TIME SERIES PHOTOMETRY OF M67: W URSAE MAJORIS SYSTEMS, BLUE STRAGGLERS, AND RELATED SYSTEMS

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ABSTRACT

We present an analysis of over 2200 V images taken on 14 nights at the Mount Laguna 1 m telescope of the open cluster M67. We show variability in the light curves of all four known W UMa variables on timescales ranging from a day to weeks. We have modeled the light curve of AH Cnc, and the total eclipses allow us to determine q = 0.16 ± 0.03 and i = 86.4 ± 0.4 deg. The position of this system near the turnoff of M67 makes it useful for constraining the turnoff mass for the cluster. We have also detected two unusual features in the light curve of AH Cnc that may be caused by prominences. We have also monitored cluster blue stragglers for variability. We present evidence hinting at low-level variations in the stragglers S1040, S968, and S1263, and we place limits on the variability of a number of other cluster blue stragglers. Finally, we provide photometry of the subgiant branch star S1063 showing variability on timescales similar to the orbital period, while the “red straggler” S1040 shows evidence of an unexplained drop in brightness at phases corresponding to the passage of the white dwarf in front of the giant.

Key words: blue stragglers — open clusters and associations: individual (NGC 2682)

1. INTRODUCTION

Thanks to high stellar densities and small velocity dispersions, stellar clusters stand out as environments with high frequencies of strong gravitational interactions between stars. In the cores of the densest globular clusters, collisions of single stars may occur relatively frequently (Hills & Day 1976). However, even for less active environments such as open clusters, strong interactions between binary stars probably play an important role in modifying the orbital parameters of the binaries and facilitating stellar collisions (Hurley et al. 2001; Portegies Zwart et al. 2001). Current thinking identifies blue stragglers as one kind of the likely products of stellar interactions, so that an in-depth understanding of these stars could lead to a better understanding of the overall importance of environmental effects within stellar clusters (see Bailyn 1995 for a review).

As a by-product of our project to monitor the partially eclipsing blue straggler S1082 (designation from Sanders 1977), we made extensive observations of the fields around the core of the open cluster M67. To get complete coverage of the light curve of S1082 (period 1.0677978 days) observations over several nights needed to be made. After it was discovered that the light curve was variable on timescales of a month or less, our observational data set was expanded further. The observations of that system are presented and analyzed in a separate paper (Sandquist et al. 2003). However, in combination with the large archive of radial velocity measurements for M67 stars (e.g., Milone & Latham 1994), photometric studies of blue stragglers can provide us with important clues to their current states and may also lead to an understanding of the evolutionary route they followed before becoming identifiable blue stragglers. W Ursae Majoris variables are one class of binary star that can produce blue stragglers after angular momentum losses cause the two stars to coalesce.

M67 is a somewhat difficult target for comprehensive variability studies because of its large angular size, but several groups have presented results for the cluster. For example, Gilliland et al. (1991) combined relatively deep observations from several different observatories in a study of the core of the cluster. They serendipitously discovered two W UMa variables (S1036 and III-79), two blue stragglers with low-amplitude δ Scuti pulsations (S1280 and S1284), and evidence of longer period variations in other stars. Their field was relatively small, however, so that it was nearly certain that other variables would be found. Recently van den Berg et al. (2002, hereafter vSVM) and Stassun et al. (2002, hereafter SvMV) presented photometric studies of variables in a larger field in M67. Their studies were initiated to look for variability among the X-ray sources within the cluster. Several of the known X-ray sources were shown to be low-amplitude variables, and photometry was presented for an additional W UMa variable (S757).

The present study complements these photometric studies in several ways. In a number of instances we are able to present better delineated light curves than vSVM and SvMV because we took shorter exposures and focused on observations in a single filter band. In addition, by combining our results with those of the other studies we are able to build a better picture of the variability of the light curves themselves on timescales ranging from days to decades for some of the better known variables. In § 2 we briefly describe the observations, in § 3 we discuss the reduction of the photometry, and in § 4 we discuss the variables.
2. OBSERVATIONS

All the photometry for this study was taken at the 1 m telescope at the Mount Laguna Observatory using a 2048 × 2048 CCD on 19 nights between 2000 December and 2002 March. The nights of observations are given in Table 1. The photometry was primarily in V band with typical exposure times of 20 s (ranging between 15 and 60 s depending partly on atmospheric transparency) to optimize the counts for the variable S1082. Exposures were usually separated by about 2.5 minutes because of a relatively long readout time for the CCD.

Guiding jitter and poor air flow at the site of the telescope typically restrict image quality to greater than 4 pixels (1.56) in the best conditions. Observing conditions for the nights varied greatly, reaching FWHM of 13 pixels for some of the worst frames. The relative sparseness of the cluster worked in our favor though because decent photometry could still be done for many of the stars in the field.

Several hundred columns of the chip developed charge transfer problems during the 2000 December run. Because of this, measurements of stars that fell near these columns were eliminated. The remainder of the chip was not noticeably affected by this problem. In the 2001 January and February runs this problem was almost entirely corrected. The CCD was replaced for the 2001 March run and a two-amplifier readout was employed, which doubled the duty cycle for our observations. For the remainder of the observations the replacement CCD was used with a one-amplifier readout.

3. ANALYSIS

3.1. Photometric Reduction

The object frames were reduced in the usual fashion, using overscan subtraction, bias frames, and flat fields (usually twilight flats, with the exception of 2000 December 11/12 and 2001 February 17/18 and 18/19, for which dome flats had to be used). We chose to rely on aperture photometry for this study. In the analysis we used the IRAF1 tasks DAOFIND and PHOT from the APPHOT package. Curve-of-growth analysis was conducted using the IRAF tool DIGIPHOT.PHTCAL.MKAPFILE to bring all photometric measurements to the same total aperture size. The general procedure is described in Stetson (1990). Individual nights were run separately through the curve-of-growth analysis.

To improve the accuracy of the relative photometry for the light curves, we used an ensemble photometry method similar to that described by Honeycutt (1992) to get a simultaneous solution for median magnitudes of all stars and relative zero points for all image frames. Our implementation is described in more detail in Sandquist et al. (2003). The solution was improved iteratively until none of the frame zero points or median star magnitudes changed by more than 0.0005 mag between iteration steps. We allowed for the possibility that magnitude residuals could be a function of star position on the CCD for each frame by fitting second-order polynomials to the residuals in the x and y directions and subtracting these fits during the solution iteration. Occasionally these corrections amounted to a few centimagnitudes.

In reducing the data, we paid close attention to possible correlations of residuals with external variables such as seeing, air mass, sky intensity, exposure time, and the photometric zero point of the frame (see Gilliland et al. 1991 for a detailed discussion of the reasons). During the photometric reductions, we discovered that the photometry of a handful of the bluest stars in the sample showed significant variations of approximately 0.02 mag from night to night. On further investigation, we found that for several of these stars the photometric variations around the median values were definitely correlated. Although we have been unable to determine the exact cause of this problem, we were able to verify that the correlations in the variation were detectable only in stars with B − V ≤ 0.3. In our sample this affected the blue stragglers S752, S968, S977, S1066, S1263, and S1267. None of these stars had strong variations, but to look for low-amplitude changes we computed a running weighted average of the residuals derived from all the stars observed on a frame and on up to six other frames closest in time. The correction was subtracted from the brightness measurement for each star. The results of this analysis will be discussed in more detail in §4.2.2.

3.2. Variability Analysis

To judge the significance of observed photometric variations, we used two different measures: the rms variations about the median magnitude σV and the Welch-Stetson index IWS (Welch & Stetson 1993). IWS measures the degree of correlation of pairs of brightness measurements, and is generally the more sensitive method of the two for detecting variability. This index gives high scores for previously known variables, with the δ Scuti star S1280 (a variable of low amplitude) having the lowest score (IWS = 2.55). In Figure 1, we plot both measures as a function of magnitude

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1 IRAF (Image Reduction and Analysis Facility) is distributed by National Optical Astronomy Observatory, which is operated by Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
for the stars in our samples to provide the reader with a means of judging the significance of the variations discussed below. This is complicated by the fact that seeing variations could result in correlated residuals for a star if a nearby star of comparable brightness contributed light to the aperture used to photometer the star. The variability indices plotted in Figure 1 were calculated for measurements with the best seeing (FWHM > 5) to reduce this confusion, although some of the stars with high scores are still affected by this effect. However, for the objects discussed in this paper we verified that there is no correlation between the photometric residuals (defined as observed minus median magnitude) and seeing.

We used two different techniques to determine periods for the variables we observed: the Lafler-Kinman statistic (Lafler & Kinman 1965, hereafter L-K), and the Lomb-Scargle (Scargle 1982, hereafter L-S) periodogram. These two statistical methods measure slightly different characteristics of trial light curves. The L-K statistic measures the quality of a light curve for a given trial period by using the sum of the differences in magnitude between observations made at adjacent phases. Variations in the overall brightness of the system on different orbits can cause problems with this test, however. The L-S periodogram is basically a harmonic decomposition of the observations.

3.3. Light-Curve Analysis

For the systems with the most stable light curves, we modeled the light curve using the program NIGHTFALL,\(^2\) which includes model atmospheres (Hauschildt, Allard, & Baron 1999) and physical effects such as detailed reflection (which is important for close binaries). Detailed fitting of the eclipsing binaries requires some care in choosing the prescription for limb darkening. Significant systematic differences in parameters such as mass ratio and inclination can result from this choice. We have chosen to use a two-parameter square root law primarily because the use of linear or quadratic limb darkening laws resulted in significantly higher \(\chi^2\) values due to poor fits to the eclipses for our variables. Our choice is supported by comparisons between predictions from model atmospheres and best-fit limb-darkening laws (Van Hamme 1993; Díaz-Cordovés, Claret, & Giménez 1995) that indicate that square root or logarithmic laws are to be preferred for stars with surface temperatures near those of our W UMa variables.

4. LIGHT CURVES

In this section, we discuss the important features of the light curves of the variable stars we detected. Unless otherwise listed, the ID numbers are from Sanders (1977). A color-magnitude diagram for the systems discussed below is shown in Figure 2.

4.1. W UMa Contact Binaries

Four W UMa binaries are currently known to be members of M67. We present observations of all these systems below, and we list their properties in Table 2.

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\(^2\) See http://www.lsw.uni-heidelberg.de/~rwichman/Nightfall.html for the program and a user manual (R. Wichmann 1998, NIGHTFALL Users Manual).
properties of M67 W UMa systems

| ID        | S757         | S1036 (EV Cnc) | S1282 (AH Cnc) | III-79 (ET Cnc) |
|-----------|--------------|----------------|----------------|-----------------|
| $T_0$     | 2,451,800.129| 2,450,500.047  | $^a$           | 2,450,000.036   |
| $P$ (days) | 0.35967 ± 0.00002 | 0.441437 ± 0.000003 | 0.360452$^{a,b}$ | 0.2704$^d$ |
| $\Delta V_p$ | 0.08         | 0.13           | 0.39           | $\geq 0.17$    |
| $\Delta V_e$ | 0.06         | 0.06           | 0.33           | 0.11            |
| $T^\prime$ | 13.51        | 12.81          | 13.44          | 15.90           |
| $B-V$     | 0.61$^b$     | 0.50$^c$       | 0.52$^a$       | 1.11$^e$        |
| $i$ (deg) | $\sim 35$   | 86$^c$         | 0.16$^{a,b,0.01}$ | ...            |
| $q$       | ...          | ...            | ...            | ...             |

$^a$ Period known to vary with time; see ephemeris of Kurochkin 1979.
$^b$ vsVM.
$^c$ Gilliland et al. 1991.
$^d$ Average $V$ magnitudes from observations in this study.
$^e$ SvMV.

S757: This star was slightly outside the field analyzed by Gilliland et al. (1991) but was identified as a probable variable star by both Nissen, Twarog, & Crawford (1987) and Rajamohan et al. (1988). SvMV discuss their identification of this system as a W UMa variable based on a likely period of 0.3600 days and color $B-V = 0.61$. They presented a partial light curve generated from two runs in 1998 and 2000 that indicate maxima and minima of roughly equal brightness. We independently identified the system and are able to refine the period to $P = 0.35967 ± 0.00002$ days from two seasons of data. In this case we found that the best period from the L-K method was in a smaller peak in the L-S periodogram. The amplitude of the light curve in $V$ is approximately 0.08 mag, although this does vary from month to month. Regardless, the small amplitude indicates that the system has a fairly low inclination ($\sim 30^\circ$). Our data phased to this best period are shown in Figure 3.

Figure 4 shows our most nearly complete single-day light curves. The observations from 2001 January in particular show significant changes in the light curve from night to night. The relative heights of the maxima clearly changed between 2000 December 7 and 2001 January 30, with phase 0.25 slightly brighter than phase 0.75 in December, but about 0.05 mag fainter in January. The magnitude level of the secondary eclipse is the portion of the light curve that seems to remain the most constant. The month timescale of these variations leads us to believe that the cause is starspots. Spots have been hypothesized on many of W UMa systems in connection with unequal brightness of the two maxima (generally called the O’Connell effect; O’Connell 1951). The case of S757 adds an additional wrinkle because the maximum following the primary eclipse did change from being brighter than the other maximum to being fainter (generally called a variable O’Connell effect). This could indicate that either there are significant spots present on both components or that hot and cool spots appeared on one component of the binary. We tend to believe the former explanation because the levels of the two maxima do not appear to remain at constant brightness. Because we focused on $V$-band observations, we do not have enough information to conduct a more detailed analysis of the temperatures of hypothesized spots. In any case, the fact that we are unable to establish the true brightness of the maximum of the light curve makes a derivation of reliable system parameters nearly impossible.

In spite of the apparent spot activity, S757 was not detected as an X-ray source in the cluster by Belloni, Verbunt, & Mathieu (1998). Both of the other W UMa systems of comparable brightness (S1036 and S1282) were detected. $L_X/L_{bol}$ increases with increasing color for field stars, which implies that S757 should be brighter than S1282 in X-rays. The periods of the two systems are very nearly the same, which means that differences in the rate of rotation are not likely to account for differences in X-ray activity. In addition, S757 falls in the region where the two X-ray fields of Belloni et al. overlap, meaning that there was a longer total integration on S757. There does not appear to be any unidentified X-ray sources in the vicinity of S757, so we are unable to explain the nondetection.

S1036 (EV Cnc): S1036 is classified as a blue straggler because accurate photometry shows it to be about 0.1 mag in $B-V$ to the blue of the cluster turnoff. Gilliland et al.
binary S757. Successive light curves have been offset by 0.07 mag.

In Table 2, we include measurements of eclipse depths $D$ which is hard to understand if the stars are in contact. In difference in temperature for the two stars, something

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be seen in Figure 5. For eclipsing binaries a difference in temperature for the two stars still have different brightness. vSVM saw

the two maxima differ in brightness by approximately 0.09 mag, as can be seen in the figure, there is very little correlation between $i$ and mass ratio $q$ (which is very poorly constrained). We checked for correlations between inclination and spot parameters and found that they were minor. The primary degeneracy is between $i$ and the filling factor $f$. The light curve clearly allows for solutions covering the range of filling factors observed for most contact binaries ($0 < f < 0.5$; Rucinski 1997). The reader should keep in mind that Figure 6 (right) was computed for a constant set of spot parameters, and some adjustment of these could reduce the $\chi^2$ value for a given combination of $i$ and $f$. Thus, solutions with the component stars detached should very much be considered to be viable. If the system is in contact, however, the inclination can be constrained to be $30^\circ < i < 38^\circ$.

At least one spot appears to be necessary in models of the light curve because the shallower minimum is misplaced away from the expected position at phase 0.5 and the two maxima still have different brightness. vSVM saw no evidence for variation in color during the orbit, although their quoted upper limit on the color variation

model a single light curve. This is true of S1036 as well. However, to check on the possibility that the determination of a subset of the system parameters might be robustly determined from these models, we first determined a set of system and spot parameters that fits the system well ($\chi^2 = 0.98$) and then proceeded to compute grids of models varying two parameters at a time. This baseline solution had $q = 0.50$, $i = 32.0^\circ$, $f = 0.47$, and two spots (spot 1: facing us at phase 0.52, radius 30", dimming factor 0.72; spot 2: facing us at phase 0.23, radius 38", dimming factor 0.80). The filling factor is $f = (C_1 - C_i)/(C_1 - C_2)$, where $C_i$ is the Jacobi potential of the common envelope and $C_1$ and $C_2$ are the corresponding potentials of the L1 and L2 points. We provide $\chi^2$ contour maps for two of these experiments in Figure 6.

As can be seen in the figure, there is very little correlation between $i$ and mass ratio $q$ (which is very poorly constrained). We checked for correlations between inclination and spot parameters and found that they were minor. The primary degeneracy is between $i$ and the filling factor $f$. The light curve clearly allows for solutions covering the range of filling factors observed for most contact binaries ($0 < f < 0.5$; Rucinski 1997). The reader should keep in mind that Figure 6 (right) was computed for a constant set of spot parameters, and some adjustment of these could reduce the $\chi^2$ value for a given combination of $i$ and $f$. Thus, solutions with the component stars detached should very much be considered to be viable. If the system is in contact, however, the inclination can be constrained to be $30^\circ < i < 38^\circ$.

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(1991) determined the period to be 10.59 hr. vSVM redetermined the period to be 0.44144 ± 0.00001 days, and they note that this does not appear to be consistent with the Gilliland et al. value, although they could not judge how significant this was because Gilliland et al. did not quote an error. Using the vSVM data in combination with our own, we are able to improve the determination of the period very slightly. Both the L-K and L-S methods agree on slightly lower but different periods. The L-S result appears to phase the data slightly better, and the measured light-curve parameters are presented in Table 2.

The asymmetry in the light curve of S1036 makes it somewhat unusual: for a contact binary with uniform surface temperature, the light-curve minima should have equal brightness. For S1036, the two maxima differ in brightness by approximately 0.02 mag. The two light-curve minima also differ in brightness by approximately 0.09 mag, as can be seen in Figure 5. For eclipsing binaries a difference in brightness of the light-curve minima normally implies a difference in temperature for the two stars, something which is hard to understand if the stars are in contact. In Table 2, we include measurements of eclipse depths $\Delta V_p = V_{p,\text{min}} - V_{\text{max}}$ and $\Delta V_s = V_{s,\text{min}} - V_{\text{max}}$, where $p$ and $s$ refer to primary and secondary minima, and $\maxref$ refers to the global maximum of the light curve.

We conducted limited modeling of S1036 using the program NIGHTFALL (see § 3.3 for details of the code). Two factors conspire to prevent definitive determination of system parameters from the light curve: low inclination and the possibility of spots. For warnings about deriving system parameters from low-inclination systems, see Rucinski (2001) and the discussion related to the system S1282 below. The asymmetries in the light curves of W UMa variables have led many researchers to model these systems with spots, usually with no more than two spots. However, there are potentially many combinations of spot parameters (spot latitude, longitude, size, and dimming factor) that can

![Fig. 4.—Most nearly complete single-day $V$ light curves for the contact binary S757. Successive light curves have been offset by 0.07 mag.](image1)

![Fig. 5.—Phased $V$ light curves for the contact binary S1036, separated by month of observation. Top: Data from van den Berg et al. (2002). Zero phase was chosen to be the photometric minimum. Our best-fit light-curve model is plotted with the 2000 December data.](image2)
was 0.05 in $B-V$. The limits on color variations placed by the vSVM data do not distinguish between the possibilities that (1) the surface temperatures of the stars are equal and the differences in maximum and minimum brightness are entirely due to cold spots or (2) there are one strong cold spot, which explains the differences in maximum brightness, and a large temperature difference between the two stars, which explains the differences in minimum brightness. However, neither hypothesis predicts color variations of more than about 0.01 mag, so much more accurate color information is needed to constrain the models strongly. As a result, we did not attempt to do a more systematic study of the binary parameters using our photometry. During our observations, we did detect slight variations in the shape of the light curve from month to month, although they are not as noticeable as those seen for S757. Given that the timescales for variations in the light curves of the other W UMa variables discussed in this paper are in the range of months or years, studies of the light curve of S1036 over a longer time baseline could help determine whether starspots are the primary factor in determining the light-curve shape.

S1282 (AH Cnc): With data from the studies of Whelan et al. (1979) and Gilliland et al. (1991), there are currently good data sets covering the entire light curve of this W UMa system for three epochs separated by over a decade. Gilliland et al. noted that both minima in the light curve appeared to have changed from curved and continuously varying (possibly indicating partial eclipses) in the Whelan et al. data set to flatter (indicating total eclipses) in their data set. Our light curves closely resemble those of Gilliland et al.: one flat-bottom eclipse covering approximately 0.1 in orbital phase and a slightly deeper and more curved primary eclipse.

Figure 7 shows our observations along with those of vSVM and Whelan et al. (1979). We have phased our observations by using the ephemeris of Kurochkin (1979), which includes a second-order time term, although we have added a phase shift of 0.5 to bring the deeper minimum to phase 0.
The deeper minimum in the Whelan et al. data is not the deeper minimum in later data according to this ephemeris. As can be seen in the observations of Whelan et al., the minima were at approximately the same brightness level in 1973. The Kurochkin ephemeris does a good job of phasing the observations of vVSM with ours, clearly illustrating the necessity of using the second-order term. We had to include an additional phase shift of 0.04 to our data and those of vVSM to bring the primary minimum to phase 0, which indicates that the ephemeris needs to be revised. (We should note that the zero point of the vVSM data appears to be different from that of our data. Shifting their data according to the difference between our median \( V \) magnitude [13.44] and their average \( V \) magnitude [13.54; SvMV] we find that the light curves differ by 0.05 mag. The difference is partly due to the difference between the median and average for this light curve. For Figure 7, we simply added a magnitude correction to their data to make comparison of the light curves easier.)

Based on the appearance of the eclipses in our data, the system is clearly an A-type W UMa binary (the deeper eclipse being a transit of the larger star by the smaller star, as seen from the curvature of the light curve near phase 0) rather than W-type as identified by Whelan et al. Given the position of S1282 near the turnoff of M67 in the color-magnitude diagram, it might have been predicted that it should be an A-type system since they are generally believed to have evolved components (Mochnacki 1981). The relationship between type and evolutionary state may be misleading, however, since S1282 appears to have effectively changed type in less than a decade (between the observations of Whelan et al. and those of Gilliland et al.). One should also look at the data for the systems ST757 (discussed above) and III-79 (discussed below), which show that one eclipse minimum can go from being the fainter of the two to the brighter in a matter of months or years. Because this is much too short to correspond to any reasonable evolutionary timescale (nuclear, thermal, or even dynamical) for the stars themselves, we believe that this shows that the evolutionary status of a W UMa variable cannot be determined without an extended study of the light curve and its potential for variation. For S1282, we do have additional information that is not always available for a W UMa system: the binary is found at the turnoff of the cluster, and so the primary star is likely to have depleted much of its core hydrogen supply.

Because S1282 was close to our primary target (S1082) in the cluster, we have photometry from most nights of observations, and on some nights we were able to cover almost an entire orbital period. Previous modeling based on the Whelan et al. data (Maceroni, Milano, & Russo 1984) indicated that the system significantly overfills the Roche lobes of the two stars. However, the presence and duration of the total eclipse invalidates the low inclination \( i = 62^\circ 9 \) that Maceroni et al. derived. Given that the Whelan et al. observations of light-curve minima occurred over a relatively short period of 2.5 months, it is possible that there was a short-term change in the light-curve shape. We have observed shorter timescale changes in the light-curve shape (for example, the deeper primary eclipse observed on 2001 January 25), and the variability seen by vVSM in their secondary-eclipse observations during two runs seems to support this. However, the amplitude of the light curve from Whelan et al. seems to be somewhat smaller than the amplitude in our data, which would tend to rule out cool spots as the cause.

While Whelan et al. did present radial velocity measurements to measure the spectroscopic mass ratio, they were not able to constrain the velocity semiamplitude of the secondary star precisely. The large differences between their light curve and later ones might also indicate that their radial velocities may have been systematically affected by spots (to give just one possibility). As a result, we will not take their spectroscopic mass ratio to be a primary constraint on light-curve models. The radial velocity measurements were good enough to show, however, that the less massive star is totally eclipsed as it passes behind the more massive star, as would be expected if the more massive star is also larger.

In most cases, W UMa light curves by themselves provide very little information about the system parameters, and attempts to derive parameters using \( \chi^2 \) fits are extremely dangerous (see Rucinski 2001 for a discussion). However, when a contact system shows total eclipses, the duration of totality strongly constrains the combination of mass ratio and inclination and is insensitive to the degree of contact (Mochnacki & Doughty 1972). Because S1282 clearly has total eclipses and a fairly stable light curve during the period of our observations and has not been modeled previously, light-curve models can provide valuable constraints.

We modeled the light curve of S1282 by using NIGHTFALL (see §3.3 for details). We focus on data from 2000 December and 2001 January because nearly the entire light curve was observed in relatively short periods of time. We decided not to attempt to model data taken in 2002 because the maximum following primary eclipse was found to be significantly fainter (0.02–0.04 mag) than the maximum following secondary eclipse, probably indicating that spots were a significant influence.

The large width of both eclipses requires an inclination near 90° and a small mass ratio. Our best-fit values for the 2000 December and 2001 January data separately are presented in Table 3. To estimate the possible errors, we ran grids of models varying \( q \) and \( i \) to determine changes in \( \chi^2 \). The resulting contour maps are shown in Figure 8. The contours correspond to levels 1.0 and 4.0 above the minimum \( \chi^2 \) fit for that data set, which should roughly delineate the 1 and 2 \( \sigma \) confidence regions \( q \) and \( i \) taken individually. As seen in the contour maps, there is little correlation between \( q \) and \( i \). The best-fit contours for the two data sets agree well, although there is a small shift in \( q \) between the results for the two data sets. Using the information from the \( \chi^2 \) maps and the systematic shifts between the best-fit models for the two data sets, we quote best-fit values of \( q = 0.16^{+0.03}_{-0.02} \) and \( i = 86^{+4}_{-2} \) deg. The variations in the best-fit parameters due to month-to-month changes in the light curve appear to be

| Quantity | December 2000 | January 2001 |
|----------|---------------|--------------|
| \( q \)  | 0.157         | 0.165        |
| \( i \)  | 0.73          | 0.62         |
| \( \chi^2 \) min | 0.41          | 1.31         |
comparable in importance to the random errors in the fitted value of $q$.

In Figure 9, we show a selection of theoretical models against the observational data. The best-fit model is almost lost among the observational points, with the poorest fit near $\phi = 0.25$. Figure 9 (top) shows two models with the best-fit inclination but with mass ratios $1\sigma$ away from the best model. The mass ratio is primarily constrained by the eclipse depths. Figure 9 (bottom) shows light curves with the best-fit mass ratio, but with different inclinations. The $i = 90^\circ$ curve is almost indistinguishable from the best-fit model, but the $i = 78^\circ$ curve has eclipses of noticeably shorter duration.

Although the derived mass ratio for the system falls near the low end of the distribution for W UMa systems, W UMa systems tend to be found preferentially at low $q$-values (Rucinski 2001), so this fact is not unusual. The filling factor for the system is constrained by the shape of the light curve before and after primary eclipse, and although it is correlated with the inclination (in the sense that lower inclinations require larger filling factors) there is negligible degeneracy between mass ratio and filling factor. For both of our best-fit models we find it necessary to use a filling factor ($f \approx 0.7$) that is probably larger than the majority of observed systems (Rucinski 1997). A lower limit on the filling factor is $f > 0.4$ based on $\chi^2$ values measured for models with $i = 90^\circ$.

The results of the light-curve analysis contradict the earlier spectroscopic analysis of Whelan et al. (1979). Although their derived radial velocities were very uncertain ($K_1 \approx 100 \pm 15$ km s$^{-1}$, $138$ km s$^{-1} < K_2 < 240$ km s$^{-1}$), the implied mass ratios are inconsistent with our photometric value. In addition, if it is assumed that the maximum $K_2$ value is approximately correct (giving a spectroscopic $q$ value closest to our photometric value), the derived total
system mass is substantially less than that predicted for a
turnoff star in M67 from stellar evolution models (~1.25
$M_\odot$) in spite of the system’s position near the turnoff in the
color-magnitude diagram. We are forced to conclude that
the radial velocity data for this system are not currently of
high enough quality to derive trustworthy masses. The
importance of a good radial velocity curve for this system
should be emphasized, since it would provide a valuable
constraint on the cluster turnoff mass and would thereby
help more accurately age-date M67.

Our extensive observations allowed us to discover some
unusual transient features in the light curves (Fig. 10). On
2001 January 23/24 and 25/26 we observed short (~30
minute) brightness increases (~0.08 mag for both, com-
pared with eclipse depths of 0.33 and 0.39 mag). Unusual
features of these two brightenings were that they were
observed at almost identical phase positions shortly before
maximum, that the following maximum did not show the
same features of these two brightenings were that they were
observed at almost identical phase positions shortly before
maximum, that the following maximum did not show the
maximum preceding the brightness increase on January 25/26
was significantly deeper (by 0.04–0.05 mag) than any other
minimum observed. These features disappeared within two
days.

These transient features bear some resemblance to vari-
tations seen in the light curve of the nearby W UMa variable
44i Boo (e.g., Duerbeck 1978), which appears to have active
periods of a few years duration interspersed with quieter
periods with undisturbed light curves. A similar cycle (prob-
ably related to the magnetic field) might help to explain the
difference between the light curves of Whelan et al. (1979)
and other observers.

The timing of the features shortly before maximum seems
to argue against stellar flares. The short duration of the fea-
tures argues against hot spots, which should persist for
longer times. One hypothesis is based on magnetically con-
fined gas (prominences) on one of the stars on the portion of
the surface facing away from the other star. If the gas has
sufficient optical depth, it could increase the effective surface
area of the binary when a large slab is aligned edge-on, but
it could cause either modest or negligible dimming of the
system when viewed face-on through the thin dimension of
the slab. The increased depth of the first half of the primary
eclipse on January 25 indicates that the feature was proba-
bly on the secondary star facing almost directly away from
the primary. Because our light curve was taken entirely in $V$,
we have no direct information on temperature. (We wish to
thank M. Blake for the suggestion that initiated this line of
thought.)

III-79 (ET Cnc): This system was discovered by Gilliland
et al. (1991) at 7$''$ from the cluster center and was also
observed by SvMV. This binary is considerably fainter than
the other three contact systems known. This system was in
the field of our 2001 March observations, with the best data
coming from night 13. We averaged observations to increase
the signal-to-noise ratio in the data. Our data are presented
in Figure 11, along with those of SvMV from 1998 January,
phased to the same linear ephemeris by using a period
($P = 0.270505$ days), consistent with the value quoted by
SvMV to within the errors. Our measured median magnitude
($V = 15.90$) agrees very well with the average magnitude of
SvMv (15.89), so no shifting in magnitude was done.

Although individual data points have considerably larger
errors than those for the other W UMa systems discussed, a
comparison of the light curves indicates a noticeable change
in the light-curve shape. While the brighter of the two light-
curve maxima follows the brighter minimum in the SvMV
and Gilliland et al. data sets, the brighter maximum appears
to follow the fainter minimum in our data. Although we do
not have data completely covering the minimum plotted at
phase $\phi = 0.5$, several points with good errors indicate that
it has dimmed noticeably. Independent of this, the $\phi = 0.5$
minimum does not reach the same depth as the $\phi = 0$ mini-
num in the light curves of Gilliland et al. and SvMv. So the
indication is that this system shows fairly extreme variations
in the shape of the light curve. Without more information
about the nature of this variation, it would be reckless to try
to model this system.

4.2. Blue Stragglers

During the course of the observations we observed most
of the cluster’s blue stragglers during the majority of at least
one night to look for variability on various timescales. The
results of this search are given in Table 4. Our list of stragglers comes primarily from the list of Ahumada & Lapasset (1995), although stars have been excluded if the accurate photometry of Fan et al. (1996) indicated that the star was close to the cluster turnoff. Stars S2223 and S2226 were added to the list, based on the photometry of Fan et al. (1996) and proper-motion membership (Sanders 1977; Lapasset 1995), although stars have been excluded if the conditions and a contaminating star was present nearby, as was the case for the straggler S975. We have provided information on the nights the stars were observed to lay the groundwork for constraining variations on longer timescales. We do, however, rule out the possibility that any of the other blue stragglers observed are W UMa variables of amplitude more than about 0.01–0.02 mag.

4.2.1. δ Scuti Stars

The blue stragglers in the CMD cover the region where the instability strip occurs. We have roughly translated the instability strip of Pamyatnykh (2000) into our observational CMD, as shown in Figure 2. We will discuss our oscillation mode analyses of the two known blue straggler δ Scuti stars S1280 and S1284 in a separate paper in preparation. However, we find several other stragglers with photometry that places them inside the instability strip: S1263, S1267, S968, S1066, and S1434 to the red of the known pulsators, and S752, S2226, S1082 and S975 to the blue. We did not observe S1434 or S2226. S752, S975, and S1267 are known as long-period binaries (P = 1003, 1221, and 846 days, respectively; Latham & Milone 1996), while S1082 contains a close binary that may be part of a triple (van den Berg et al. 2001; Sandquist et al. 2003). Therefore, these systems are less likely to show photometric variations due to pulsation (although it is possible that components of the long-period binaries will still fall in the instability strip; in particular, the brightest component of S1082 shows some evidence of being a δ Scuti star; Sandquist et al. 2003). As a result, S968, S1066, and S1263 are the best candidates to search for pulsation. Gilliland & Brown (1992) observed S1263 extensively, and

| IDa | V    | B−V  | σV   | IWS  | Nights Observedb | Nobs  | Results          |
|-----|------|------|------|------|------------------|-------|-----------------|
| 145 |      |      |      |      | None             |       |                 |
| 277 |      |      |      |      | None             |       |                 |
| 751 | 12.70| 0.008| 0.53 | 5−9  | 1418             | Am star; possible flare detected |
| 752 | 11.32| 0.018| 0.75 | 4−9, 15, 17−19 | 1610             | No variation |
| 792 | 11.99| 0.007| 1.01 | 5−9, 12, 13, 17−19 | 1261             | Am star; possible low amplitude; timescale ~ days |
| 968 | 11.25| 0.010| 0.74 | 5−9, 11, 15, 17−19 | 1659             | Photometry affected by faint companion |
| 975 | 11.05| 0.47  | 7.26 | 1−9, 11, 15, 17−19 | 1659             | No variation |
| 977 | 10.02| 0.006| 0.69 | 5−9, 18, 19       | 504              | No variation |
| 984 | 12.26| 0.014| 1.64 | 1−9, 11, 15, 17−19 | 1732             | No variation |
| 997 | 12.13| 0.006| 0.92 | 1−9, 11, 15, 17−19 | 1655             | No variation |
| 1005| 12.68| 0.010| 1.57 | 1−9, 11, 15, 17−19 | 1654             | No variation |
| 1031| 13.29| 0.007| 0.32 | 1−9, 11, 15, 17−19 | 1644             | No variation |
| 1036| 12.81| 0.046| 90.59| 1−9, 11, 15, 17−19 | 1651             | W UMa variable (EV Cnc) |
| 1066| 10.95| 0.003| 0.24 | 1−9, 11−13, 17−19 | 2061             | No variation |
| 1072| 11.31| 0.006| 0.97 | 1−9, 11−13, 17−19 | 2073             | No variation |
| 1082| 11.20| 0.024| 33.59| 1−9, 11−13, 17−19 | 2097             | RS CVn variable (ES Cnc) |
| 1165|      |      |      |      | None             |       |                 |
| 1183| 12.66| 0.011| 0.07 | 15   | 66               | No variation |
| 1195| 12.29| 0.003| 0.40 | 15   | 78               | No variation |
| 1263| 11.06| 0.007| 0.98 | 1−9, 11, 17−19   | 1275             | Possible low amplitude; timescale ≥ 10 days |
| 1267| 10.90| 0.005| 0.45 | 1−4, 11         | 484              | No variation |
| 1273| 12.25| 0.006| 0.63 | 1−9, 11−13, 17−19 | 1451             | No variation |
| 1280| 12.23| 0.009| 2.55 | 1−9, 11−13, 17−19 | 1685             | δ Scu variable (EV Cnc) |
| 1282| 13.44| 0.133| 108.08| 1−14, 17−19     | 1864             | W UMa variable (AH Cnc) |
| 1284| 10.93| 0.012| 9.41 | 1−9, 11−13, 17−19 | 2015             | δ Scu variable (EX Cnc) |
| 1434| 10.70| 0.11 |     | None           |       |                 |
| 1440|      |      |      | None           |       |                 |
| 1947|      |      |      | None           |       |                 |
| 2204| 12.89| 0.013| 1.03 | 1−9, 11, 15, 17−19 | 1717             | No variation |
| 2223| 13.30| 0.012| 0.92 | 1−9, 11−13, 17−19 | 2084             | No variation |
| 2226|      |      |      | None           |       |                 |

a ID from Sanders 1977.
b Night IDs given in Table 1.
c Photometry corrected for color-related errors at the 0.02 mag level.
d May be a normal turnoff star.
also found no sign of variation. We do not find convincing
evidence of pulsation in any of the three stars, although this
may be due to low pulsation amplitudes or higher frequency
(overtone) oscillations. We discuss all three stars in § 4.2.2
with regard to longer period variations.

4.2.2. Possible Variables

As discussed earlier, to tightly constrain the photometric
variations present in some of the bluest blue stragglers, we
were forced to subtract a systematic error (probably related
to color response of the filter plus CCD combination) that
appeared as correlated slow low-amplitude variations
among several stars. Once this correction was made several
of the stars no longer showed any signs of significant varia-
tion (S977, S1066, and S1267). The remaining three (S752,
S968, and S1263) still showed trends and will be discussed
below. None of these stars tripped the variability condition
$\Delta W_s \geq 1.5$, although in the case of S752 at least there is
fairly clear evidence of variability in one interval of time.
Before presenting the results, we note that we looked for
correlations of the magnitude residuals with seeing and air
mass for each star below and found no evidence that such
effects were responsible.

S752: As noted earlier, S752 is known to be a binary sys-
tem ($P = 1003$ days; $e = 0.32 \pm 0.12$; Latham & Milone
1996) containing an Am star. This star was outside the field
observed by Gilliland et al. (1991), and although it was
observed by SvMV it was not reported as variable. Simoda
(1991) observed the star and found it to be nonvariable. We
present our observations in Figure 12. While the vast major-
ity of our measurements show no indication of variability,
our 2000 December observations give the indication of a
decrease in brightness of 0.03 mag over the course of a week,
punctuated with something resembling a flare (0.05 mag
increase in brightness lasting over 3 hr). However, see
Gilliland et al. 1991 for a discussion of false flaring.

S968: This blue straggler was not in the field observed by
Gilliland et al. (1991) but was observed by SvMV although
they did not report it as being variable. Our observations
are shown in Figure 13. For most of the nights this star was
observed, it was fairly consistent with constant brightness.

On other nights there appeared to be noticeable trends dur-
ing a night (most notably 2001 February 18/19). This
behavior could explain the nondetection by SvMV.

S1263: SvMV indicate that their observations of this star
have significant scatter of up to 0.03 mag, and Kim et al.
(1996) find large dispersion in their measurements. There
does appear to be a long-term drift in the brightness of the
star (of approximately 0.02 mag) as seen in Figure 14, even
after removing the effects of correlated residuals. Some of
our nights of observations were compromised by very poor
seeing and contamination by MMJ 5951 (Montgomery,
Marschall, & Janes 1993), which is about 9° away. Based on
trends seen in the photometric residuals in measurements
during the poorest seeing, we eliminated measurements with
seeing greater than 4° FWHM. We attempted to look for
periodic signals in the data, although we did not find con-
vincing evidence of any (the best indications were for a
period of 17.5 days). This system is not known to be part of
a binary, so it should be monitored further to determine the
manner of its variation.
4.3. Long-Period Variables

S1040: This system was determined by Mathieu, Latham, & Griffin (1990) to be a single-lined spectroscopic binary having a circular orbit and a period $P = 42.8271 \pm 0.0022$ days. The position of S1040 to the blue side of the red giant branch in the color-magnitude diagram makes it a “red straggler.” Using ultraviolet imaging and spectra, Landsman et al. (1997) showed that the secondary companion to the red giant primary is likely to be a helium white dwarf. Landsman et al. (1997) also laid out a hypothetical history for the system in which a main-sequence binary began mass transfer at a period of approximately 2 days when the more massive star had a helium core mass of $0.16 M_\odot$. Mass transfer continued until the envelope of the initially more massive star was depleted, creating a system composed of a helium white dwarf and a blue straggler. Once the blue straggler evolved to the red giant branch, a system like S1040 would be created.

In previous variability studies, (Gilliland et al. 1991) found evidence for low-amplitude $(0.012 \text{ mag})$ variation with a period of 7.97 days, while vSVM found no evidence of variation. We plot our data (averaged in 0.1 days bins to improve the errors) in Figure 15 and tabulate it in Table 5. We have observed several nights for which the system brightness decreased by as much as 0.06 mag compared with the peak level. When the data is phased to the ephemeris of Mathieu et al. (1990), there is an indication of a systematic decrease in brightness at a phase corresponding to the passage of the white dwarf in front of the giant. Because our phase coverage is incomplete, we are unable to determine the exact depth of the feature. However, a feature of this depth and shape cannot be explained as an eclipse of the red giant by the white dwarf. Observations on two nights do not match up well with the light curve formed from the rest of the observations. We probed a variety of periods from 1 to 70 days, but did not find satisfactory light curves from any of the best trial periods from the L-K or L-S methods. Additional observations should be made to better determine the shape of the light curve and the nature of the variation.

![Fig. 15.— $V$ light curve for the “red straggler” binary S1040. Observations have been averaged in bins 0.1 days in duration. The data have been phased to the spectroscopic ephemeris of Mathieu, Latham, & Griffin (1990). Phase $\phi = 0$ corresponds to maximum positive radial velocity of the brighter star in the system.](image)

TABLE 5

| HJD − 2,450,000 | V    | $\sigma_V$ | $N_{\text{obs}}$ |
|-----------------|------|------------|------------------|
| 1884.9294       | 11.5231 | 0.0006 | 33               |
| 1885.0391       | 11.5243 | 0.0008 | 27               |
| 1886.8586       | 11.5184 | 0.0007 | 36               |
| 1886.9615       | 11.5157 | 0.0006 | 43               |
| 1887.0468       | 11.5177 | 0.0007 | 32               |
| 1890.8688       | 11.5076 | 0.0006 | 42               |
| 1890.9386       | 11.4998 | 0.0014 | 14               |
| 1891.8734       | 11.5064 | 0.0008 | 37               |
| 1891.9872       | 11.5092 | 0.0006 | 51               |
| 1892.0607       | 11.5101 | 0.0008 | 28               |
| 1930.7983       | 11.5395 | 0.0058 | 1                |
| 1933.7805       | 11.5209 | 0.0005 | 55               |
| 1933.8308       | 11.5210 | 0.0005 | 63               |
| 1933.9312       | 11.5191 | 0.0005 | 57               |
| 1934.0118       | 11.5181 | 0.0007 | 31               |
| 1935.7288       | 11.5128 | 0.0007 | 45               |
| 1935.8314       | 11.5152 | 0.0005 | 60               |
| 1935.9333       | 11.5138 | 0.0006 | 54               |
| 1936.0000       | 11.5114 | 0.0010 | 17               |
| 1939.8739       | 11.4991 | 0.0008 | 36               |
| 1939.9386       | 11.4952 | 0.0018 | 8                |
| 1940.7053       | 11.5028 | 0.0007 | 37               |
| 1940.8386       | 11.4972 | 0.0007 | 46               |
| 1940.9371       | 11.5010 | 0.0007 | 47               |
| 1941.7175       | 11.5034 | 0.0005 | 49               |
| 1941.8186       | 11.5074 | 0.0005 | 48               |
| 1941.9199       | 11.5052 | 0.0005 | 50               |
| 1941.9883       | 11.5018 | 0.0010 | 14               |
| 1958.6849       | 11.4962 | 0.0036 | 7                |
| 1958.8989       | 11.4972 | 0.0006 | 50               |
| 1958.9531       | 11.4961 | 0.0017 | 5                |
| 1959.8451       | 11.5077 | 0.0006 | 47               |
| 1959.9218       | 11.5017 | 0.0009 | 28               |
| 2296.7175       | 11.5428 | 0.0008 | 21               |
| 2300.0020       | 11.5423 | 0.0008 | 20               |
| 2311.6980       | 11.5368 | 0.0009 | 23               |
| 2311.7991       | 11.5394 | 0.0005 | 44               |
| 2311.8994       | 11.5383 | 0.0005 | 46               |
| 2311.9536       | 11.5345 | 0.0019 | 5                |
| 2316.6882       | 11.5028 | 0.0009 | 46               |
| 2316.7888       | 11.5104 | 0.0006 | 53               |
| 2316.8887       | 11.5079 | 0.0007 | 45               |
| 2316.9590       | 11.5038 | 0.0011 | 23               |
| 2352.6743       | 11.5638 | 0.0006 | 47               |
| 2352.7751       | 11.5613 | 0.0005 | 50               |
| 2352.8530       | 11.5622 | 0.0006 | 34               |

S1063: This system is a binary with orbital period of $18.396 \pm 0.005$ days and eccentricity $0.206 \pm 0.014$ (Latham et al. 1992; Mathieu et al. 2003), although an orbit has not yet been published for the system. S1063 is known to be unusual in its X-ray emission (Belloni et al. 1998) and position in the color-magnitude diagram (fainter than the subgiant branch). There is good evidence of proper-motion membership though (Sanders 1977; Girard et al. 1989, greater than $90\%$ probability).

This system fell just outside the Gilliland et al. field, but was observed by vSVM in their examination of X-ray sources. vSVM identified the system as a nonperiodic variable based on an examination of periods up to the length of their longest interval of continuous observations (18 days).
Their Figure 5 makes it clear that at the very least there is a great deal of variability in the light curve and that the variation is not obviously related to the orbital characteristics of the system.

We averaged observations from a given night in 0.1 day windows to improve the error in our measurements, and they are presented in Table 6. In our data, the system shows slight photometric trends during the course of a night, but systematic offsets in the star’s photometry are clearly detected from night to night. Using an L-S periodogram, we do not find any evidence of variation on the orbital timescale, but there is slight evidence of variation with a period of approximately 23 days. This period seems to bring the maxima and minima of our data into approximate alignment. As shown in Figure 16, a comparison of data from different observing runs indicates that the brightness level of the minimum of the light curve probably varies by a few centimagnitudes from cycle to cycle. During the course of our observations the light curve appeared to maintain a roughly similar shape, but one that appears to differ from the portions observed by vSVM. Although the system does not show periodicity in the orbital period, the similarity of the timescale may indicate that the variability is related via tides and/or magnetic activity. Further progress on this system will require observations over much longer periods and a more detailed examination of the relationship with the orbit. (We have three nights of observations of another subgiant branch system [S1113], but our phase coverage for this system is fairly poor, so we do not discuss it.)

### TABLE 6

| mJD (HJD−2,450,000) | V     | σV   | N<sub>obs</sub> |
|---------------------|-------|------|-----------------|
| 1884.9297           | 13.4520 | 0.0010 | 33              |
| 1885.0391           | 13.4550 | 0.0014 | 27              |
| 1886.8594           | 13.4854 | 0.0011 | 36              |
| 1886.9609           | 13.4899 | 0.0008 | 43              |
| 1887.0469           | 13.4912 | 0.0010 | 32              |
| 1890.8711           | 13.5676 | 0.0011 | 43              |
| 1890.9375           | 13.5754 | 0.0025 | 13              |
| 1891.8750           | 13.5556 | 0.0012 | 37              |
| 1891.9833           | 13.5590 | 0.0010 | 52              |
| 1892.0625           | 13.5538 | 0.0015 | 27              |
| 1933.7305           | 13.9066 | 0.0007 | 55              |
| 1933.8320           | 13.5129 | 0.0006 | 64              |
| 1933.9338           | 13.5140 | 0.0007 | 58              |
| 1934.0117           | 13.5138 | 0.0010 | 29              |
| 1935.7305           | 13.5668 | 0.0008 | 45              |
| 1935.8320           | 13.5704 | 0.0007 | 60              |
| 1935.9336           | 13.5697 | 0.0007 | 54              |
| 1936.0000           | 13.5757 | 0.0013 | 17              |
| 1939.8750           | 13.6060 | 0.0010 | 36              |
| 1939.9375           | 13.6033 | 0.0027 | 7               |
| 1940.7070           | 13.5926 | 0.0009 | 37              |
| 1940.8398           | 13.5944 | 0.0010 | 47              |
| 1940.9375           | 13.5924 | 0.0011 | 46              |
| 1941.7188           | 13.7157 | 0.0008 | 50              |
| 1941.8242           | 13.6096 | 0.0007 | 49              |
| 1941.9258           | 13.6093 | 0.0007 | 49              |
| 1941.9922           | 13.5667 | 0.0016 | 12              |
| 1958.6797           | 13.5500 | 0.0104 | 4               |
| 1958.8984           | 13.5577 | 0.0008 | 49              |
| 1958.9531           | 13.5658 | 0.0025 | 5               |
| 1959.8984           | 13.5886 | 0.0010 | 51              |
| 1970.6785           | 13.5418 | 0.0008 | 63              |
| 1970.7390           | 13.5450 | 0.0008 | 75              |
| 1970.8828           | 13.5474 | 0.0009 | 67              |
| 1972.6914           | 13.5598 | 0.0007 | 97              |
| 1972.7930           | 13.5630 | 0.0010 | 89              |
| 1972.8594           | 13.5639 | 0.0022 | 17              |
| 1974.6758           | 13.5433 | 0.0024 | 30              |
| 2296.7188           | 13.5082 | 0.0008 | 21              |
| 2300.0000           | 13.5386 | 0.0009 | 20              |
| 2311.6992           | 13.6108 | 0.0010 | 24              |
| 2311.8008           | 13.6122 | 0.0006 | 44              |
| 2311.9023           | 13.6116 | 0.0006 | 48              |
| 2311.9531           | 13.6154 | 0.0027 | 3               |
| 2316.6875           | 13.5574 | 0.0016 | 42              |
| 2316.7891           | 13.5538 | 0.0008 | 53              |
| 2316.8906           | 13.5541 | 0.0009 | 46              |
| 2316.9609           | 13.5599 | 0.0019 | 22              |
| 2352.6758           | 13.5144 | 0.0007 | 48              |
| 2352.7773           | 13.5164 | 0.0006 | 51              |
| 2352.8555           | 13.5183 | 0.0008 | 32              |

5. CONCLUSIONS

We have presented V observations for the open cluster M67 and have discussed the light curves for the known W UMa contact binaries and the monitoring of the majority of the blue stragglers for variability. We find that all the known W UMa binaries show light-curve variations that occur on timescales of days to months. Two systems (S757 and III-79) show large changes in the shapes of their light curves. The relative brightnesses of both the two maxima and the two minima in the light curve of S757 have been observed to change on timescales of less than a month. The faint system III-79 shows a substantial change in the shape of the light curve between the 1998 January observations of SvMV and our observations in 2001 March. The other two systems (S1036 and S1282) show smaller variations. S1282 changed between a W-type and an A-type configuration between the 1973 observations of Whelan et al. (1979) and the 1988 observations of Gilliland et al. (1991). The existence of two systems that appear to change between these subtypes indicates that the classification is perhaps not a robust indicator of the evolutionary state of the stellar components. The blue straggler system S1036 shows smaller light-curve variations, but a stronger and more stable O'Connell effect.

We have verified that S1282 is a highly inclined totally eclipsing system with $q = 0.16^{+0.03}_{-0.02}$ and $i = 86^{+4}_{-8}$ deg. Because this system falls right at the cluster turnoff, we strongly encourage further spectroscopic work to provide a constraint on the cluster turnoff mass and thus on the cluster age. This system has also shown unusual short disturbances in its light curve that may relate to magnetic activity and should be followed up.

Among the blue stragglers, in addition to the two known δ Scuti pulsating variables, we find possible evidence of longer period variations in the stars S752, S968, and S1263. While these stars did not satisfy our criteria for a definite claim of variability, we see trends in the photometry and apparent changes in the mean brightness level that should be investigated.

Finally, we present a series of observations of two long-period binary systems. For the poorly understood subgiant branch system S1063, there are indications of quasi-periodicity on timescales similar to the orbital period, as well as variations in the mean brightness level of the light
curve. For the giant–white dwarf system S1040, we find evidence of a drop in brightness at phases corresponding to the passage of the white dwarf in front of the giant by using the ephemeris derived by Mathieu et al. (1990). Although this drop in brightness cannot be due to an eclipse of the giant by the white dwarf itself, there may be associated material within the system that could account for the variability. This information can probably be used to constrain the inclination of the system.

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