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# Time-Series Ensemble Photometry and the Search for Variable Stars in the Open Cluster M11

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# TIME-SERIES ENSEMBLE PHOTOMETRY AND THE SEARCH FOR VARIABLE STARS IN THE OPEN CLUSTER M11

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## ABSTRACT

This work presents the first large-scale photometric variability survey of the intermediate-age (∼200 Myr) open cluster M11. Thirteen nights of data over two observing seasons were analyzed (using crowded field and ensemble photometry techniques) to obtain high relative precision photometry. In this study we focus on the detection of candidate member variable stars for follow-up studies. A total of 39 variable stars were detected and can be categorized as follows: one irregular (probably pulsating) variable, six $\delta$ Scuti variables, 14 detached eclipsing binary systems, 17 W UMa variables, and one unidentified/candidate variable. While previous proper-motion studies allow for cluster membership determination for the brightest stars, we find that membership determination is significantly hampered below $V = 15,\ R = 15.5$ by the large population of field stars overlapping the cluster main sequence. Of the brightest detected variables that have a high likelihood of cluster membership, we find five systems in which further work could help constrain theoretical stellar models, including one potential W UMa member of this young cluster.

*Key words:* binaries: eclipsing — $\delta$ Scuti — open clusters and associations: individual (M11)

## 1. INTRODUCTION

Our Galaxy's collection of open clusters presents an important population of stars for many areas of modern astrophysics, in particular for studies of variable stars and extrasolar planets. Because of the characteristics common to stars in open clusters (namely, the age and chemical composition), much more information can be obtained for a particularly interesting cluster member star than could be otherwise deduced for an isolated field star. The high spatial density of stars in clusters provides the opportunity to survey many stars at one time, a property important in increasing the probability of detection for extrasolar planetary transits. Other advantages of open cluster surveys for extrasolar planets have been summarized by von Braun et al. (2005). Observations of the various types of variable stars in clusters can provide the other critical remaining parameters necessary for studying the physics of stars: masses, radii, and luminosities. In the case of eclipsing binary systems and extrasolar planets, photometric observations of the eclipses yield constraints on the orbital inclination and relative radii, the necessary complements to radial velocity measurements that allow for the determination of the absolute system parameters. With the absolute properties measured, strong tests of structure and evolution become possible for both extrasolar planets (Baraffe et al. 2003; Chabrier et al. 2004; Burrows et al. 2004) and stars (e.g., Ribas 2003; Lacy et al. 2004).

In this paper we focus on the search for variable stars in the open cluster M11, identifying systems important for follow-up studies. In § 2 we introduce the target and previous studies of this object. In § 3 we describe the observations of the cluster. Section 4 details the data analysis, photometry, and search for variable stars. In § 5 we describe the cluster color-magnitude diagram (CMD). The light curves for the detected variable stars are presented in § 6. We give our conclusions and indicate future work in § 7.

## 2. THE TARGET CLUSTER: M11

The open cluster M11 (NGC 6705, C1848−063) is a rich and dense open cluster, containing on the order of several thousand stars. It is both relatively young and metal-rich (see below), both of which are advantageous for searches for planetary transits; younger planets will be larger on average (causing a deeper transit and thus being more easily detectable) and have been observed to show a preference for metal-rich host stars (Santos et al. 2003). Here we present an overview of some relevant previous studies of M11 and the known variable stars in M11.

### 2.1. *Previous Studies of M11*

M11 has historically been the focus of cluster dynamics studies, but little work has been done on the variable star content. The earliest significant photometric study of M11 was conducted by Johnson et al. (1956), who derived a CMD from the *UBV* photographic data for stars brighter than $V = 15$. They were the first to note the detection of a population of approximately 30 red giant stars and found the cluster age to be intermediate between Praesepe and the Pleiades. Recent estimates of the age of M11 by Sung et al. (1999) find an age of $(200-250) \times 10^6$ yr. A study of the cluster dynamics for stars brighter than $V \sim 15$ mag was done by McNamara & Sanders (1977) based on the proper-motion study by McNamara et al. (1977). These studies also noted the presence of a halo of low-mass stars, which was later confirmed by Solomon & McNamara (1980). Mathieu (1984) performed further photometry of M11 to form a complete and

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consistent sample of photometric measurements to complement the proper-motion measurements of McNamara et al. (1977). This study also examined, in detail, the cluster structure and dynamics of M11. It was not until the study by Brocato et al. (1993) that the cluster CMD was observed below $V \sim 15$; observations reached a limiting magnitude of $V \sim 22$. The most recent photometry has been presented by Sung et al. (1999), who covered an area of approximately $40'.0 \times 40'.0$ around the center of M11. They derived an unreddened distance modulus of $(V_0 - M_v) = 11.55 \pm 0.10$ (distance = 2 kpc) and a cluster radius of $16'$ (=9.5 pc for a distance of 2 kpc). Spectroscopic measurements have also been made of the red giant branch population of M11. Gonzalez & Wallerstein (2000) presented an abundance analysis of 10 red giant stars in M11 and derived a metallicity of [Fe/H] $= +0.10 \pm 0.14$ from high-resolution spectra.

In the Galaxy, the cluster is located at ($l = 27^\circ.3$, $b = -2^\circ.8$) near the Scutum star cloud and the Sagittarius-Carina arm, resulting in very large contamination of the cluster CMD from the field population (Sung et al. 1999). As first noted by Mathieu (1984), the CMD of the M11 field appears to have not only the typical red field star population, which is easily distinguished from the cluster main sequence (MS), but also has a population of stars overlapping the cluster MS starting at approximately $V = 15$ and fainter. This has also been noted by Brocato et al. (1993) but is most clearly seen in Figure 10 of Sung et al. (1999). Here the population of stars is shown divided into four different sections: (1) the MS of M11, (2) the "blue" field star population, (3) field (lower division) and cluster (small upper division) giant stars, and (4) the "red" field star population. It is the population of field stars from group 2 that hampers membership estimation for many of the detected variables in this study. Without direct distance measurements, it is difficult to say with certainty that a given star falling in the overlap region (groups 1 and 2) is either a cluster member or a member of the bluer field star population. As further confirmation that the stars in group 2 are not cluster members, Sung et al. (1999, Fig. 5) derived a CMD for a region nearby M11 that clearly showed the bimodal field star population.

### 2.2. *Known Variable Stars in M11*

Observations of photometrically variable stars in this cluster and its vicinity are rare. To date, no comprehensive study of the variable star population has been published. The most well-studied potential cluster member is BS Scuti, an Algol-type eclipsing binary ($P = 3.8$ days; Hall & Mallama 1974). The star IT Scuti, located much closer to the cluster center, is characterized as a slow irregular variable, although no light curve has been published. The only previously known, confirmed $\delta$ Scuti variable is V369 Scuti (McNamara et al. [1977] star 624; $P = 0.223$ days; Hall & Mallama 1970). A recent survey for variability in M11 was performed by Paunzen et al. (2004), but the search concentrated on the brightest stars only. They note the detection of one variable star (star 770 from McNamara et al. [1977]) but do not indicate the type of variability detected nor present a light curve. Finally, two spectroscopic binaries (stars 926 and 1223, discovered in a radial velocity survey by Mathieu et al. [1986]) were analyzed by Lee et al. (1989). We discuss our observations of these previously known and any suspected variable stars in § 4.3.

## 3. OBSERVATIONS

The data for this study were obtained at the 1 m telescope at the Mount Laguna Observatory using a $2048 \times 2048$ CCD. In total, M11 was observed over the two observing seasons of 2002 and 2003, and 13 nights of data employed in this study are presented here. Only observations for which the nightly transparency (weather conditions) were good, excellent, or photometric were used in this study. Table 1 presents the log of the observations; observing conditions are also noted, with error estimates to give some indication of the photometric stability of the nightly data. Given a CCD plate scale of $0''.4$ pixel$^{-1}$, the total surveyed area around the cluster center was $13'.7 \times 13'.7$. In radial extent we have observed out to a radius of $6'.8$ from the cluster center; our observations have primarily covered the central portion of the cluster. Time-series observations (exposure times of 500 s were used in all monitoring data) were done exclusively in the $R$ band to maximize the number of surveyed stars. Owing to the large readout time of the CCD, there was a delay of approximately 6.7 minutes between exposures. Observations were made on 2002 September 2–3 in the $V$ band (exposure times of 10, 60, and 300 s) for use in the construction of the $(V - R)$ color index.

TABLE 1

Observation Log for M11

| UT Double Date | No. Images | Average Seeing (arcsec) |
|---|---|---|
| 2002 Aug 8–9 | 31 | $2.9 \pm 0.5$ |
| 2002 Aug 10–11 | 40 | $3.8 \pm 0.6$ |
| 2002 Aug 12–13 | 39 | $4.7 \pm 1.8$ |
| 2002 Aug 13–14 | 38 | $5.0 \pm 1.9$ |
| 2002 Aug 14–15 | 37 | $4.5 \pm 0.9$ |
| 2002 Aug 15–16 | 35 | $4.8 \pm 0.6$ |
| 2003 May 30–31 | 18 | $4.8 \pm 0.7$ |
| 2003 May 31–1 | 45 | $4.9 \pm 0.8$ |
| 2003 Jun 1–2 | 39 | $6.2 \pm 3.0$ |
| 2003 Jun 2–3 | 48 | $6.9 \pm 3.3$ |
| 2003 Jun 5–6 | 44 | $6.4 \pm 3.3$ |
| 2003 Jun 6–7 | 50 | $4.9 \pm 1.8$ |
| 2003 Jun 7–8 | 49 | $4.5 \pm 0.6$ |

Note.—The photometry in this study is uncalibrated.

## 4. DATA ANALYSIS

### 4.1. *Data Reduction*

Observations of the target cluster were reduced in the standard fashion, employing IRAF[2] routines to correct the raw data. The bias level was subtracted using a fit to the overscan region of the CCD frames, and the overall noise level was further adjusted using a set of master bias frames. Pixel-to-pixel sensitivity variations were corrected through the use of flat-fielding. Twilight flats were used where possible; otherwise, dome flats were employed.

### 4.2. *Photometry*

Photometry was performed using the DAOPHOT II ALLSTAR suite of programs (Stetson 1987). Typically, 80–100 bright, well-isolated stars were selected in construction of the frame point-spread function (PSF). The selection was also constrained by the division of the frame into 25 spatial bins, ensuring that the PSF stars were adequately spread across the frame (which aids in mapping any possible PSF variations across the image). In order to perform consistent photometry from night to night, one master star list of 11,267 stars (constructed from the best frames of 2002

[2] The Image Reduction and Analysis Facility software is distributed by the National Optical Astronomy Observatory.

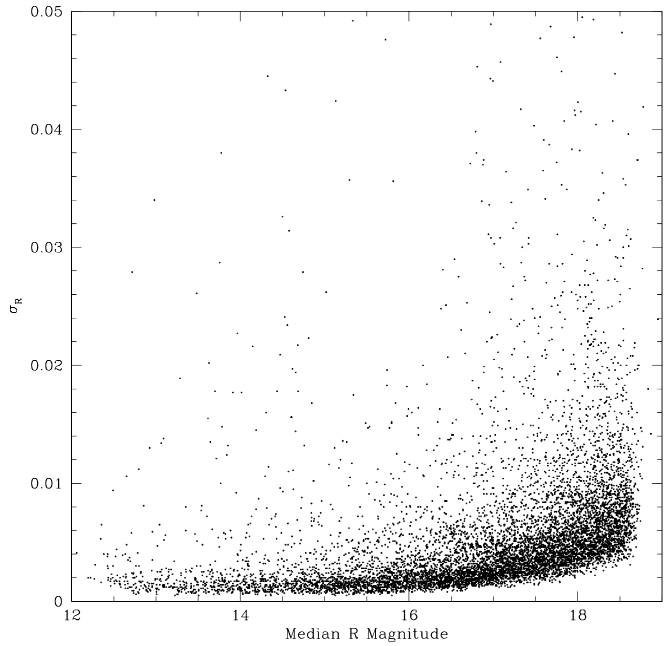


FIG. 1.—Results of the ensemble procedure used to iteratively determine the nightly zero points and median magnitudes. The error in the median $R$ magnitude, $\sigma_R$, as a function of median $R$ magnitude is shown.

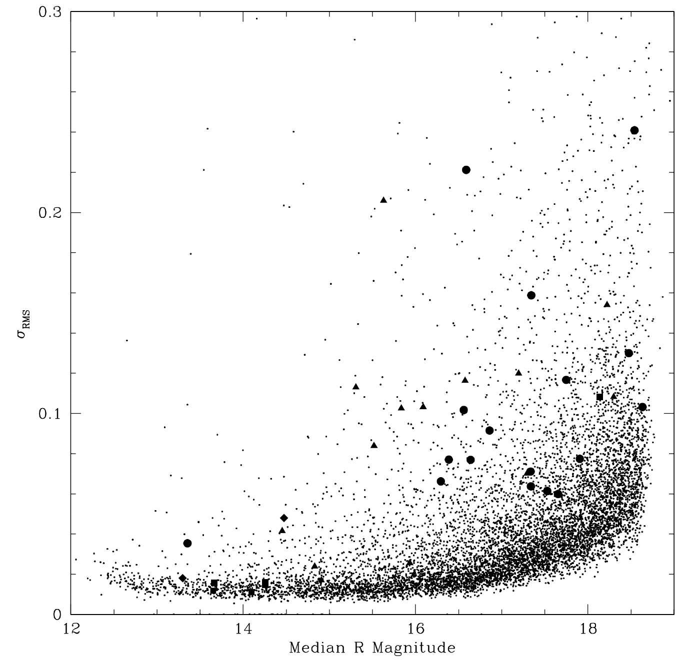


FIG. 2.—Results of the calculation of the rms variation $\sigma_{\rm rms}$ about the median $R$ magnitude for the total data set. The detected variables are denoted as follows: *squares*, $\delta$ Scuti or pulsating variables; *circles*, W UMa variables; *triangles*, detached eclipsing binaries; *diamonds*, unknown/unidentified variables.

August 8 and 9) was used uniformly throughout this study, and only these stars were studied for variability. The large numbers of stars in each frame ensured excellent frame-to-frame positional transformations, with typical transformations being accurate to better than 0.1 pixels. Night-to-night differences in the frame center and seeing conditions hindered measurements of every master star in every frame, but typically 9000–10,500 stars were measured in each night of data.

In order to improve the relative photometry for the light curves, ensemble techniques (Sandquist et al. [2003], based on a general method by Honeycutt [1992]) were used to determine a simultaneous, robust solution for the median magnitudes of all stars and the relative frame zero points. The initial solution resulted from the star-to-star comparisons determined from the positional transformations, and the solution was improved via iteration until neither the frame zero points nor the median magnitudes varied by more than 0.0003 mag. Also included in the iterative procedure was the possibility that the magnitude residuals could be a function of frame $x$- and $y$-position. Second-order polynomials were fitted to the magnitude residuals, and the solution was subtracted during the iterations. At most, these corrections were only a few hundredths of a magnitude. Figure 1 displays the results of the ensemble techniques, showing the error in the median $R$ magnitude as a function of median $R$ magnitude.

### 4.3. *Variable Star Detection*

The search for variable stars in the data set was conducted using several techniques. Because transits of extrasolar planets exhibit characteristics different from those of typical eclipsing binary systems and pulsating variables (primarily in amplitude and variability signature), we optimize our detection methods to search for detached eclipsing binary systems, W UMa variables, and $\delta$ Scuti and pulsating variables (that is, the higher amplitude variables). Algorithms optimized for planetary transit searches and low-amplitude variables will be implemented in a subsequent study. As a general test of variability, the rms variation about the $R$-band median magnitude was calculated for each star. The results of this calculation are shown as a function of median $R$ magnitude in Figure 2. Because this index is sensitive to outlier or spurious measurements, the variability statistics $I_{\rm WS}$ from Welch & Stetson (1993) and $J$ from Stetson (1996) were also employed, the statistics very often used when searching light curves for variability (Hebb et al. 2004; Bruntt et al. 2003; Mochejska et al. 2002). These indices use the correlation between closely spaced (in time) data pairs to determine variability. More specifically, the $I_{\rm WS}$ statistic is given as

$$I_{\rm WS} = \frac{1}{\sqrt{n(n-1)}} \sum_{i=1}^{n} \left[ \left( \frac{m_1 - m_{\rm med}}{\sigma_1} \right) \left( \frac{m_2 - m_{\rm med}}{\sigma_2} \right) \right]_i,$$

where $m_{1,2}$ are the first- and second-magnitude measurements of the $i$th data pair, $\sigma_{1,2}$ are the propagated errors of the magnitude differences, $m_{\rm med}$ is the calculated median magnitude, and $n$ is the total number of data pairs. The results for the $I_{\rm WS}$ calculation are shown in Figure 3. Also, the Lomb-Scargle power spectrum (Scargle 1982) was calculated between 1 hr and 1 day (period sampling of 0.001 day) for every light curve in the data set, and the peak power and corresponding period were recorded. The Lomb-Scargle routine can be used in this way as a variability detection method. Being a Fourier analysis method, it is particularly sensitive to stars with periodically varying light curves resembling sine or cosine functions (such as the W UMa variables).

While the $I_{\rm WS}$ and $J$ variability statistics are generally more sensitive to variability than the rms search, the relatively high level of the noise in Figure 3 makes the detection of variables difficult. This most likely arises as a consequence of correlated seeing variations in a spatially crowded field in which stars of comparable magnitude have a significant amount of overlap (see Sandquist & Shetrone 2003; Hebb et al. 2004 for further discussion). To overcome this difficulty we calculate the $I_{\rm WS}$ and $J$ statistics for each star *for each night* of data and examine those stars that have a large percentage change in the statistic from

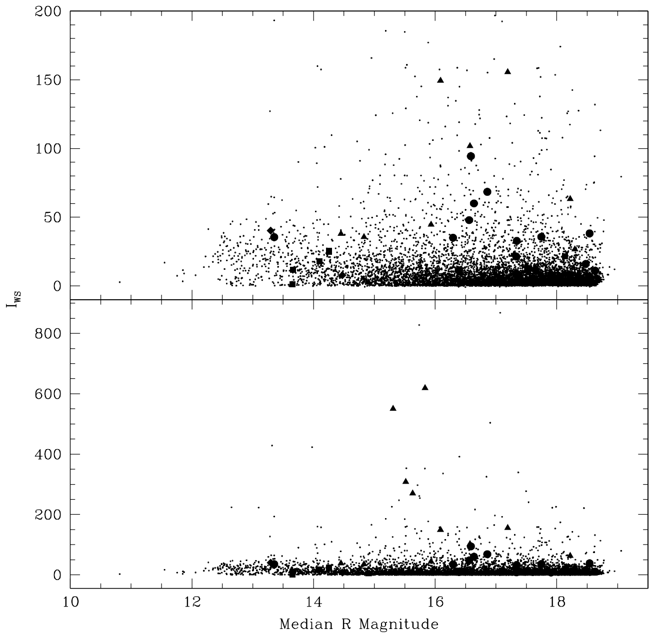


FIG. 3.—Results of the calculation of the Welch-Stetson variability index $I_{WS}$ as a function of median $R$ magnitude for the total data set. The top panel is identical to the bottom but highlights the low-scoring variables. The symbols are the same as in Fig. 2.

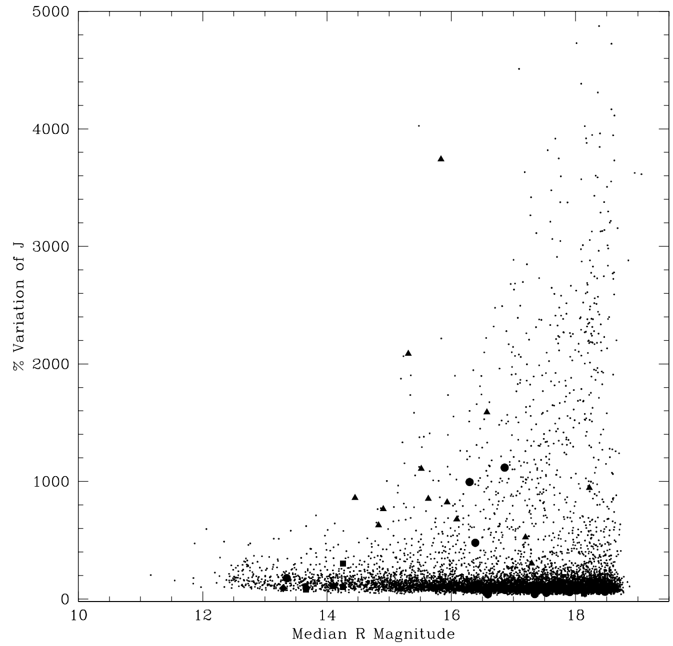


FIG. 4.—Results of the calculation of the percentage of night-to-night changes in the Stetson $J$ variability statistic as a function of median $R$ magnitude for the total data set. This calculation is sensitive to the detection of eclipsing binary stars; see § 4.3 for details. The detected variables are denoted as follows: *squares*, $\delta$ Scuti or pulsating variables; *circles*, W UMa variables; *triangles*, detached eclipsing binaries; and *diamonds*, unknown/unidentified variables.

night to night. This will be particularly useful for detecting detached eclipsing binary systems, as the system will have little or no intrinsic variability on some nights (low $I_{WS}$ or $J$ when the system is not eclipsing) but will have relatively high variability scores (high $I_{WS}$ or $J$ when the system is eclipsing) on others. The results of this calculation are displayed in Figure 4, showing that 13 of the 14 detected detached eclipsing binary systems stand out easily above the noise. While the $I_{WS}$ and $J$ statistics are imperfect due to the crowded field conditions, the use of multiple detection techniques (designed to identify specific types of variability) significantly increases the probability of detection. In general, variables were detected by viewing the light curves of stars above a reasonably low threshold in these statistics ($I_{WS} > 15$, $J > 15$, percentage variation of $J > 200\%$).

Once a variable star was detected, the period was determined using two slightly different techniques. Both the Lomb-Scargle (Scargle 1982) periodogram and the variation of the Lafler-Kinman algorithm (Lafler & Kinman 1965) by Deeming (Bopp et al. 1970) were calculated for each variable star that showed multiple events in the data set. The Lomb-Scargle calculation consists of fitting sine and cosine terms of various frequencies corresponding to possible periodicities in the data. The Lafler-Kinman search examines the light curve, folded on a trial period, for the minimization of differences between data points that are adjacent in phase space. Agreement between the two methods was excellent.

In order to confirm any suspected variable stars that may be in the M11 field and cross-reference our detections with previous studies, a search of the General Catalog of Variable Stars (Kholopov et al. 1998) was undertaken. This search revealed three suspected variables in the cluster field: NSV 11410 (suspected long-period, slowly irregularly pulsating variable), 11402 (suspected long-period, slowly pulsating variable), and 24615 (unspecified variable type). The star NSV 24615 is located near, if not coincident with, the brightest star in the cluster (HD 174512), which was saturated in our study. Searches around the coordinates of NSV 11410 and NSV 11402 did find nearby stars, but no variability was detected. Given that the suspected variables are proposed slow variables, it remains plausible that the stars actually are variable in nature but that variability would be undetected over a short span of observations (3–10 days). No long-term (year-to-year) variability was noted in the light curves. Of the six previously known variable stars (see § 2.2), three were saturated (V369 Sct and the two spectroscopic binaries of Lee et al. [1989]), and two were located outside the field of study (BS Sct and IT Sct). Thus, photometry was obtained only for star 770 from McNamara et al. (1977). However, no sign of variability was detected. The star does appear to be a cluster member (by position on the CMD) but does not lie in the theoretical instability strip. Given that V369 Scuti (and possibly star 770 from McNamara et al. [1977]) is the only known variable star in the field of M11 covered in this study, all the variable stars in this study are new discoveries.

## 5. COLOR-MAGNITUDE DIAGRAM

One tool for estimating cluster membership for the detected variable stars is the CMD. Figures 5 and 6 show the CMD of the M11 field derived from the measurement of 8259 stars in this study; this is the total sample of stars measured in both the $R$ and $V$ images. Also marked are the detected variable stars from Table 2 and the theoretical instability strip from Pamyatnykh (2000). The theoretical isochrones from the Yonsei-Yale ($Y^2$) stellar evolution models (Kim et al. 2002) are shown for comparison (color-$T_{\rm eff}$ transformations from Lejeune et al. [1998]). The metallicity was chosen as $Z = 0.02$ in order to make a direct comparison with the CMDs of Sung et al. (1999). Figure 6 shows the theoretical isochrone from the Padova group (Girardi et al. [2000], with color-$T_{\rm eff}$ transformations described in Girardi et al. [2002]), generated for an identical metallicity and age ($\log t_{\rm age} = 8.3$ yr). Because the observed data are uncalibrated, the magnitudes and colors were shifted to match the theoretical isochrones. The derived

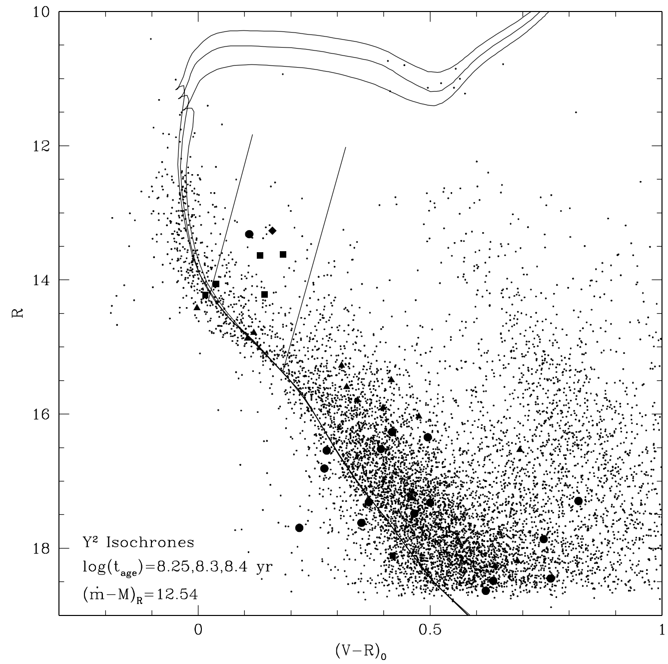


FIG. 5.—$R$, $(V-R)$ CMD. Overlaid are the $Y^2$ theoretical isochrones and the theoretical instability strip from Pamyatnykh (2000). The detected variable stars are denoted as follows: *squares*, $\delta$ Scuti or pulsating variables; *circles*, W UMa variables; *triangles*, detached eclipsing binaries; and *diamonds*, unknown/unidentified variables.

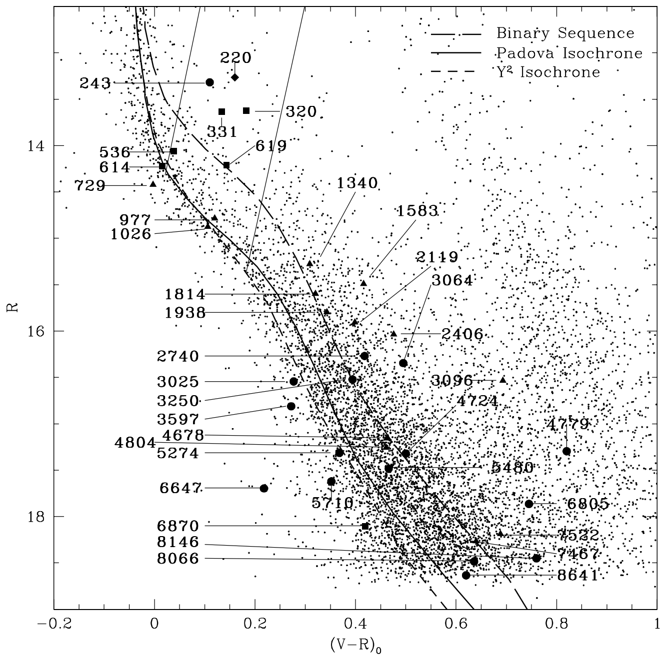


FIG. 6.—$R$, $(V-R)$ CMD with variable stars identified. Overlaid are the theoretical isochrone from the Padova and $Y^2$ groups, the theoretical binary sequence, and the theoretical instability strip from Pamyatnykh (2000). The symbols are the same as in Fig. 2.

unreddened distance modulus from Sung et al. (1999) was used to shift the $Y^2$ models to the apparent magnitude scale by adding the appropriate amount of reddening, assuming $E(B-V)=0.428$ and $R=3.1$ (Sung et al. 1999). This shifting of the observed data was done only for convenient plotting. We have not produced standard magnitudes, and we have not done anything requiring standard magnitudes.

As first noted by Mathieu (1984), the CMD of the M11 field appears to have not only the typical red field star population, which is easily distinguished from the cluster MS but also, a population of stars overlapping the cluster MS starting at approximately $V\sim 15$ ($R\sim 15.5$) and fainter. The field population is bimodal; there exists a "red" field star population [$(V-R)_0>0.7$] and a "blue" field star population [$0.25<(V-R)_0<0.7$]. The blue field star population hampers the identification of cluster members via the CMD for many of the detected variable stars in this study. Membership for individual variables is discussed in §§ 6.1–6.3.

## 6. LIGHT CURVES

### 6.1. *δ Scuti Variables*

In Figure 7 we show sample light curves for the six $\delta$ Scuti variables (stars 320, 331, 536, 614, 619, and 6870) detected in this study. As can be seen in Figures 5 and 6, the cluster MS just begins to intersect the faint edges of the theoretical instability strip (Pamyatnykh 2000), and so a $\delta$ Scuti population in this cluster is not surprising. Given the bright magnitude of these objects, membership probabilities are available from the McNamara et al. (1977) proper-motion study; these are given in Table 2.

Particularly interesting is the variable star 6870, which shows an amplitude of variation of more than an order of magnitude greater than the five other detected $\delta$ Scuti variables. This star is likely a member of a subclass of $\delta$ Scuti variables known as high-amplitude $\delta$ Scuti variable stars (see Rodriguez 2004 and references therein). These differ from regular $\delta$ Scuti pulsators in that they have significantly larger amplitudes of variation (often greater than 0.3 mag), appear to have only one or two radial pulsation modes (and no nonradial modes), and have slower rotation speeds (Rodríguez et al. 1996). Star 6870 is likely a field population MS star, as $\delta$ Scuti variability would position the star inside or near the instability strip if it were a cluster member. Use of the period-density relation for $\delta$ Scuti stars (Breger 2000) yields a stellar density typical of MS stars.

### 6.2. *Semidetached and Detached Eclipsing Binaries*

In Figure 8 we show the light curves for the 14 detached eclipsing binary systems detected in this study. Multiple eclipses were detected for 6 of the 13 systems, and hence periods were determined (listed in Table 2) for these systems. Stars 1814 and 4678 show characteristics of RS CVn-type eclipsing binaries, namely, the large light-curve scatter and rapidly changing light-curve shapes (presumably due to quickly changing starspot activity). Stars 1583 and 3096 show light curves typical of Algol-type semidetached systems, while stars 1340 and 1938 show little or no outside-of-eclipse light variations and are likely detached systems. In 8 of the 14 detected systems only one or two events were detected, and therefore, periods could not be determined.

In terms of cluster membership, we are only able to make reasonable judgments about the brightest stars owing to the overlap of the field star population noted in § 5. Both stars 729 and 977 show positions on the CMD consistent with cluster membership. The proper-motion study by McNamara et al. (1977) further supports this conclusion; they determine membership probabilities of 81% and 52% for stars 729 and 977, respectively. While McNamara et al. (1977) find a very low membership probability for star 1026 (7%), the position of this system near the cluster MS suggests it is likely a cluster member. Stars 1340, 1814, and 1938 show positions near the equal-mass binary sequence, but given the presence of the overlapping field star population below $R=\sim 15.5$, we are unable to definitively claim cluster

TABLE 2
Detected Variable Stars

| ID (1) | GSC (2) | $ID_{MPS}$ (3) | $P$ (%) (4) | R.A. (5) | Decl. (6) | $m_V$ (7) | $\sigma_V$ (8) | $m_{R_{med}}$ (9) | $\sigma_{R_{med}}$ (10) | $(V-R)_0$ (11) | $I_{WS}$ (12) | $\sigma_R$ (13) | $T$[a] (14) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 220 | ... | 683 | 0 | 18 51 14.8 | −06 18 26.3 | 13.665 | 0.006 | 13.2648 | 0.0015 | 0.160 | 45.06 | 0.016 | 4 |
| 243 | 5126:4687 | 1268 | 62 | 18 51 00.2 | −06 14 49.2 | 13.706 | 0.006 | 13.3183 | 0.0050 | 0.110 | 78.94 | 0.041 | 3 |
| 320 | 5126:5601 | 1711 | 98 | 18 50 43.6 | −06 19 47.5 | 14.044 | 0.006 | 13.6210 | 0.0014 | 0.183 | 5.59 | 0.013 | 1 |
| 331 | 5126:4823 | 676 | 0 | 18 51 15.1 | −06 15 43.8 | 14.006 | 0.006 | 13.6330 | 0.0021 | 0.134 | 24.14 | 0.017 | 1 |
| 536 | 5126:5659 | 1531 | 96 | 18 50 52.4 | −06 15 59.1 | 14.339 | 0.007 | 14.0610 | 0.0021 | 0.038 | 10.15 | 0.016 | 1 |
| 614 | 5126:5664 | 1237 | 83 | 18 51 00.6 | −06 14 04.4 | 14.479 | 0.007 | 14.2232 | 0.0015 | 0.016 | 38.97 | 0.017 | 1 |
| 619 | ... | 1097 | 80 | 18 51 03.9 | −06 21 35.2 | 14.595 | 0.007 | 14.2124 | 0.0017 | 0.143 | 57.77 | 0.018 | 1 |
| 708 | ... | 1521 | 0 | 18 50 52.5 | −06 10 07.7 | ... | ... | 14.4427 | 0.0213 | ... | 7.39 | 0.047 | 4 |
| 729 | ... | 900 | 81 | 18 51 08.1 | −06 16 01.7 | 14.659 | 0.007 | 14.4220 | 0.0022 | −0.003 | 46.98 | 0.040 | 2 |
| 977 | ... | 1596 | 52 | 18 50 49.1 | −06 14 49.7 | 15.146 | 0.007 | 14.7862 | 0.0019 | 0.120 | 45.78 | 0.026 | 2 |
| 1026 | ... | 1715 | 7 | 18 50 43.4 | −06 13 18.0 | 15.220 | 0.007 | 14.8742 | 0.0016 | 0.106 | 38.043 | 0.018 | 2 |
| 1340 | ... | ... | ... | 18 51 17.0 | −06 12 38.6 | 15.825 | 0.009 | 15.2757 | 0.0017 | 0.309 | 224.04 | 0.104 | 2 |
| 1583 | ... | ... | ... | 18 50 33.4 | −06 21 19.2 | 16.149 | 0.009 | 15.4925 | 0.0032 | 0.416 | 597.41 | 0.093 | 2 |
| 1814 | ... | ... | ... | 18 51 23.1 | −06 20 49.2 | 16.157 | 0.012 | 15.5967 | 0.0114 | 0.320 | 219.03 | 0.208 | 2 |
| 1938 | ... | ... | ... | 18 51 16.5 | −06 11 47.3 | 16.377 | 0.009 | 15.7942 | 0.0022 | 0.343 | 604.43 | 0.094 | 2 |
| 2119 | ... | ... | ... | 18 50 41.9 | −06 22 56.9 | 16.543 | 0.009 | 15.9045 | 0.0016 | 0.399 | 7.15 | 0.025 | 2 |
| 2406 | ... | ... | ... | 18 50 59.4 | −06 22 05.3 | 16.750 | 0.010 | 16.0339 | 0.0077 | 0.476 | ... | 0.109 | 2 |
| 2740 | ... | ... | ... | 18 50 59.4 | −06 13 43.5 | 16.907 | 0.010 | 16.2690 | 0.0099 | 0.418 | 47.01 | 0.066 | 3 |
| 3025 | ... | ... | ... | 18 50 41.1 | −06 21 53.1 | 16.996 | 0.012 | 16.5437 | 0.0227 | 0.277 | 117.17 | 0.219 | 3 |
| 3064 | ... | ... | ... | 18 51 00.8 | −06 22 33.6 | 17.080 | 0.010 | 16.3454 | 0.0098 | 0.495 | 21.24 | 0.079 | 3 |
| 3096 | ... | ... | ... | 18 51 19.7 | −06 15 20.8 | 17.467 | 0.010 | 16.5342 | 0.0022 | 0.693 | 739.04 | 0.145 | 2 |
| 3250 | ... | ... | ... | 18 50 37.7 | −06 16 19.2 | 17.056 | 0.010 | 16.5221 | 0.0128 | 0.394 | 59.21 | 0.100 | 3 |
| 3408 | ... | ... | ... | 18 51 14.2 | −06 17 42.2 | ... | ... | 16.5916 | 0.0079 | ... | 89.16 | 0.094 | 3 |
| 3597 | ... | ... | ... | 18 51 17.6 | −06 11 36.9 | 17.303 | 0.011 | 16.8114 | 0.0113 | 0.272 | 34.01 | 0.092 | 3 |
| 4678 | ... | ... | ... | 18 50 36.4 | −06 12 24.3 | 17.858 | 0.013 | 17.1555 | 0.0057 | 0.462 | 9.01 | 0.115 | 2 |
| 4724 | ... | ... | ... | 18 50 35.2 | −06 18 41.0 | 18.126 | 0.013 | 17.3207 | 0.0073 | 0.500 | 25.38 | 0.064 | 3 |
| 4779 | ... | ... | ... | 18 50 43.7 | −06 23 29.2 | 18.455 | 0.013 | 17.2955 | 0.0102 | 0.919 | 7.38 | 0.073 | 3 |
| 4804 | ... | ... | ... | 18 50 42.4 | −06 17 18.2 | 17.958 | 0.013 | 17.2570 | 0.0027 | 0.461 | 19.42 | 0.068 | 2 |
| 5274 | ... | ... | ... | 18 51 24.0 | −06 10 48.0 | 17.972 | 0.012 | 17.3137 | 0.0280 | 0.368 | 42.41 | 0.163 | 3 |
| 5480 | ... | ... | ... | 18 50 41.5 | −06 12 07.8 | 18.290 | 0.016 | 17.4844 | 0.0075 | 0.466 | 25.80 | 0.070 | 3 |
| 5710 | ... | ... | ... | 18 50 48.7 | −06 11 34.9 | 18.249 | 0.014 | 17.6210 | 0.0085 | 0.352 | 7.784 | 0.061 | 3 |
| 6647 | ... | ... | ... | 18 50 33.5 | −06 21 48.3 | 18.395 | 0.018 | 17.6968 | 0.0100 | 0.218 | 40.682 | 0.128 | 3 |
| 6805 | ... | ... | ... | 18 50 38.1 | −06 19 53.8 | 18.799 | 0.021 | 17.8643 | 0.0063 | 0.745 | 12.516 | 0.088 | 3 |
| 6870 | ... | ... | ... | 18 51 18.8 | −06 13 22.4 | 18.766 | 0.016 | 18.1076 | 0.0117 | 0.419 | 28.16 | 0.113 | 1 |
| 7467 | ... | ... | ... | 18 51 23.0 | −06 21 41.2 | 19.145 | 0.021 | 18.2640 | 0.0114 | 0.640 | 34.06 | 0.107 | 2 |
| 7522 | ... | ... | ... | 18 51 22.6 | −06 21 01.9 | 19.115 | 0.021 | 18.1868 | 0.0043 | 0.688 | 45.02 | 0.141 | 2 |
| 8066 | ... | ... | ... | 18 50 32.3 | −06 19 53.4 | 19.211 | 0.024 | 18.4849 | 0.0269 | 0.636 | 47.64 | 0.263 | 3 |
| 8146 | ... | ... | ... | 18 51 10.2 | −06 12 50.1 | 19.332 | 0.022 | 18.4508 | 0.0170 | 0.760 | 21.12 | 0.132 | 3 |
| 8641 | ... | ... | ... | 18 51 09.3 | −06 11 47.1 | 19.588 | 0.028 | 18.6337 | 0.0137 | 0.620 | 20.23 | 0.133 | 3 |

Notes.—The data included in the table columns are as follows: Col. (1): Variable identification number from this study. Col. (2): Variable identification number from the *Hubble Space Telescope* Guide Star Catalog. Col. (3): Variable identification number from McNamara et al. (1977). Col. (4): Membership probability as determined by McNamara et al. (1977). Col. (5): Right ascension (J2000.0; units of right ascension are hours, minutes, and seconds). Col. (6): Declination (J2000.0; units of declination are degrees, arcminutes, and arcseconds). Col. (7): Mean $V$ apparent magnitude. Col. (8): The 1 $\sigma$ error on the mean $V$ apparent magnitude. Col. (9): Median $R$ apparent magnitude. Col. (10): The 1 $\sigma$ error on the median $R$ apparent magnitude. Col. (11): $(V-R)$ color index (shifted to match theoretical isochrones; see § 5 for details). Col. (12): Computed value for the Welch-Stetson variability statistic $I_{WS}$. Col. (13): Computed value for the Stetson $J$ variability statistic. Col. (14): Type of variability.

[a] Type of variable star: 1, $\delta$ Scuti or pulsating variable; 2, detached eclipsing binary; 3, W UMa variable; 4, unknown/unidentified variable.

membership without further data on these or fainter systems. Finally, although star 2119 shows total eclipses in its light curve, its position in the CMD indicates that it is almost certainly a part of the field population, so we have not pursued it further.

### 6.3. *W Ursae Majoris Variables*

In Figure 9 we show the light curves for the 17 W UMa variables (contact binary systems) detected in this study. The differences in the shapes of the light curves of these systems are primarily due to three main effects: the orbital inclination (influencing the depth of eclipses), the degree of fill-out of the Roche geometry (influencing the steepness of the eclipses and the "broadness" of the light curves at quadratures), and the mass ratio. In order to make a judgment regarding the geometric configuration of these systems, we modeled the data of the brightest systems using the Binary Maker 3 light-curve synthesis program (Bradstreet & Steelman 2002). Given the lack of spectroscopically determined mass ratios, elaborate fitting of the data using the Wilson-Devinney code (Wilson & Devinney 1971, hereafter WD71) or other fitting routines is not worthwhile for those systems that do not exhibit total eclipses. A mass ratio of $q = 0.4$ was assumed when modeling those systems. Modeling shows that these variables can easily be described as contact binary systems. We discuss the light curves and synthetic models of stars 3025 and 5274 below, both of which show evidence for total eclipses. In the

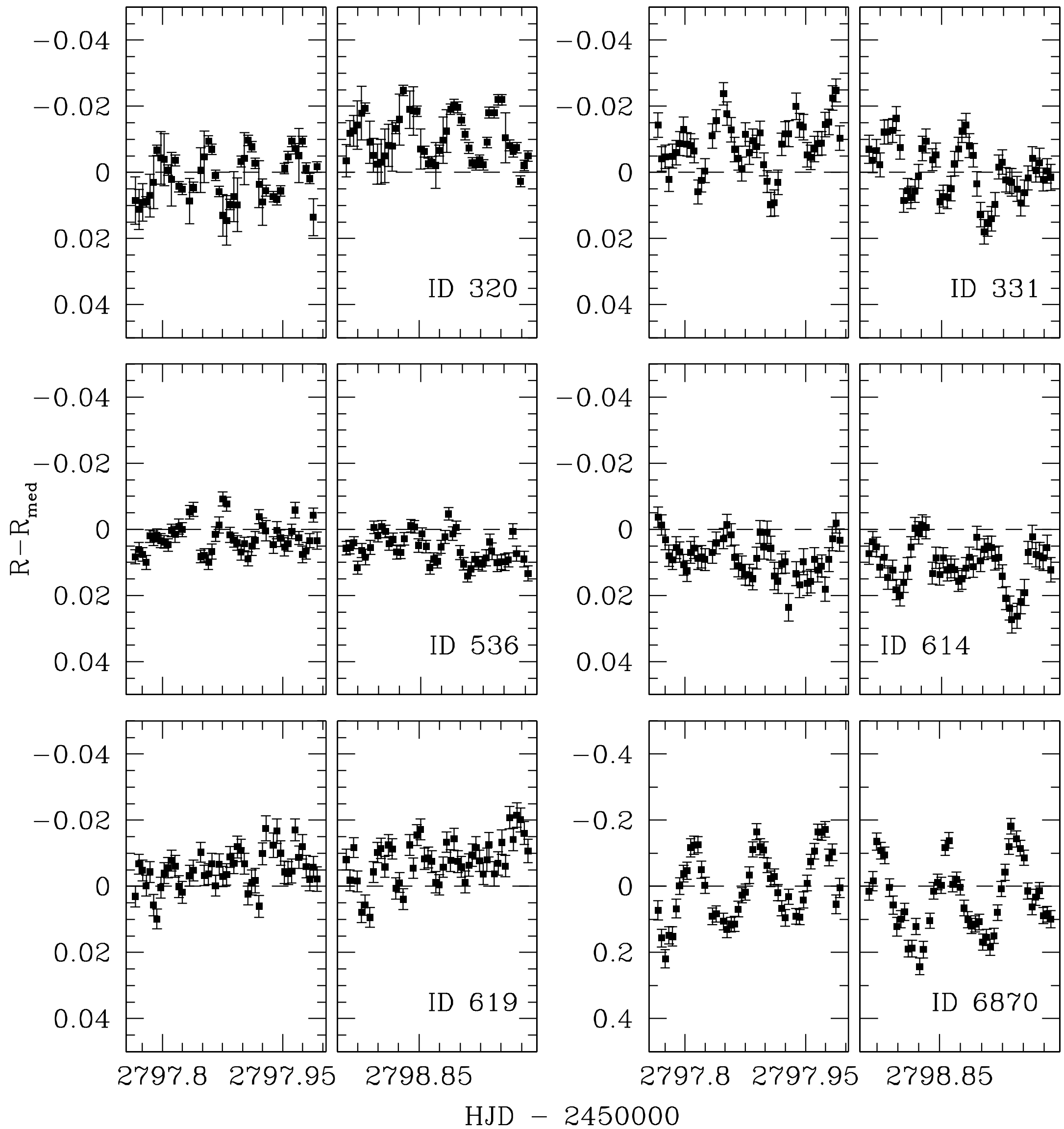


Fig. 7.—Light curves for the six $\delta$ Scuti variables detected in this study. Two nights of data are shown for each star.

case of totally eclipsing light curves the assumption of an arbitrary mass ratio is unnecessary; the duration of totality strongly constrains the possible combinations of inclination and mass ratio.

The CMD presents the primary tool by which to estimate cluster membership for these contact systems. It is likely that the detected systems are members of the field population for two reasons: (1) the large spatial separation of systems from the cluster center and (2) positions on the CMD that are inconsistent with the cluster MS and binary sequence. In the first case, we find that the radial distances from cluster center (col. [7], Table 3) are likely inconsistent with cluster membership in all but five (stars 243, 2740, 3408, 8146, and 8641) of the 17 cases. Figure 10 shows the positions of the detected W UMa systems relative to the brightest nonvarying cluster stars ($R > 15$), the cluster center, and the cluster half-mass radius (as determined by Mathieu 1984). For reference, Figure 10 also shows the positions of the other detected variables. These indicate that the W UMa systems are more concentrated within the field population than the other three types of detected variables, especially considering that dynamical evolution should concentrate member binary systems at the cluster center. In the second case, only 3 of the 17 W UMa systems (stars 5480, 8066, and 8641) have CMD positions between the cluster MS and binary sequence. While this could be indicative of cluster membership, we stress that the possible presence of differential reddening, statistically uncertain $V$ magnitudes that contribute to the $(V - R)$ position on the CMD, and the overlapping field star population in the CMD complicate these judgments. In summary, given the two criteria above for consideration of cluster membership, only star 8641 appears to have both a radial distance from the cluster center and a CMD position consistent with membership. While star 2740 is located spatially close to the cluster center, it is not easily distinguishable from the field star population on the CMD. No $V$ measurement was obtained for star 3408 due to the crowded nature of the M11 field, and hence no CMD information is available for that system. Because proper-motion data are available for star 243, we discuss the possibility of cluster membership below.

**Star 3025**: Short total eclipses are evident in the light curve of the variable star 3025 in Figure 11. Initial models were generated using Binary Maker 3, and the WD71 code was used to refine

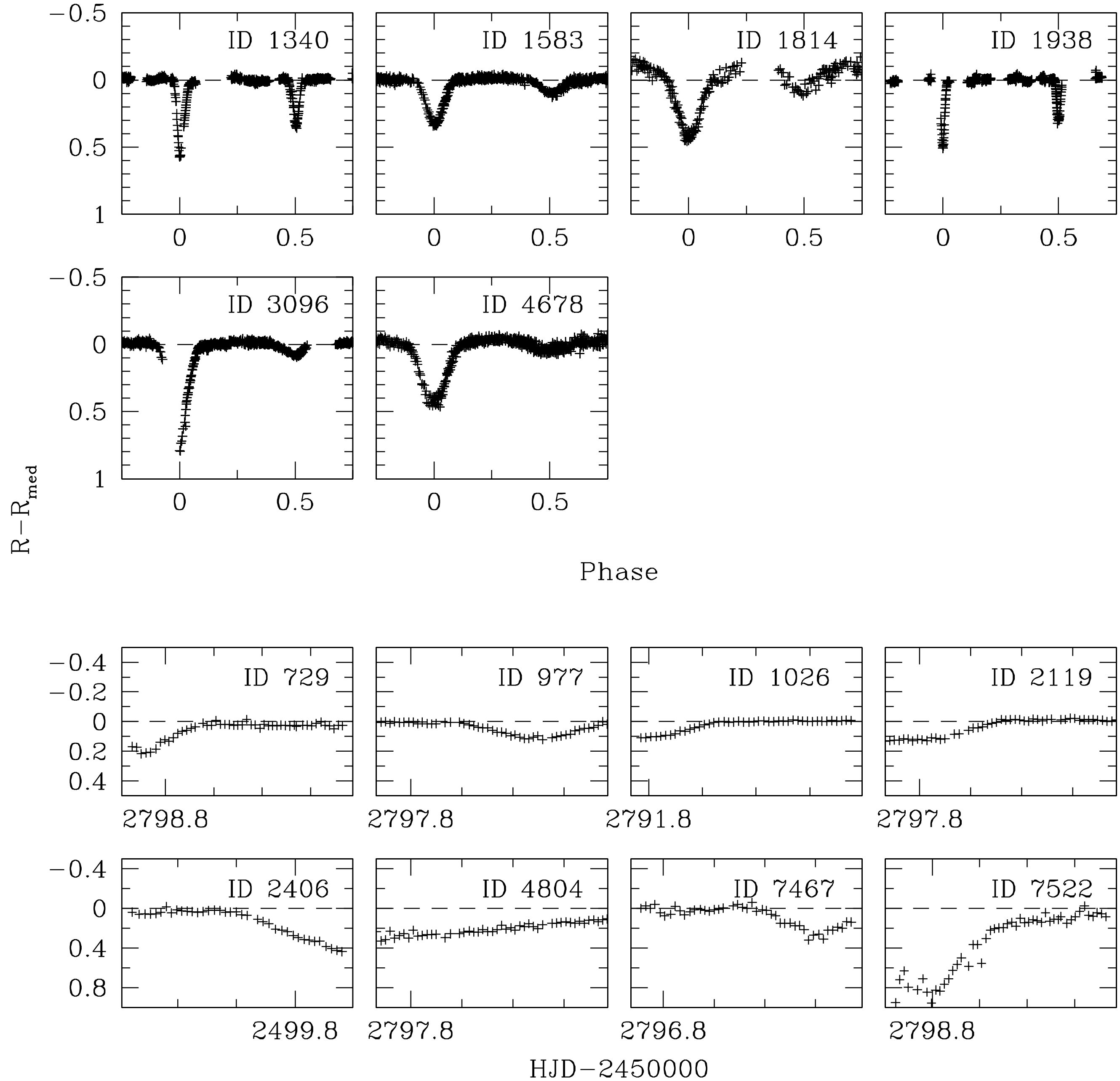


Fig. 8.—Light curves (types EA or EB) for eclipsing binary systems detected in this study. *Top panels*: Eclipsing binaries in which multiple eclipses were observed, allowing for the determination of an ephemeris. *Bottom panels*: Eclipse events for those systems in which only one or two eclipses were detected and no ephemeris could be determined.

these input model parameters. Figure 11 shows the observed light curve of star 3025 (data have been binned into 200 normal points), the three-dimensional model generated from Binary Maker 3, and the WD71 solution. The model parameters (adopted and fitted) are given in Table 4. The ephemeris (probable errors in parentheses) derived from the period study is given by the time of primary minimum = 2,452,495.74767 + 0.441864(3). Our analysis indicates that star 3025 is likely a typical A-type contact system, the larger star being hotter by approximately 100 K.

**Star 5274**: Individual nights of data for the variable star 5274 show evidence of a total primary eclipse. An initial model was generated using Binary Maker 3, biasing the solution to one with a combination of mass ratio, fill-out, and inclination that matched the total eclipse. To take a more unbiased approach to the analysis we used this initial model as input to WD71 to derive a final differential corrections solution. Figure 12 shows the observed light curve of star 5274 (data have been binned into 200 normal points), along with these two solutions. The model parameters are given in Table 5. We find the WD71 solution highly influenced by (1) the large scatter in the light curve and (2) the significant asymmetry in the quadratures (likely due to the presence of cool spots). The WD71 corrections appear to be favoring a lower inclination solution in order to fit the shoulders of quadrature around phase 0.25. Thus, the WD71 solution represents an averaging of the two different brightnesses at quadrature. We did not model the presence of spots in this system because of the large scatter and the lack of multibandpass observations. Our analysis finds star 5274 to be a W-type contact binary system, the larger star being cooler

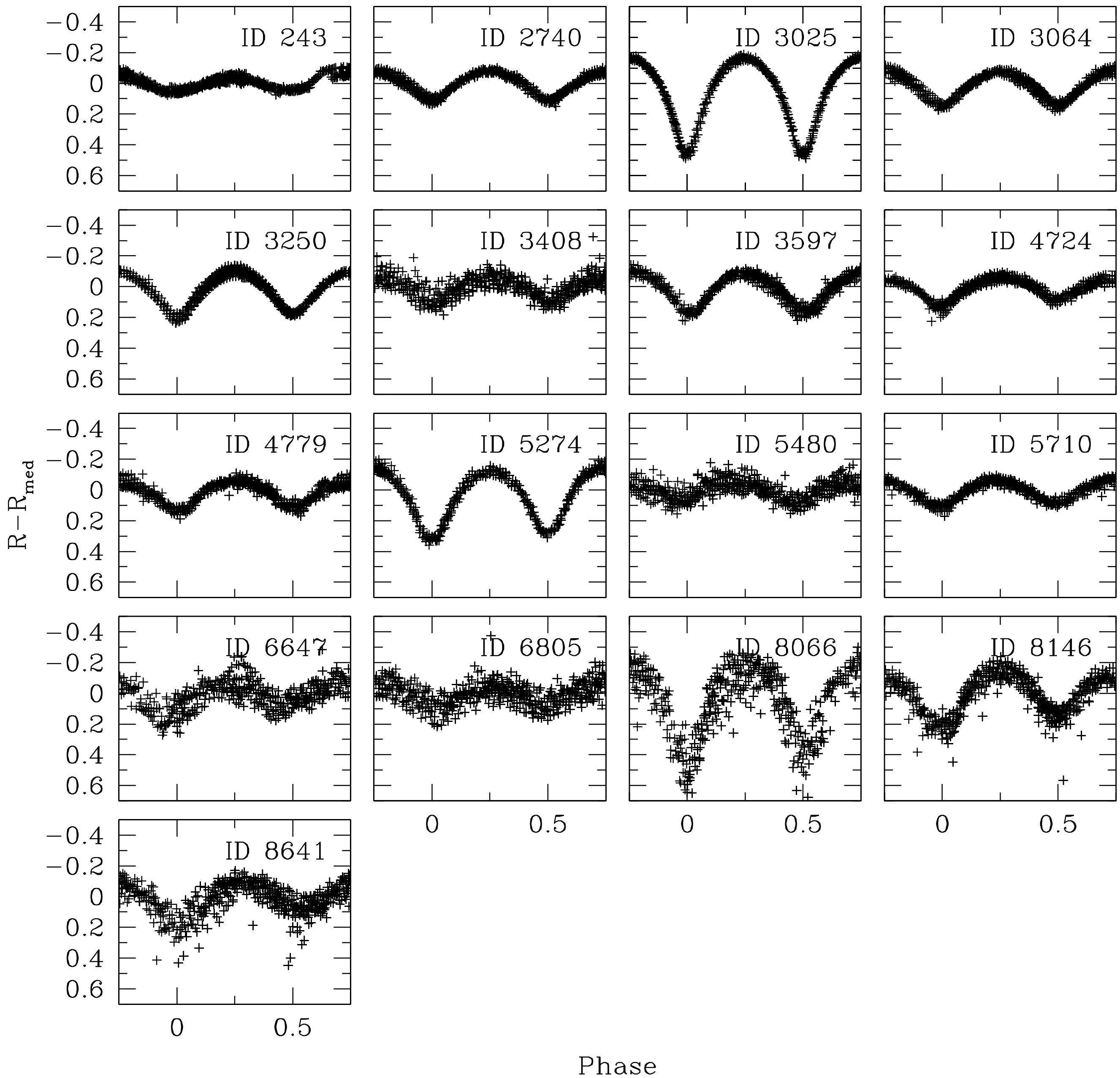


FIG. 9.—Light curves (type EW) for the W UMa variable stars detected in this study.

by approximately 450 K. The ephemeris (probable errors in parentheses) derived from the period study is given by the time of primary minimum $= 2{,}452{,}796.92403 + 0.3468800(1)$. While we believe the system to be totally eclipsing, the lower inclination solution calls into question the derived mass ratio. Given the large scatter in the data and the uncertainties in the inclination–mass ratio combination, these models should be considered preliminary. Higher precision, multifilter light curves are necessary to further constrain these models.

**Star 243**: For the variable star 243, independent cluster membership information is available from the proper-motion study of McNamara et al. (1977), who find a moderate probability of membership (62%). This object is also radially located within the cluster half-mass radius, adding further circumstantial evidence that this variable could be a cluster member. In terms of location on the CMD, this object falls inside the theoretical instability strip. It is unlikely, however, that this object is a cluster pulsating $\delta$ Scuti variable, since the necessary period ($P = 0.43289$ days for 1 pulse per cycle) would be at least an order of magnitude greater than typical $\delta$ Scuti variables. The light curve of star 243 is consistent with those of very low inclination W UMa variables, and given the longer period of the system, this presents a more reasonable interpretation of the variability. Spectroscopic data would help in the resolution of the true nature of this system and refine the question of membership in M11.

Despite this circumstantial evidence for cluster membership, the young age of the cluster may preclude a population of W UMa members. The presence of contact binary stars in young clusters would likely require either (1) the formation of systems with small initial orbital separations, such that an angular momentum loss mechanism could bring the stars into contact on a short timescale (Guinan & Bradstreet 1988), or (2) the birth of binary systems in the contact phase. While these scenarios may not be unlikely, the detection of contact systems in young or intermediate-age open

TABLE 3

Periods, Amplitudes, and Radial Distances from Cluster Center for Detected Variable Stars

| ID (1) | GSC (2) | $ID_{MPS}$ (3) | $P$ (%) (4) | Period[a] (days) (5) | Amplitude (mag) (6) | $r$ (arcmin) (7) | $T$[b] (8) |
|---|---|---|---|---|---|---|---|
| 220 | . . . | 683 | 0 | . . . | 0.05 | 3.71 | 4 |
| 243 | 5126:4687 | 1268 | 62 | 0.86577(1) | 0.17 | 1.55 | 3 |
| 320 | 5126:5601 | 1711 | 98 | 0.05453(1) | 0.02 | 5.99 | 1 |
| 331 | 5126:4823 | 676 | 0 | 0.04521(1) | 0.04 | 3.08 | 1 |
| 536 | 5126:5659 | 1531 | 96 | 0.04201(1) | 0.01 | 2.63 | 1 |
| 614 | 5126:5664 | 1237 | 83 | 0.06522(1) | 0.02 | 2.23 | 1 |
| 619 | . . . | 1097 | 80 | 0.04154(1) | 0.02 | 5.39 | 1 |
| 708 | . . . | 1521 | 0 | . . . | 0.15 | 6.63 | 4 |
| 729 | . . . | 900 | 81 | . . . | 0.20 | 1.32 | 2 |
| 977 | . . . | 1596 | 52 | . . . | 0.10 | 3.71 | 2 |
| 1026 | . . . | 1715 | 7 | . . . | 0.10 | 5.66 | 2 |
| 1340 | . . . | . . . | . . . | 3.79130(1) | 0.55 | 5.02 | 2 |
| 1583 | . . . | . . . | . . . | 1.11763(1) | 0.35 | 8.95 | 2 |
| 1814 | . . . | . . . | . . . | 0.70569(1) | 0.50 | 6.83 | 2 |
| 1938 | . . . | . . . | . . . | 5.62050(1) | 0.50 | 5.59 | 2 |
| 2119 | . . . | . . . | . . . | . . . | 0.10 | 8.53 | 2 |
| 2406 | . . . | . . . | . . . | . . . | 0.40 | 5.95 | 2 |
| 2740 | . . . | . . . | . . . | 0.39464(1) | 0.30 | 2.65 | 3 |
| 3025 | . . . | . . . | . . . | 0.441864(3) | 0.65 | 7.87 | 3 |
| 3064 | . . . | . . . | . . . | 0.44110(1) | 0.20 | 6.37 | 3 |
| 3096 | . . . | . . . | . . . | 1.65174(1) | 0.80 | 4.27 | 2 |
| 3250 | . . . | . . . | . . . | 0.35208(1) | 0.35 | 6.28 | 3 |
| 3408 | . . . | . . . | . . . | 0.25532(1) | 0.20 | 3.18 | 3 |
| 3597 | . . . | . . . | . . . | 0.47349(1) | 0.30 | 5.91 | 3 |
| 4678 | . . . | . . . | . . . | 0.72546(1) | 0.45 | 7.64 | 2 |
| 4724 | . . . | . . . | . . . | 0.41706(1) | 0.20 | 7.32 | 3 |
| 4779 | . . . | . . . | . . . | 0.38382(1) | 0.30 | 8.72 | 3 |
| 4804 | . . . | . . . | . . . | . . . | 0.30 | 5.21 | 2 |
| 5274 | . . . | . . . | . . . | 0.3468800(1) | 0.40 | 7.56 | 3 |
| 5480 | . . . | . . . | . . . | 0.43009(1) | 0.20 | 6.73 | 3 |
| 5710 | . . . | . . . | . . . | 0.46243(1) | 0.20 | 5.84 | 3 |
| 6647 | . . . | . . . | . . . | 0.43220(1) | 0.30 | 9.22 | 3 |
| 6805 | . . . | . . . | . . . | 0.34516(1) | 0.20 | 7.20 | 3 |
| 6870 | . . . | . . . | . . . | 0.08081(1) | 0.40 | 4.89 | 1 |
| 7467 | . . . | . . . | . . . | . . . | 0.30 | 7.43 | 2 |
| 7522 | . . . | . . . | . . . | . . . | 0.80 | 6.89 | 2 |
| 8066 | . . . | . . . | . . . | 0.42260(1) | 0.70 | 8.46 | 3 |
| 8146 | . . . | . . . | . . . | 0.29357(1) | 0.40 | 3.84 | 3 |
| 8641 | . . . | . . . | . . . | 0.45950(1) | 0.30 | 4.72 | 3 |

Notes.—The data included in the table columns are as follows: Col. (1): Variable identification number from this study. Col. (2): Variable identification number from the *Hubble Space Telescope* Guide Star Catalog. Col. (3): Variable identification number from McNamara et al. (1977). Col. (4): Membership probability as determined by McNamara et al. (1977). Col. (5): Period of detected variability. Col. (6): Maximum peak-to-peak amplitude of detected variability. Col. (7): Radial distance from cluster center. Col. (8): Type of variability.

[a] Probable errors (as determined by the precision of the period search) are given in parentheses. In some cases insufficient data (lack of multiple events) prevented a period determination.

[b] Type of variable star: 1, $\delta$ Scuti or pulsating variable; 2, detached eclipsing binary; 3, W UMa variable; 4, unknown/unidentified variable.

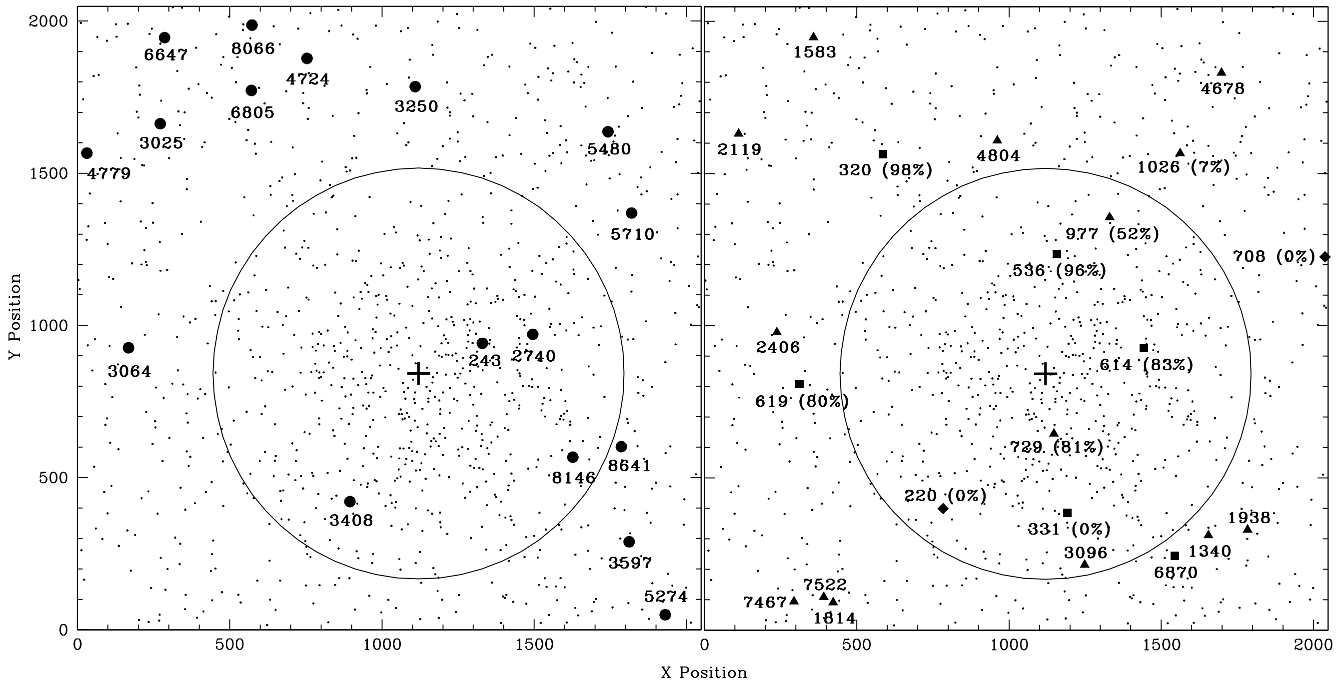


FIG. 10.—Reference frame positions for the variables detected in this study. *Left*: W UMa variables (*circles*). *Right*: Detected detached eclipsing binary systems (*triangles*), $\delta$ Scuti or pulsating variables (*squares*), and unknown/unidentified variables (*diamonds*). Shown for reference are stars brighter than $R = 15$ (*dots*) and the cluster half-mass radius ($r = 4'.5$; Mathieu 1984).

clusters (ages less than ~1 Gyr) remains elusive. Observational difficulties result from the presence of faint W UMa variables in a bright, crowded field; image exposure times must be long to detect faint variables, but longer exposure times result in the overexposure of the brightest stars.

### 6.4. *Candidate Variables*

In this study, two variable stars were detected that could not be readily identified from the shape of their light curves. The

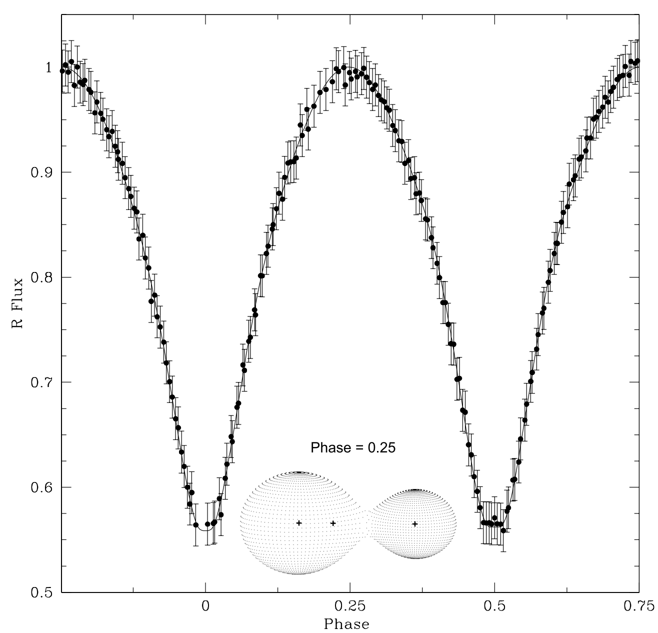


FIG. 11.—Phased light curve of star 3025 (200 *R*-band normal points) shown with the adopted Wilson-Devinney differential corrections synthetic fit.

TABLE 4

WILSON-DEVINNEY LIGHT-CURVE SOLUTION FOR STAR 3025

| Parameter | Value |
|---|---|
| Mass ratio | 0.417(2) |
| Period (days) | 0.4418638 |
| Inclination (deg) | 82.52(14) |
| Fill-out factor | 0.245 |
| Third light | 0.00 (assumed) |
| Phase shift | 0.00 (assumed) |
| Wavelength (Å) | 6400 |
| $\Omega_1$ | 2.6477(48) |
| $r_1$ (pole) | 0.44127(118) |
| $r_1$ (side) | 0.47349(163) |
| $r_1$ (back) | 0.50528(233) |
| $T_1$ (K) | 7300 (assumed) |
| $L_1$ | 0.6956(12) |
| $g_1$ | 1.00 (assumed) |
| $x_1$ | 0.405 (assumed) |
| $A_1$ | 1.00 (assumed) |
| $\Omega_2$ | 2.6477(48) |
| $r_2$ (pole) | 0.29830(99) |
| $r_2$ (side) | 0.31296(125) |
| $r_2$ (back) | 0.35532(252) |
| $T_2$ (K) | 7196(7) |
| $L_2$ | 0.3044 |
| $g_2$ | 1.00 (assumed) |
| $x_2$ | 0.405 (assumed) |
| $A_2$ | 1.00 (assumed) |

NOTES.—Parameter descriptions: fill-out factor, parametric characterization of the equipotential surface (percentage that the surface potential lies between the inner and outer Lagrangian surfaces); $\Omega_{1,2}$, parametric characterization of the gravitational equipotential surface; $r_{1,2}$ (pole, side, back), radii along differing axes of the system; $T_{1,2}$, effective surface temperature; $L_{1,2}$, fractional luminosity; $g_{1,2}$, gravity darkening (brightening) exponent; $x_{1,2}$, limb-darkening coefficient (from van Hamme 1993); $A_{1,2}$, bolometric albedo (reflection coefficent).

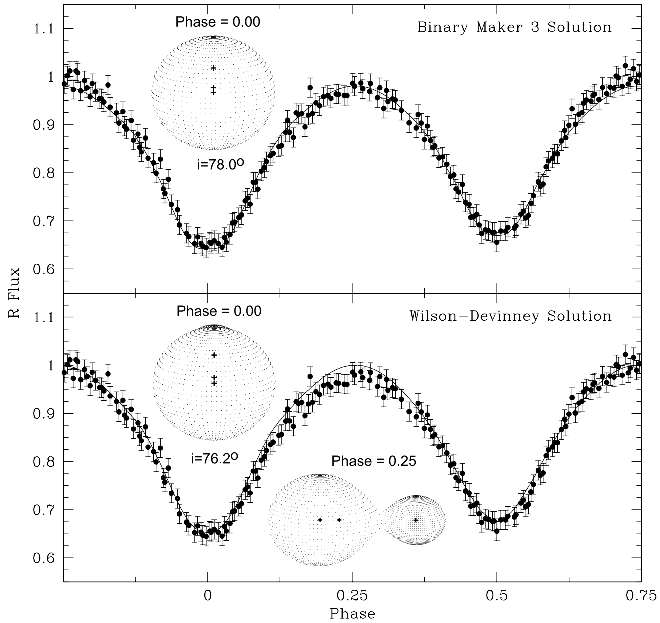


Fig. 12.—Phased light curve of star 5274 (200 $R$-band normal points) shown with the initial Binary Maker 3 synthetic fit (*top*) and the adopted Wilson-Devinney differential corrections synthetic fit (*bottom*). The three-dimensional models are displayed at phase 0.00 in both cases, showing that the Wilson-Devinney model just barely produces a nontotal primary eclipse.

data are shown in Figure 13, and we describe them individually below.

**Star 220**: This object, while located within the theoretical instability strip on the cluster CMD (see Fig. 6), has a membership probability of 0% as determined by McNamara et al. (1977). However, the proper-motion study by Su et al. (1998) finds a membership probability of 100%. Photometric variations are observed on both long (as shown in Fig. 13) and short timescales (at nearly the Nyquist frequency of the observations, ~10 minutes). The presence of the short- or long-term variability was observed to differ from night to night; thus, it is unclear to which category of variable stars this object belongs. The appearance of multiple frequencies of variability and possible cluster membership (and hence a CMD position in the instability strip) tends to argue for a type of pulsating variable.

**Star 708**: This object was near the edge of the reference frame and hence was only measured in two nights of observing. No $V$-band data were obtained for this star (since it was located just outside the reference frame), so the position on the CMD was not determined. It is unclear whether the minima in the light curves are a result of eclipses (from either a detached eclipsing binary or contact binary system) or minima in stellar pulsation.

TABLE 5
Light-Curve Solutions for Star 5274

| Parameter | Binary Maker 3 | Wilson-Devinney |
|---|---|---|
| Mass ratio | 0.25 | 0.236(6) |
| Period (days) | 0.3468800 | 0.3468800 |
| Inclination (deg) | 78.0 | 76.16(75) |
| Fill-out factor | 0.25 | 0.468 |
| Third light | 0.00 | 0.00 (assumed) |
| Phase shift | 0.50 | 0.50 (assumed) |
| Wavelength (Å) | 6400 | 6400 |
| $\Omega_1$ | 2.3135 | 2.2501(75) |
| $r_1$ (pole) | 0.47892 | 0.49062(293) |
| $r_1$ (side) | 0.52012 | 0.53639(441) |
| $r_1$ (back) | 0.54701 | 0.56554(608) |
| $T_1$ (K) | 6650 | 6550 (assumed) |
| $L_1$ | 0.7377 | 0.7462(64) |
| $g_1$ | 0.32 | 0.32 (assumed) |
| $x_1$ | 0.38 | 0.38 (assumed) |
| $A_1$ | 0.50 | 0.50 (assumed) |
| $\Omega_2$ | 2.3135 | 2.2501(75) |
| $r_2$ (pole) | 0.25770 | 0.26200(503) |
| $r_2$ (side) | 0.26953 | 0.27534(635) |
| $r_2$ (back) | 0.31077 | 0.32720(1586) |
| $T_2$ (K) | 7000 | 6995(22) |
| $L_2$ | 0.2623 | 0.2538 |
| $g_2$ | 0.32 | 0.32 (assumed) |
| $x_2$ | 0.38 | 0.38 (assumed) |
| $A_2$ | 0.50 | 0.50 (assumed) |

Notes.—Parameter descriptions: fill-out factor, parametric characterization of the equipotential surface (percentage that the surface potential lies between the inner and outer Lagrangian surfaces); $\Omega_{1,2}$, parametric characterization of the gravitational equipotential surface; $r_{1,2}$ (pole, side, back), radii along differing axes of the system; $T_{1,2}$, effective surface temperature; $L_{1,2}$, fractional luminosity; $g_{1,2}$, gravity darkening (brightening) exponent; $x_{1,2}$, limb-darkening coefficient (from van Hamme [1993]); $A_{1,2}$, bolometric albedo (reflection coefficent).

## 7. CONCLUSIONS

In conclusion, this work presents the first large-scale photometric variability survey of the intermediate-age (~200 Myr) open cluster M11. A total of 39 variable stars were detected and can be categorized as follows: one irregular (probably pulsating) variable, six $\delta$ Scuti variables, 14 detached eclipsing binary systems, 17 W UMa variables, and one unidentified/candidate variable. While previous proper-motion studies (McNamara et al. 1977; Su et al. 1998) allow for cluster membership determination for the brightest stars, we find that the membership determination is significantly hampered below $V = 15$, $R = 15.5$ by the large population of field stars with photometric colors similar to those of the cluster MS.

Of the detected systems, several are worth noting for follow-up work. First, three detached eclipsing binaries (stars 729, 977, and 1026) are likely cluster members but will require further photometric data to deduce the orbital period. Given more photometric and spectroscopic data on these systems, the derivation of the absolute parameters (masses and radii) could be useful in constraining theoretical stellar models. Second, of the six $\delta$ Scuti variables detected in this study (all of which are likely cluster members), further studies of the pulsation periods of stars 536 and 614 would make excellent tests of the blue edge of the theoretical instability strip. Third, the W UMa variable star 243 is a potential cluster member. If it can be confirmed that it is a cluster member and also a W UMa variable, it would be the first confirmation of a contact system in an open cluster younger than 0.7 Gyr. Further photometric study can help confirm the orbital period and light-curve variations, while spectroscopic observations will be critical in confirming the binary nature of the system. If the system is in fact a contact binary, it is likely that the spectrum will show double lines. Finally, we find two W UMa variables that exhibit total eclipses in their light curves and present preliminary models using Binary Maker 3 and Wilson-Devinney differential corrections. While the total secondary eclipse of the field W UMa variable star 3025 constrains the mass ratio of the system photometrically, a spectroscopic mass ratio would be more appropriate and would help in the determination of the absolute parameters of the system. Inspection of the light curve of star 5274 yields evidence of a total primary eclipse. However, the large scatter in the data and asymmetries in

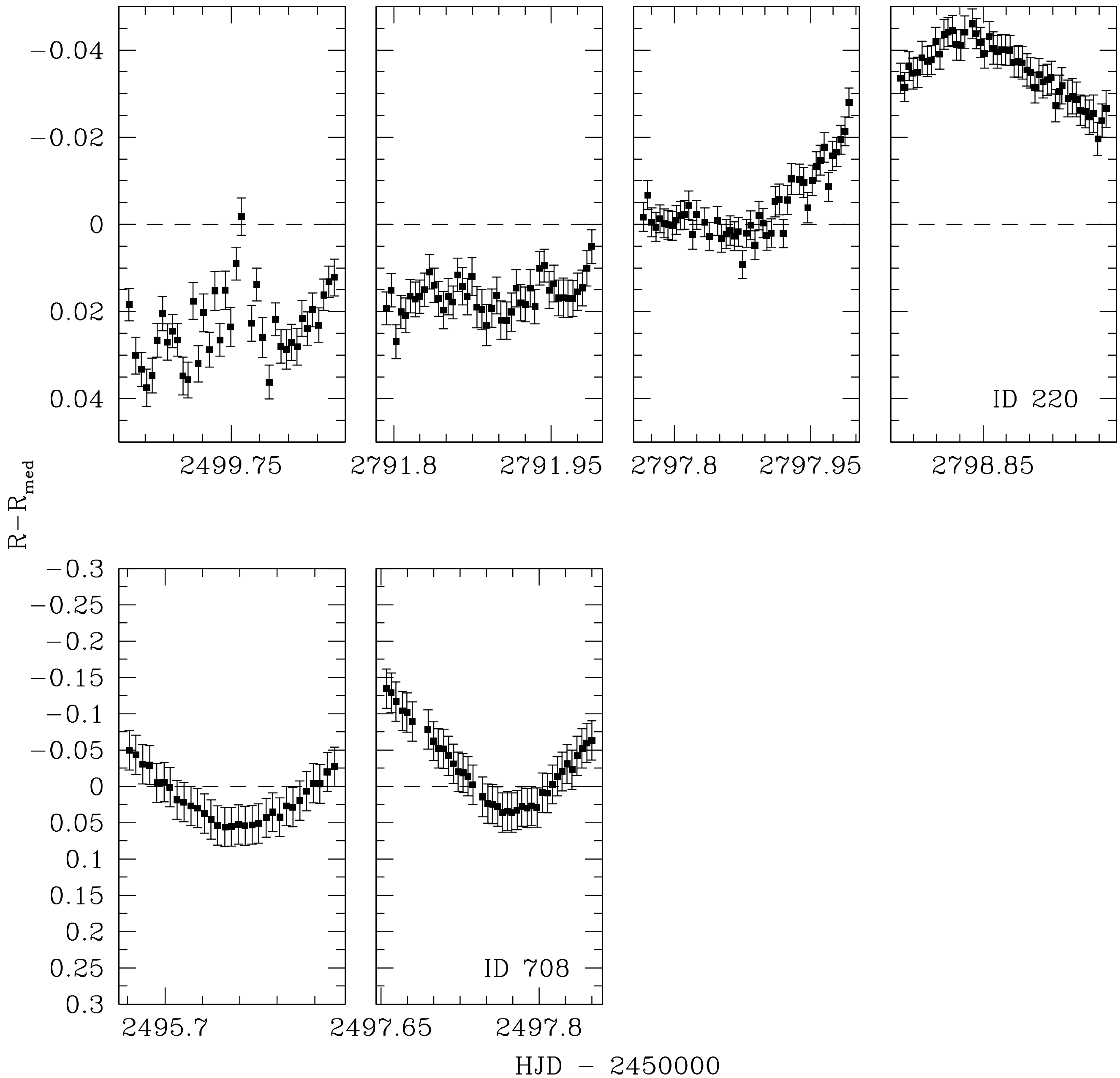


Fig. 13.—Light curves for the unknown/unidentified variables detected in this study. Four nights of data are shown for star 220 (showing both the long- and short-term variations). Two nights of data are shown for star 708.

the light curve favor a lower inclination solution that forces a partial eclipse model. Further high-precision, multifilter light curves and a spectroscopic mass ratio are necessary to further refine our preliminary models of this system.

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