Eclipsing Binaries in the Young Large Magellanic Cloud Cluster NGC 1850

STUART F. TAYLOR

Center for High Angular Resolution Astronomy (CHARA), Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303; taylor@chara.gsu.edu

Received 2004 September 14; accepted 2004 October 15; published 2004 November 15

ABSTRACT. I present light curves for two detached eclipsing binary stars in the region of the LMC cluster NGC 1850, which is possibly a young globular cluster still in formation. One, a likely O-type star, is a newly detected eclipsing binary in the region of the very young subcluster NGC 1850A. This binary is among a small number of highly massive O-type stars in binary systems found in LMC clusters. These two eclipsing binaries are the first to be discovered in the well-studied NGC 1850, and the O-type star is the first eclipsing binary found in NGC 1850A. Light curves for two Cepheid variables in the NGC 1850 region are also shown. The discovery of two eclipsing binaries in the young globular-like cluster NGC 1850 is discussed in terms of the importance of the binary fraction to globular cluster evolution.

1. INTRODUCTION

Binary stars influence globular cluster evolution to a far greater degree than has long been believed (Meylan & Heggie 1997; Hut et al. 1992). Once thought not to exist in numbers significant enough to influence the evolution of globular clusters (GCs), binary stars are now seen as providing energy to GC single stars and halting core collapse. Not only has the importance of binary stars to theoretical studies increased, but observers are now detecting globular cluster binaries, overturning earlier observational reports that GCs do not contain significant numbers of primordial 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, which has LMC globular-like clusters (GLCs, also called “young, globular-like stellar associations”) such as NGC 1850 and NGC 1818, with ages on the orders of 10^7 or even 10^6 yr. Preliminary observational work has led to the discovery of some binaries in the field near these clusters (Sebo & Wood 1995), but surveys are needed in order to compare the binary fraction of these “young” GLCs with that of the better studied but older Milky Way GCs.

Observations are needed to address the central question of how binaries affect the dynamical evolution of young globular-like clusters. The detection reported here of two eclipsing 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.

I present new time series imaging of the LMC cluster NGC 1850 and an analysis of photometric variables using image subtraction methods. I present four light curves for NGC 1850 region systems. First, I discuss the finding of a second detached eclipsing binary in the region of NGC 1850 (referred to here as “Variable 5” or “V5”), which is the first eclipsing binary found in the region of the subcluster NGC 1850A. Next, I present an eclipsing binary (“Variable 1” or “V1”) in the larger region of NGC 1850, which was found by the Optical Gravitational Lens Experiment (OGLE) collaboration (Udalski 2003); its light curve is also presented here. The OGLE group has graciously confirmed that their data show V5 to be an eclipsing binary that was originally missed in their large, comprehensive catalog of MC eclipsing binaries (Udalski et al. 1999; Udalski 2003; publicly available from the OGLE project Web site), and the data from the much longer term OGLE project have provided a better determination of the period than the current data set alone (A. Udalski 2004, private communication).

2. OBSERVATIONS AND PREPROCESSING

Seven nights of observations of a field roughly centered on NGC 1850 were taken during 2002 February 20–23 and March 3–5 with the 0.9 m Cerro Tololo Inter-American Observatory (CTIO) telescope. These observations were taken in the “Cousins I” band (I_c) and are summarized in Table 1. The telescope was equipped with a 2048 x 2048 Tektronix CCD camera with a 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 amplifiers; one

1 See http://sirius.astrouw.edu.pl/~ogle.
for each quarter of the frame. The raw data were reduced using the standard Image Reduction and Analysis Facility (IRAF\(^2\)) tasks ZEROCOMBINE and FLATCOMBINE. The task XCCDPROC was used to combine the four subframes produced by the four amplifiers.

### 3. DATA REDUCTION AND ANALYSIS: IMAGE SUBTRACTION AND LIGHT CURVES

Relative photometric light curves for photometric binary stars were extracted from the \(I\)-band data using the image subtraction package ISIS\(^3\) (Alard & Lupton 1998; Alard 1999, 2000). Image subtraction was chosen to deal with the highly crowded fields because it is more effective than traditional photometry for the detection of variable stars (Bonanos & Stanek 2003), and it works especially well in highly crowded fields (Wozniak 2000; Zebrun et al. 2001).

The “optimal image subtraction” method of Alard (1999) and Alard & Lupton (1998) using Alard’s ISIS image subtraction reduction packages requires the following steps:

1. **Image alignment**: A new version of each image is produced, which is then aligned to one of the images that has been chosen as the grid “register” image. The alignment is done by matching locations of stars and can actually work better for a 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 for spatial scale variation within the image.

2. **Reference image creation**: From a user-selected list of the best seeing 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 point-spread function (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 that the seeing of the best images are artificially degraded to that of each individual image, rather than as in earlier image subtraction efforts, in which all images were degraded to the seeing of the worst image. ISIS had difficulty processing the full 13.6 \(\times\) 13.6 frames, but ran successfully when the frames were cropped to 120 \(\times\) 120. On the subtracted images, the constant stars ideally will cancel out, with only a signal from the variable stars remaining (Fig. 1); in practice, residual signals from brighter stars remain, complicating identification of varying stars. Fortunately, true variable stars have smooth difference signals with PSFs resembling that of stars, while imperfections in the PSFs of bright stars create residuals with a characteristic wave pattern (shown in Fig. 1). This generally allows truly varying stars to be identified, but the high amount of residual noise in the densely crowded region toward the center of the cluster may obscure variable stars that might otherwise be identifiable. The presence of noise from brighter stars is a consequence of their 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 out above the background.

4. **Variable star identification**: From the subtracted images, images of the normalized mean absolute deviation are stacked to create a variable star-finding image in which variable stars stand out well, but defects from a single image also show up. The ISIS software identifies variations that have more than a single increase in an individual image in order 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 variations from bad columns, but these are easily recognizable by eye and edited out by hand.

5. **Light curve photometry**: Differenced 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. A list file of these light curves, giving positions and other properties of the light curves, is also generated. Because these light curves are created from image-subtracted images rather than the original, the differential signal is outputted, and because the images are relative to a reference image, the values are negative as well as positive. While the disadvantage of image subtraction is that the 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 (Schwarzenberg-Czerny 1996), optimized for searching for a periodicity in unevenly sampled observations, is used to obtain preliminary values for the periods, although 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).

For each variable star light curve presented here, the differentiated

### Table 1

| Number of Observations |
|-------------------------|
| Filter | Exposure Time (s) | Number of Frames |
| \(I_c\) | 100 | 99 |
| \(I_c\) | 300 | 73 |

\(^{2}\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

\(^{3}\) Available at http://www2.iap.fr/users/alard/package.html.
Fig. 1.—Reference image of NGC 1850 (left) along with the same region from an image subtraction frame (right). These images show the central region of NGC 1850 in an 80 arcsec$^2$ frame (north is up, east is left). The central region of the main body of NGC 1850 is seen below left of center, and NGC 1850A is the small cluster of stars to its right. The subtracted image is the difference between the reference and individual images. Stars such as V5 and V2, which were brighter during the time of the reference image, show as white PSFs, while stars such as SW 17 and V4, which were brighter during the time of this particular frame, appear as black PSFs. V2 and SW 17 stand out as a pair near the center of the image, with strong residual PSFs (SW 17 is the prominent black PSF and V2 is the prominent white PSF). V5 is the prominent white PSF on the right side of NGC 1850A. V4 is also apparent as a black PSF slightly left of the main NGC 1850 body’s center. V1 was not in eclipse during either time, and thus leaves no PSF in this subtracted image.

flux counts $F_{\text{difference}}$ are divided by the normalized flux counts from the reference image $F_{\text{ref}}$ using PSF profile-fitting photometry. (ISIS outputs aperture photometry counts as well.) The magnitude difference $\Delta m$ is the usual $2.5 \log (F_{\text{difference}}/F_{\text{total}})$.

A detailed description of using ISIS in practice is given by Bruntt$^4$ (2003).

4. PHOTOMETRIC VARIABLE STARS IN NGC 1850 FIELD-OF-VIEW REGION

Here I present relative photometric light curves for four stars in the NGC 1850 region, including two detached eclipsing binary (EB) stars (V1 and V5) and two Cepheid variables (V2 and V4). Data for a nearby LMC field star are presented in § 5. These variables are summarized in Tables 2–5, which extensively use data from the OGLE project (Udalski et al. 1999; Udalski 2003), obtained online and through the gracious private communication of A. Udalski (2003). Both OGLE II and OGLE III data were used; OGLE II data for its more rigorous absolute calibration, and the still preliminary OGLE III data for its better relative precision. Table 2 gives the periods of the variables to within roughly 0.01 day and the amplitudes of the variation, with errors of less than 0.1 mag. For the eclipsing binaries, the two values are for the primary and secondary eclipses. Table 3 gives the variables’ OGLE II photometry in $V$, $B$, and $I$ magnitudes.

The most significant find is V5, a detached eclipsing binary with a period of 3.13 days that, unless it is a very coincidentally

4 Available at http://astro.phys.au.dk/~bruntt/tuc47.html.

| Variable | Variable Type | Period (days) | Amplitude(s) |
|----------|---------------|---------------|--------------|
| 1        | Detached EB   | 1.48          | 0.7, 0.6     |
| 2        | Cepheid       | 8.56          | 0.5          |
| 3        | Detached EB   | 3.11          | 1.7, 1.1     |
| 4        | Cepheid       | 5.57          | 0.2          |
| 5        | Detached EB   | 3.13          | 0.35, 0.25   |

| Variable | $V$          | $B$          | $I$          | $B-V$         |
|----------|--------------|--------------|--------------|---------------|
| 1        | 18.09 ± 0.17 | 18.16 ± 0.20 | 18.16 ± 0.13 | +0.07         |
| 2        | 14.65 ± 0.36 | 15.34 ± 0.24 | 13.91 ± 0.15 | +0.70         |
| 3        | ...          | ...          | 18.02 ± 0.65 | ...           |
| 4        | 14.49 ± 0.11 | 14.97 ± 0.09 | 13.89 ± 0.07 | +0.47         |
| 5        | 14.40 ± 0.12 | 14.23 ± 0.10 | 14.55 ± 0.08 | −0.17         |
TABLE 4

OGLE, MACHO, and Previous Identifiers for Variables

| Variable ID | MACHO ID | OGLE ID |
|-------------|----------|---------|
| 1           |          | OGLE 050842.01–684456.1 |
| 2           | SW 58    | LMC 118.2 18259 |
| 3           |          | LMC 110.7 1437 |
| 4           |          | OGLE 050846.31–684539.7 |
| 5           |          | LMC_SC11 162262 |

positioned LMC foreground star, is probably a member of the young subcluster NGC 1850A. The subcluster has an age in the range of 4 to 6 Myr, as reported by Sebo & Wood (1995) and Gilmozzi et al. (1994), although Caloi & Cassatella (1998) report an age spread of about 10 Myr. However, Caloi & Cassatella point out that if massive cluster stars are often members of binary systems, then this larger age spread may not be valid. The position of V5 is shown in Figure 2, and the light curve of V5 is shown in Figure 3.

V5 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 V5 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, V1, was previously noted in the OGLE collaboration’s LMC eclipsing binary star catalog (Udalski 2003) and is also a detached eclipsing binary with a 1.48 day period. Its position is shown in Figure 4, and its light curve is shown in Figure 5. Although it is 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 B, V, and I magnitudes give partial confirmation that V5 and V1 are members of the NGC 1850 group, because as shown below, their luminosities are consistent with the LMC mean distance modulus of 18.50 ± 0.13 (Panagia et al. 1991), although they still could be LMC foreground stars. I use the Gilmozzi et al. (1994) reddening value of $E(B-V) = 0.18 \pm 0.02$ mag for NGC 1850, which gives an interstellar extinction of $A_v = 3.1E(B-V) = 0.56 \pm 0.06$ mag. Using the OGLE II photometry of $m_v = 14.40 \pm 0.12$ mag for V5, this interstellar extinction and distance modulus gives an absolute magnitude of $M_v = -4.66 \pm 0.19$. For a single star, $M_v = -4.7$ corresponds to V5 as spectral type O5 or O6 (Hanson et al. 1997). Being binary, V5 could have a primary between $M_v = -4.7$ and $-3.9$ mag, going from the case of a dim secondary to the case of a pair of equal luminosity type O8 stars. Spectral types O5/O6 have $(B-V) = -0.30$ mag, and spectral type O8 has $(B-V) = -0.285$ mag (Wegner 1994). OGLE II photometry gives the B magnitude of V5 as $14.23 \pm 0.10$, which gives a raw $(B-V) = -0.17 \pm 0.15$ mag. When adjusted for reddening, V5 has a resulting measured $(B-V)$ value of $-0.35 \pm 0.15$ mag, which is only slightly

TABLE 5

Positions of Variables: 2000

| Variable | R.A. | Decl. |
|----------|------|-------|
| 1        | 05 08 42.01 | -68 44 56.1 |
| 2        | 05 08 43.17 | -68 45 33.2 |
| 3        | 05 09 59.80 | -68 44 25.3 |
| 4        | 05 08 46.31 | -68 45 39.8 |
| 5        | 05 08 38.94 | -68 45 45.7 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

Fig. 2.—Finder chart for V5 in a 60 arcsec$^2$ field; north is up, and east is left.

Fig. 3.—I-band difference magnitude for phased light curve of V5, a newly found detached eclipsing binary in the central region of the young subcluster of NGC 1850, referred to as NGC 1850A.
higher than the \((B-V) = -0.30\) mag expected from an O5 magnitude star at NGC 1850’s reddening value. [Other authors’ LMC distance moduli vary more than this \(\pm 0.12\) mag error, and \((B-V)\) values are not definitive for O stars, so V5 could be an earlier or later type O star, which would not change the distance conclusion here.] While the magnitudes are consistent with V5 being an NGC 1850 member, the difference between NGC 1850’s (and NGC 1850A’s) distance modulus and that of the LMC is not well known (Gilmozzi et al. 1994), so the measured values would also be consistent with V5 being an LMC background star. Since only its LMC membership is established, confirmation of the membership of V5 in NGC 1850A is important for using V5 to study NGC 1850A.

Similarly, the OGLE photometry of V1 \((m_\text{r} = 18.09 \pm 0.17\) mag) and the LMC distance modulus and the NGC 1850 interstellar reddening used above give V1 an \(M_\text{r} = -0.97 \pm 0.22\) mag, corresponding to a type B2 to B3 star (dim secondary), which have \((B-V) = -0.23\) to \(-0.18\) mag, ranging to a pair of \(M_\text{r} = -0.2\) mag type B5 stars, which have \((B-V) = -0.15\) mag (Wegner 1994). The OGLE photometry for V1 yields a \(B\) magnitude of \(18.16 \pm 0.20\), which gives a raw \((B-V) = 0.07 \pm 0.26\) mag that, when adjusted for reddening, is \((B-V) = -0.11 \pm 0.27\) mag. This is in good agreement with the LMC distance modulus, although V1 will require further study to exclude the possibility of its being an LMC foreground star.

Definitive confirmation of V5 and V1 as cluster members would put the currently known NGC 1850 binary star census at two (both detached). It would be worthwhile to obtain spectroscopic orbits that, combined with light curves, would provide direct distances to NGC 1850 and NGC 1850A (Andersen 1991; Fitzpatrick et al. 2003). Determination of separate distances to V1 and V5 has the potential of providing distance measurement between the main body and NGC 1850A, and also a better measurement of NGC 1850’s position within the LMC. This is especially important, as “double” or “multiple” clusters in the LMC have a significant chance of being merely chance superposition (Dieball et al. 2002).

Spectra that could provide an accurate spectral type for V5 would be of special interest, as it is one of only a relatively small number of early to middle type-O binaries known. A recent catalog of spectroscopic binary orbits published up to 2001 June (the CHARA spectroscopic binary catalog; Taylor et al. 2003)\(^5\) is available and lists 70 type-O star orbits among its total of 2353 orbits, with 12 of these stars being type O6 and earlier, nine of type O7, 19 type O8, and 25 type O9. In 2002, new orbits were published by Massey et al. (2002), bringing an additional three orbits for stars of massive type O3 and one of type O5, but the number of young detached stars with known masses at the highest stellar masses remains small (Gies 2003).

In addition to the early-type binaries described above, several previously known Cepheid variables were also clearly seen in the current image-subtracted data set. However, the phase coverage was only sufficient to produce two clear Cepheid light curves, labeled here as V2 and V4.

V2 is a cluster Cepheid variable with an 8.56 day period. It was known to Sebo & Wood and earlier authors (Sebo & Wood 1995) and is listed as SW 58. It is identified in the OGLE online catalog of LMC Cepheid variables (Udalski et al. 1999) and is in the MACHO LMC survey Internet database.\(^6\) The position of V2 is shown in Figure 6, and its light curve is shown in Figure 7. The difficulty of measuring the magnitude of a star in such a crowded core region of stars is illustrated by the MACHO data, in which only 141 of the 1215 \(B\)-band measurements and 120 of the 530 \(R\)-band measurements of V2

\(^5\) Available at http://www.chara.gsu.edu/~taylor/catalogpub.

\(^6\) See http://wwwmacho.mcmaster.ca.
had errors low enough to be usable. V1 and V4 are in similarly crowded, difficult-to-measure regions.

V2 shows brightly in many image-subtracted frames, such as Figure 1 (right), where it is the southwest-most object of the two strongest image-subtracted signals in the frame. The other prominent nearby signal is “SW 17” (Sebo & Wood Variable 17), which has a longer period than was covered by the current data. Despite being in the cluster core region, SW 17’s period-derived luminosity was found by Sebo & Wood (1995) to be inconsistent with other NGC 1850 Cepheids, particularly V2 (SW 58), indicating that SW 17 is a foreground star.

V4 is another Cepheid variable discovery of OGLE, having a period of 5.57 days (Udalski et al. 1999), and is shown in Figure 8, in which the contrast has been adjusted to more easily see the bright stars such as V4. The light curve of V4 is shown in Figure 9.

5. THE LMC FIELD ECLIPSING BINARY

The light curve of an LMC field eclipsing binary star, V3 (finder chart Fig. 10), is shown in Figure 11. It is presented as an excellent example of an eclipsing binary that shows up clearly in image-subtracted frames. The MACHO project, using traditional photometry, has V3 cataloged on their Web site, 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 in the very early stages of the image subtraction analysis, when 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 Web site’s light curve of V3, and the star’s dimming is apparent in the original images). The current light curve produced the same
Fig. 9.—$I$-band difference magnitude phased light curve of V4, a Cepheid variable also in the OGLE Cepheid variables online catalog (Udalski et al. 1999).

3.11 day period and greater than 1 mag change in brightness, but does not cover the secondary minimum.

6. MOTIVATION: GLOBULAR CLUSTER EVOLUTION

Study of MC GLCs is needed to answer the question of whether they represent a younger stage of GC evolution, or if they are really dense open clusters unrelated to true GCs. Studies to determine whether young GLCs, intermediate-age GLCs, and “old” Milky Way GCs have related binary fractions could help answer this question. Comparisons of observations against models of the binary fraction during GC evolution, such as studied by Fregeau et al. (2003), are also needed. This would include both color-magnitude diagram analyses (such as Elson et al. 1998) and the somewhat more direct method of finding binary fractions from measurements of the fraction of stars that are eclipsing binaries.

Previously surveyed GCs for photometric binaries include 47 Tuc (Albrow et al. 2001; Kaluzny et al. 1997a; Kaluzny 1998; Edmonds et al. 1996), NGC 6934 (Kaluzny et al. 2001), M22 (Kaluzny & Thompson 2001), $\omega$ Cen (Kaluzny et al. 1996, 1997b), M5 (Yan & Reid 1996), M71 (Yan & Mateo 1994), NGC 6397 (Rubenstein & Bailyn 1996; Kaluzny 1997), M4 (Kaluzny et al. 1997c; Ferdman et al. 2004), NGC 3201 (von Braun & Mateo 2002; von Braun 2003), NGC 4372 (Kaluzny & Krzeminski 1993), M10 (von Braun 2003), and M12 (von Braun 2003), with a compilation of W UMa–type (contact or semidetached) binary stars compiled and discussed by Rucinski (2000). GC binary fractions have also been studied using *Chandra* in the X-ray region (including Pooley 2003). Most of the photometric work was done by the conventional technique of first determining the numerical magnitudes and then looking for periods in the photometric time series. However, Kaluzny et al. (2001) and Albrow et al. (2001) were able to use Alard & Lupton’s improved method of image subtraction (Alard & Lupton 1998; Alard 1999, 2000). They started their analysis with conventional techniques, but after using image subtraction were able to find six additional variable stars not found using their previous procedures. The work by Kaluzny et al. is of particular interest, because it was done with a modest sized ground-based telescope (1.2 m). Other authors who have improved their results using image subtraction include Wozniak (2000), Mochejska et al. (2001a, 2001b), Kaluzny et al. (2001),...
Zebrun et al. (2001), Kaluzny & Thompson (2001), and Brunett et al. (2003). 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. Comparative studies of variable stars in young GLCs are lacking compared to studies of Milky Way GCs, such as those listed above.

Observations with both moderate size and larger telescopes can then be used to evaluate CMD studies of young GCs, and results from both can be compared with results from the relatively better studied “old” GCs of the Milky Way.

7. FUTURE WORK: BINARY FRACTION

The current work shows that the binary fraction of a GLC much younger than Milky Way GCs can be directly addressed with current techniques, in addition to CMD analysis. Because of their importance to the study of GC evolution, longer duty-cycle surveys of MC GLCs are needed to determine the binary fraction of stars in NGC 1850 and similarly dense MC clusters in order to understand whether these binary fractions are consistent with dynamical models of GC evolution, and whether MC GLC and Milky Way GC binary fractions as a function of age follow a consistent pattern. Spectroscopic study of V5 and V1 would provide important data about the distance to the well-studied GLC NGC 1850. These observations demonstrate than an extension of binary fraction measurements to young clusters, even in regions of crowded stellar fields, is now possible.

I am grateful to Alberto Miranda and the staff at the National Science Foundation’s Cerro Tololo Inter-American Observatory, in particular Edgardo Cosgrove, Manuel Hernandez, and Malcolm Smith, for their assistance. The generous encouragement and support of research at Georgia State University under Harold A. McAlister is acknowledged. The support for use of the CTIO 0.9 m telescope by Todd Henry and the SMARTS Consortium is also gratefully acknowledged. CHARA members Doug Gies and William Bagamalo provided helpful discussion. Computer network support by John McFarland, Rajesh Deo, James P. Kinney III, and Ginny Mauldin-Kinney is appreciated. This research was supported by a Research Program Enhancement grant from the Georgia State University Research Office. This paper utilizes work from the OGLE project (Udalski et al. 1999; Udalski 2003; Wyrzykowski et al. 2003) and public domain data originally obtained by the MACHO Project, whose work was performed under the joint auspices of the US Department of Energy, National Nuclear Security Administration, by the University of California, Lawrence Livermore National Laboratory, under contract No. W-7405-Eng-48, the National Science Foundation through the Center for Particle Astrophysics of the University of California, under cooperative agreement AST-8809616, and the Mount Stromlo and Siding Spring Observatory, which is part of the Australian National University. I appreciate the contributions of analysis code, OGLE data, and valuable suggestions from Kaspar von Braun, Michael Reid, Hans Bruntt, Barbara J. Mochejska, Virginia McSwain, Christophe Alard, and Andrzej Udalski.

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