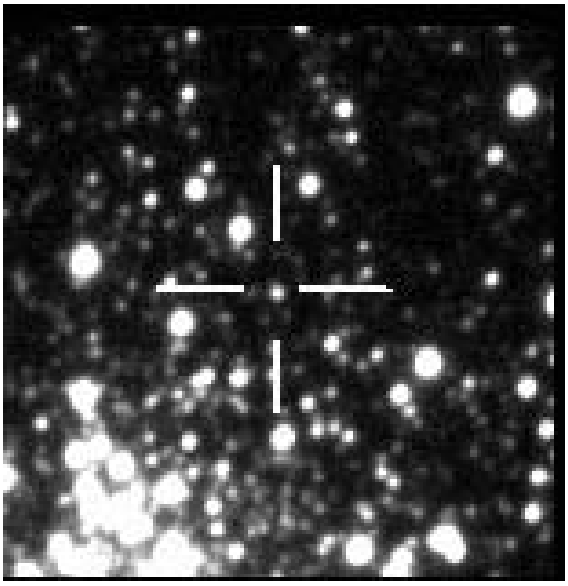

Fig. 2.— Finder Chart for V1, a detached eclipsing binary in the region of NGC 1850, in a 60 arcsec square field, with North up and East left.

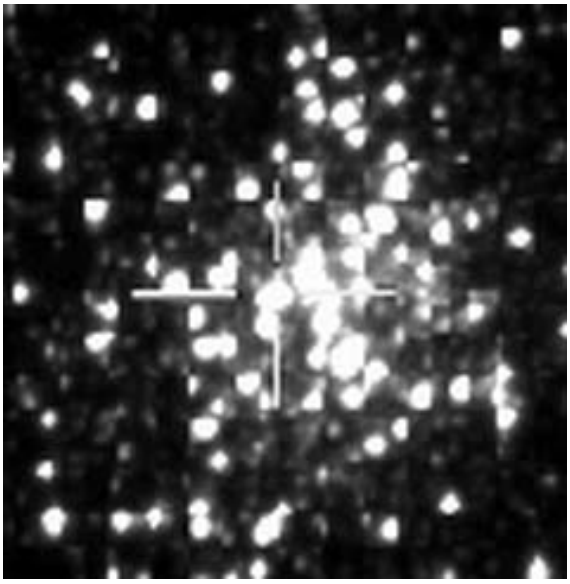

Fig. 3.— Finder Chart for V4, deep inside the NGC 1850 region, in a 60 arcsec square field, with North up and East left. The contrast has been adjusted such that the bright stars of the core region of NGC 1850 can be seen well here.

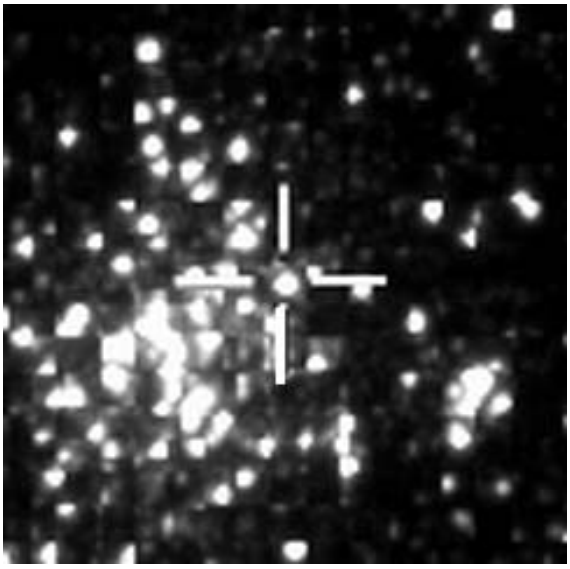

Fig. 4.— Finder chart for V2 (OGLE Cepheid LMC_SC11 250938) in a 60 arcsec square field, with North up and East left.

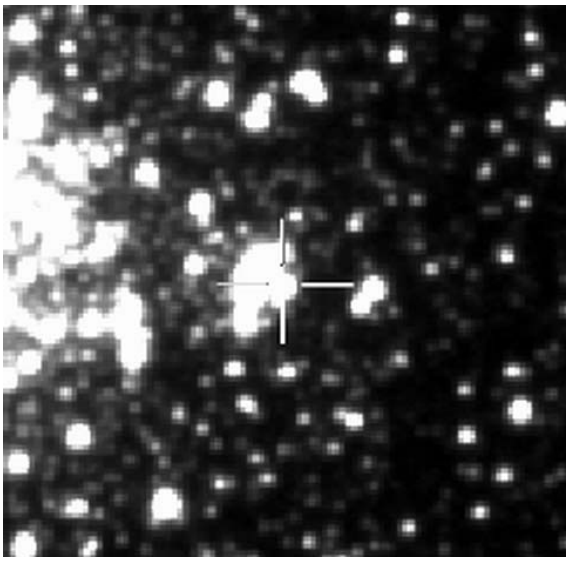

Fig. 5.— (Temporarily using four-variable plot until produce separate finder for V6.) Finder chart for V6 in a 60 arcsec square field, with North up and East left.

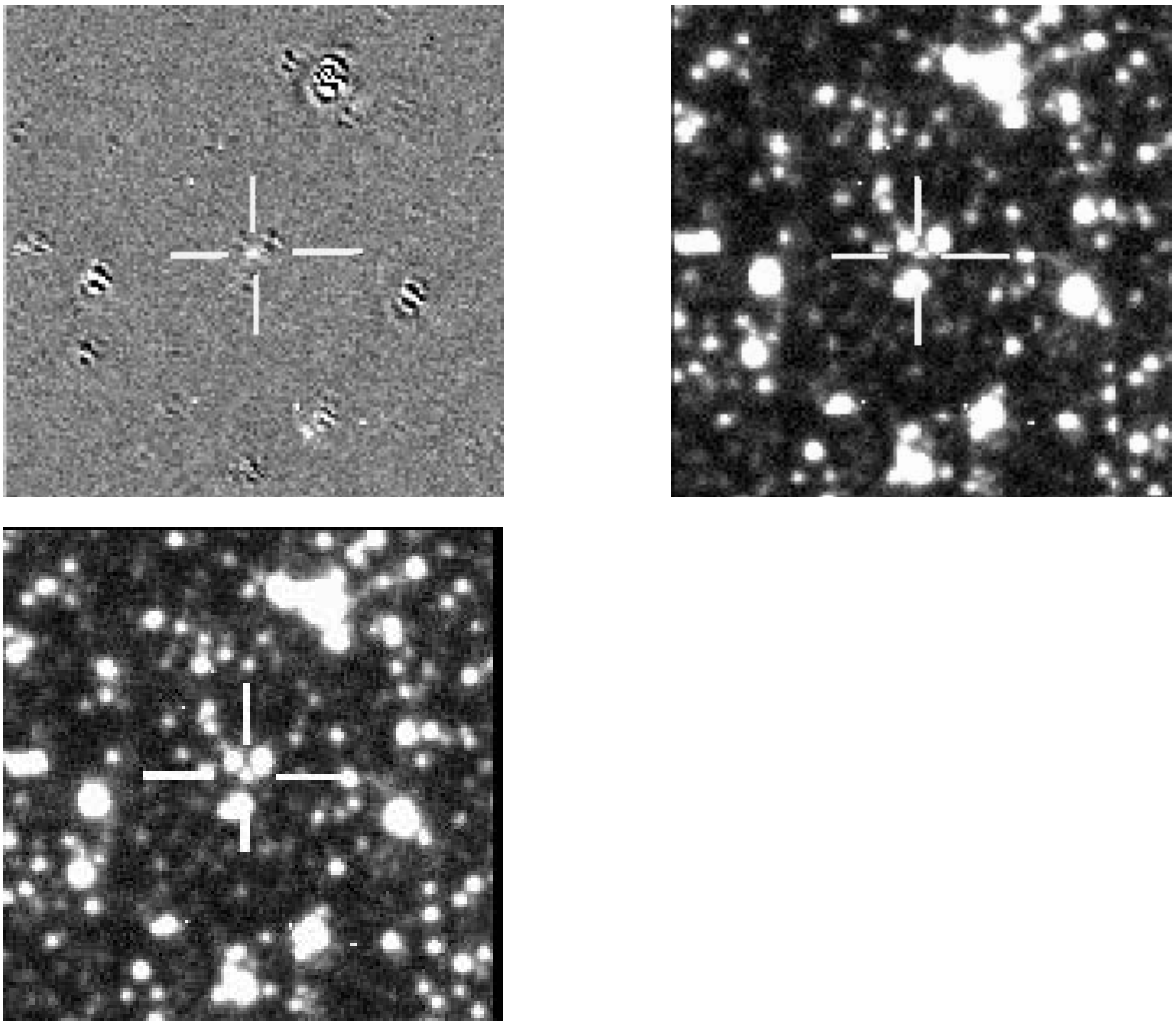

Fig. 6.— The detached eclipsing binary found among LMC field stars in the field of view of NGC 1850 frames stands out clearly in the image-subtracted image, the first of these three images. In the last two images, this system's roughly 1 magnitude drop is sufficient to show up more clearly than most variable stars in the visual images. (These images were cropped to position the eclipsing binary star at the center of each image.) In the image-subtracted image, it can be seen how well the majority of stars are subtracted to the level of the background but how brighter stars leave a characteristic noise residual signal. The truly varying star gives a clearly stellar-like signal that continues for the images during the eclipse (as opposed to a few noise spots that appear in only one image). This star is clearly brighter in the middle image than during the eclipse eight days earlier seen in the last image. The image-subtracted image of this star's variation shows up clearly despite this star's image being blended with images of neighboring stars. (North is up, east is left.)

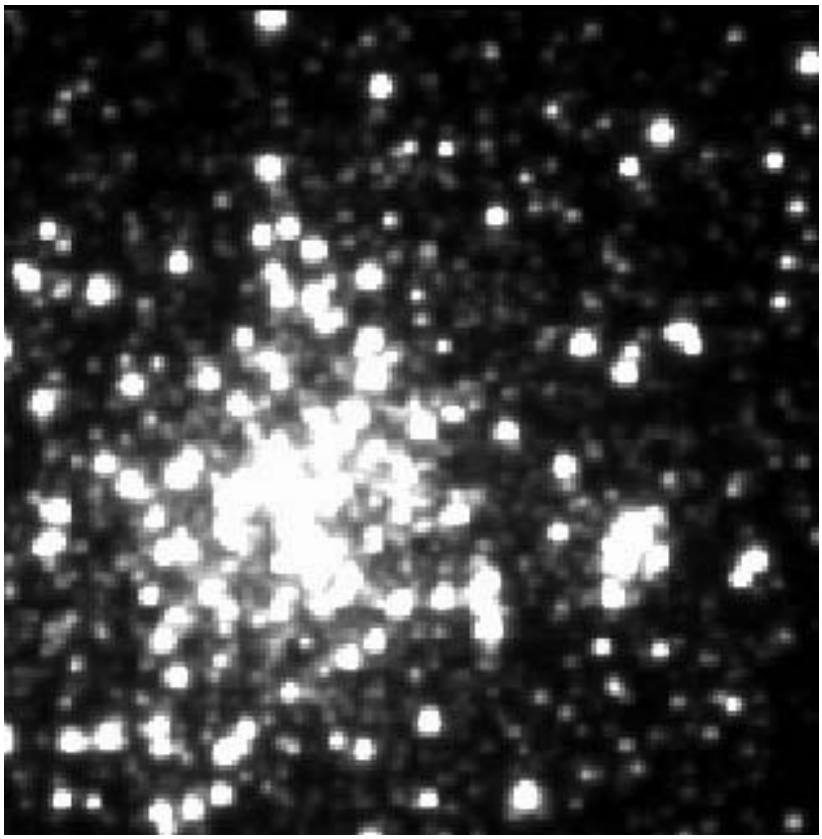

Fig. 7.— Central region of NGC 1850, including NGC 1850A, in an 80 arcsecond square frame (north up, east left).

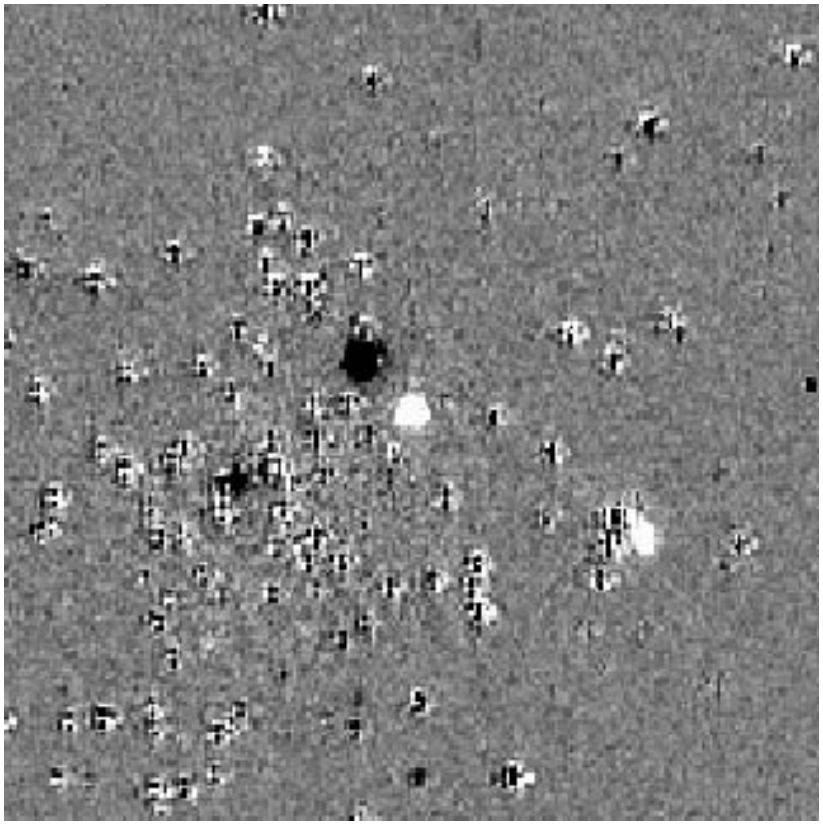

Fig. 8.— Image subtraction of central region of NGC 1850, including NGC 1850A, in an 80 arcsecond square frame (north up, east left), in which V6, V2, and SW 17 stand out strongly, and V4 is apparent as well. This image is near minima of V6 and V2 (which show as bright PSFs, from defining the reference image as positive from which the individual image is subtracted; thus, stars such as SW 17 and V4, which at this time are brighter than in the reference image appear black, and stars dimmer than the reference image appear white).

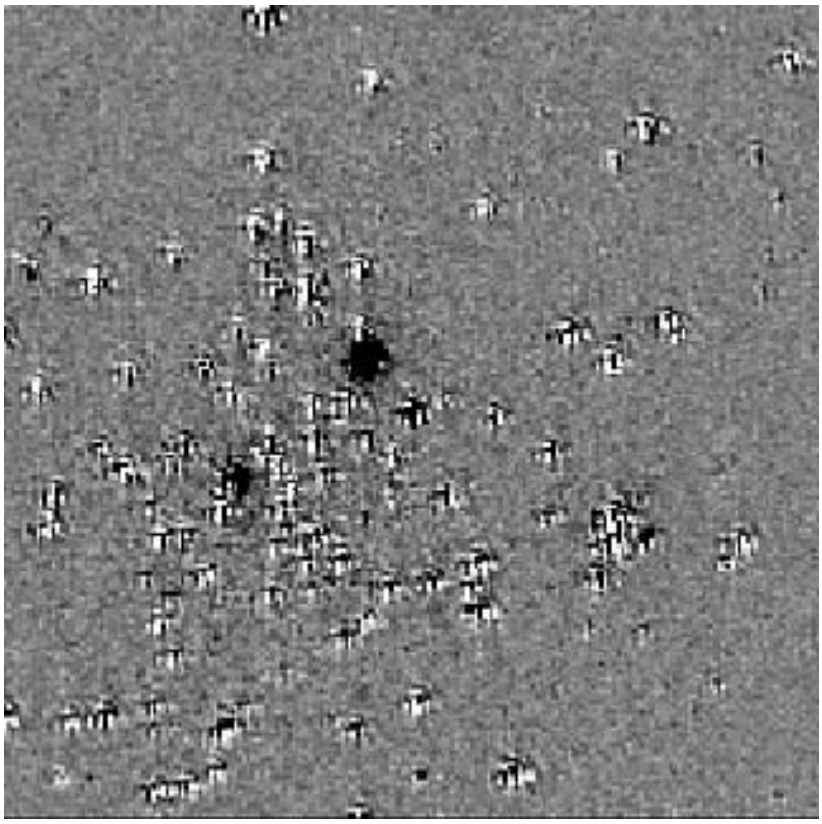

Fig. 9.— Image subtraction of same NGC 1850 central region, when variable 6 can be seen to be slightly darker than (and thus the star is brighter at this time) than at the time of the reference image. (V4 and V2 are also brighter than in the reference image.)

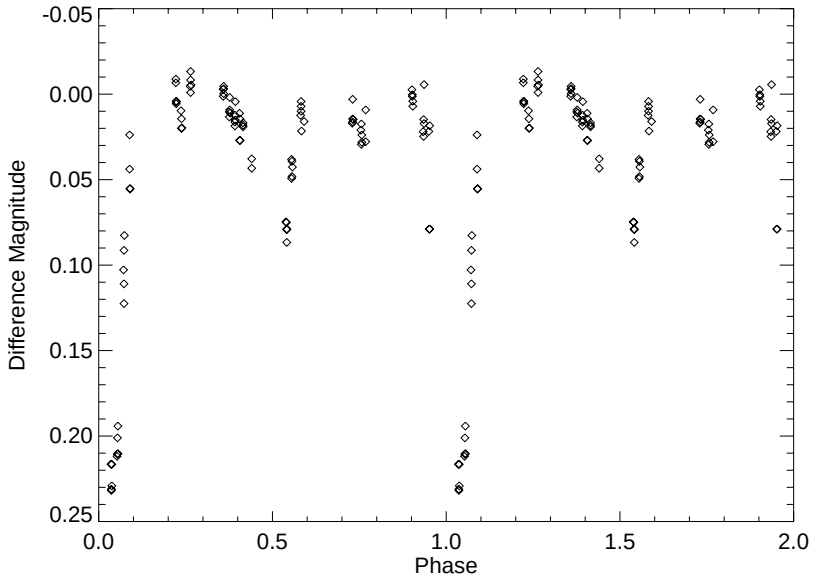

Fig. 10.— Difference magnitude for phased light curve variable 6, a newly-found detached eclipsing binary in the central region of the young subcluster of NGC 1850 referred to as NGC 1850A.

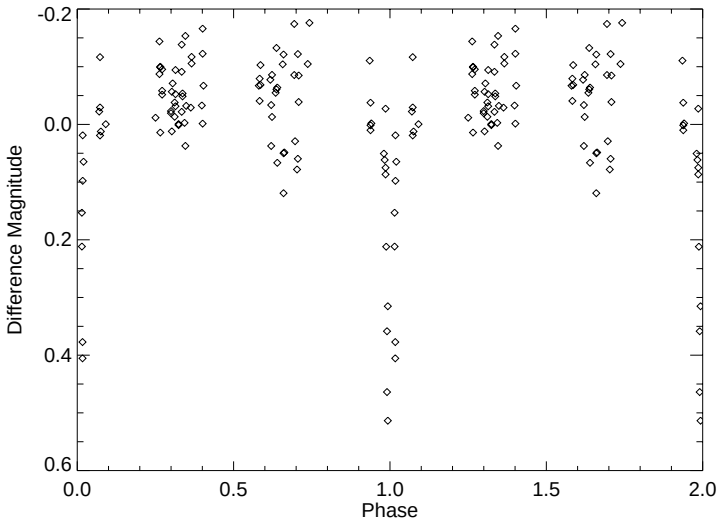

Fig. 11.— Difference magnitude phased light curve for variable 1, a detached eclisping binary likely in the region of NGC 1850.

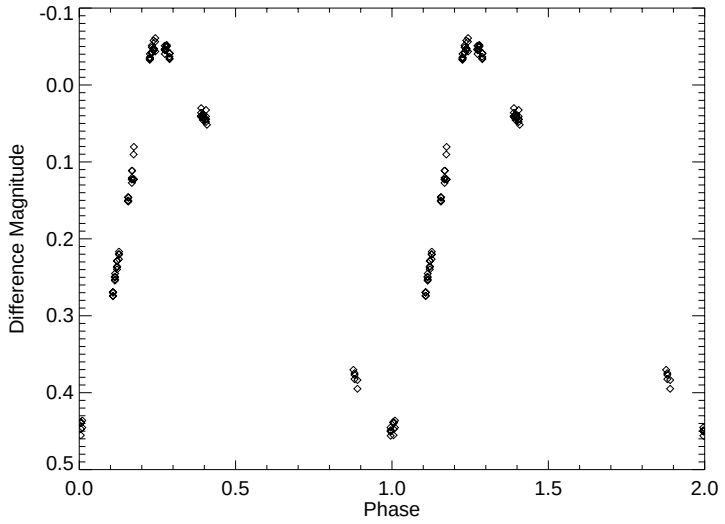

Fig. 12.— Difference magnitude phased light curve for variable 2, a Cepheid variable that is not only in the line-of-sight region of NGC 1850, but also that Sebo & Wood (1995) found a period-derived luminosity consistent with the distance of the cluster.

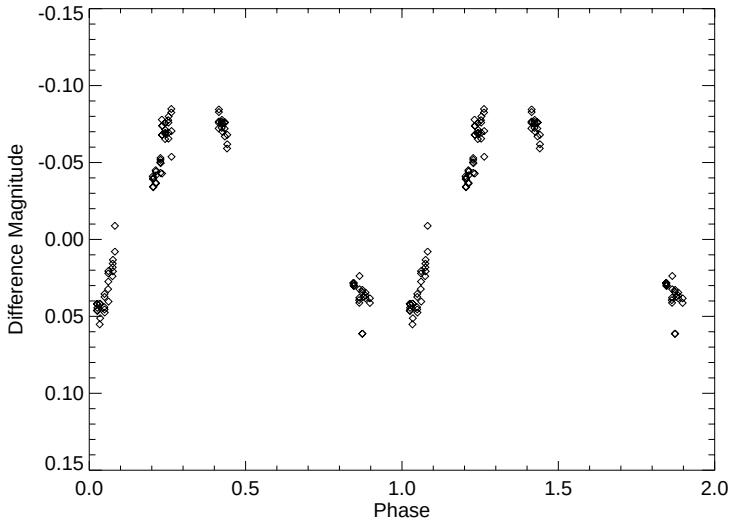

Fig. 13.— Difference magnitude phased light curve for variable 4, a Cepheid variable also in the OGLE Cepheid Variables online catalog (Udalski et al. 1999).

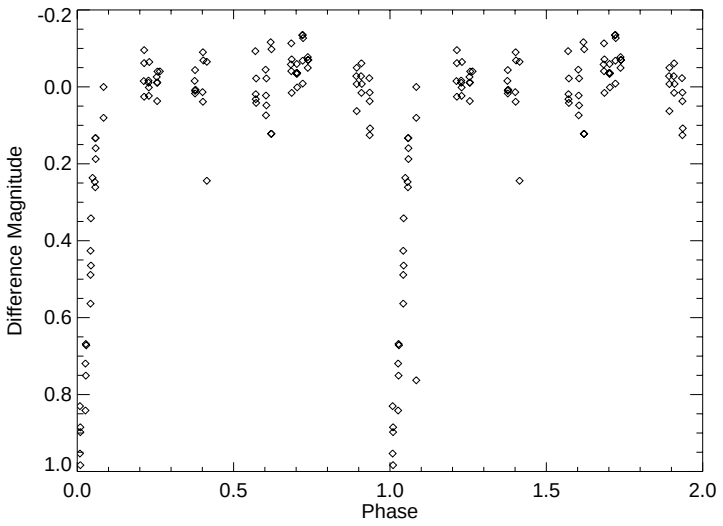

Fig. 14.— Difference magnitude phased light curve for variable 3, an LMC field detached eclisping binary with dramatic dimming, but which has a PSF that is badly blended with brighter neighboring stars.