

## PHOTOMETRY RESULTS FOR THE GLOBULAR CLUSTERS M10 AND M12: EXTINCTION MAPS, COLOR-MAGNITUDE DIAGRAMS, AND VARIABLE STAR CANDIDATES

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### ABSTRACT

We report on photometry results of the equatorial globular clusters (GCs) M10 and M12. These two clusters are part of our sample of GCs, which we are probing for the existence of photometrically varying eclipsing binary stars. During the search for binaries in M10 and M12, we discovered the signature of differential reddening across the fields of the clusters. The effect is stronger for M10 than for M12. Using our previously described dereddening technique, we create differential extinction maps for the clusters, which dramatically improve the appearance of the color-magnitude diagrams (CMDs). Comparison of our maps with the dust emissivity maps of Schlegel, Finkbeiner, & Davis (SFD) shows good agreement in terms of spatial extinction features. Several methods of adding an  $E_{V-I}$  zero point to our differential maps are presented, of which isochrone fitting proved to be the most successful. Our  $E_{V-I}$  values fall within the range of widely varying literature values. More specifically, our reddening zero-point estimate for M12 agrees well with the SFD estimate, whereas the one for M10 falls below the SFD value. Our search for variable stars in the clusters produced a total of five variables: three in M10 and two in M12. The M10 variables include a binary system of the W Ursae Majoris (W UMa) type, a background RR Lyrae star, and an SX Phoenicis pulsator, none of which is physically associated with M10. M12's variables are two W UMa binaries, one of which is most likely a member of the cluster. We present the phased photometry light curves for the variable stars, estimate their distances, and show their locations in the fields and the CMDs of the GCs.

*Key words:* binaries: eclipsing — color-magnitude diagrams — dust, extinction — globular clusters: individual (M10, M12, NGC 3201) — stars: Population II — stars: variables: general

*On-line material:* color figures

### 1. INTRODUCTION

Variable stars have historically served as important tools and “laboratories” in our understanding of star formation, the formation of stellar clusters, and the calibration of distance determination methods. In particular, the study of eclipsing binary stars (EBs) in a globular clusters (GC) may be used to obtain a value for the cluster's distance and a constraint concerning turnoff masses of the GC stars (Paczynski 1996).

Simply detecting EBs in the fields of GCs and confirming cluster membership is a straightforward—although data-intensive—task. These systems expand the relatively meager sample of EBs that are currently confirmed GC members (see, e.g., Mateo 1996; McVean et al. 1997; Rubenstein 1997; Rucinski 2000; Clement et al. 2001, and references therein). A statistical evaluation of the number of known member EBs in GCs can help in the determination of physical quantities such as the binary frequency in GCs as a parameter in the study of dynamical evolution of GCs (Hut et al. 1992).

Member stars of the clusters interact with each other, primarily toward the core of the GC where the stellar density is much higher than in the GC halo. Because of consequent redistribution of stellar kinetic energies and orbits, the core stars gradually diffuse into the halo that, as a result, grows in size. At the same time, the cluster core itself shrinks, and

its density will theoretically reach infinitely high values in a finite period of time ( $10t_{\text{relax}}-20t_{\text{relax}}$ , according to simulations, see Binney & Tremaine 1987), a phenomenon known as core collapse. Binary stars will most likely be located toward the GC center because of the fact that (1) they are more likely to form in regions of high stellar density, and (2) they will sink toward the core because of their high masses after a few cluster relaxation times. Since the binding energy of one individual hard binary<sup>1</sup> can be as high as a few to 10% of the binding energy of the entire GC, they may act as an energy source (similar to the nuclear reaction inside the centers of stars) to halt core collapse. A binary fraction as low as 10% in the cluster core will suffice to cool the central region of the GC by reversing the outward flow of energy toward the halo (Binney & Tremaine 1987; Hut et al. 1992) and arrest core collapse.

An additional use of simply detecting member EBs in GC lies in the calibration of absolute magnitudes of and corresponding distances to W Ursae Majoris (W UMa) binaries (Rucinski 1994, 1995, 2000; see also § 4.3).

<sup>1</sup> Hard binaries are systems whose binding energies are higher than the kinetic energies of the system itself and of the field star with which it might interact. Consequently, hard binaries tend to not be disrupted by encounters with other stars, but actually turn part of their kinetic energy into additional binding energy of the system.

The simultaneous analysis of photometric and spectroscopic data for individual EB systems can moreover provide a direct estimate of the distance to the system (Andersen 1991; Paczyński 1996) and thus, if the EB is a GC member, to the GC itself. The main sources of error in this distance determination are (1) the relation between surface brightness and effective temperature of the binary and (2) the precise determination of the interstellar reddening along the line of sight to the EB, which can vary substantially across the field of view of the GC. The distance determination method itself, however, is free of intermediate calibration steps and can provide direct distances out to tens of kiloparsecs. In turn, the knowledge of the distances to GCs can then be used to calibrate a variety of other methods, such as the relation between luminosity and metallicity for RR Lyrae stars. The very same analysis can, in principle, be used to obtain the Population II masses of the individual components of the EB system (Paczyński 1996) to provide a fundamental check of stellar models at low metallicities.

We are currently undertaking a survey of approximately 10 Galactic GCs with the aim of identifying photometrically variable EBs around or below the main-sequence turnoff (MSTO). Our observing strategy, aimed at detecting binaries in the period range of approximately 0.1–5 days (Hut et al. 1992), consists of repeated observations of a set of GCs during each night of an observing run. Multiple runs are helpful in detecting variables with a period of close to 1 day (or to a multiple thereof).

M10 (NGC 6254) and M12 (NGC 6218) are two equatorial clusters in our sample, located at  $\alpha = 16^{\text{h}}57^{\text{m}}08^{\text{s}}.9$  and  $\delta = -4^{\circ}05'58''$  (J2000.0;  $l = 15^{\circ}14$ ,  $b = 23^{\circ}08$ ) and at  $\alpha = 16^{\text{h}}47^{\text{m}}14^{\text{s}}.5$  and  $\delta = -1^{\circ}56'52''$  (J2000.0;  $l = 15^{\circ}72$ ,  $b = 26^{\circ}31$ ), respectively (Harris 1996). They are nearby (M10, 4.4 kpc; M12, 4.9 kpc), which makes them attractive targets for monitoring studies. Both clusters have been probed for the existence of variable stars in the past (for a summary, see Clement et al. 2001). Previous studies searched for luminous variables on the red giant and/or horizontal branch of the clusters and therefore do not overlap with the magnitude range covered in this work.

Details on our photometry observations and basic data reductions are given in § 2. We discuss how we correct for interstellar extinction along the line of sight to M10 and M12 in § 3. Section 4 contains the description and the results of our search for variable stars in the clusters including the phased light curves for the variables in the cluster fields and our estimates concerning distances and cluster membership. The methods used for §§ 3 and 4 are outlined in detail in two previous publications, namely von Braun & Mateo (2001), BM01 hereafter, and von Braun & Mateo (2002), BM02 hereafter, respectively. Finally, we summarize and conclude with § 5.

## 2. OBSERVATIONS AND DATA REDUCTIONS

### 2.1. Observations

The observations for M10 and M12 were obtained during multiple runs between 1995 June and 1999 May at the Michigan-Dartmouth-MIT (MDM) Observatory's 1.3 m and the Las Campanas Observatory (LCO) 1 m Swope Telescope. Tables 1 and 2 list the details. During all observing runs, we used 2048<sup>2</sup> pixel CCDs with different field sizes and standard Johnson-Cousins *VI* filters. The number of

TABLE 1  
M10 OBSERVATIONS

Date	Telescope	Field-of-View Size <sup>a</sup>	Number of Epochs <sup>b</sup>
1996 Apr .....	MDM 1.3 m	14.9	4
1997 May .....	LCO 1 m	23.5	29
1997 Jun .....	MDM 1.3 m	14.9	35
1997 Aug .....	LCO 1 m	23.5	23
1998 May <sup>c</sup> .....	LCO 1 m	23.5	25
1998 Aug .....	MDM 1.3 m	17	16
1998 Aug .....	LCO 1 m	23.5	14
1999 May .....	MDM 1.3 m	17	12

<sup>a</sup> In units of arcminutes on the side.

<sup>b</sup> This number of 600 s exposure time epochs is more or less evenly divided between *V* and *I*.

<sup>c</sup> During this run, we took additional 10 s exposures to complete the CMD in brighter regions. These shorter exposures were not used to look for variables.

epochs was about evenly divided between *V* and *I*. During two runs, we took additional shorter (10 s) exposures to complete the color-magnitude diagrams (CMDs) in the brighter regions (see Tables 1 and 2). These shorter observations were not used to look for variable stars because of infrequent time coverage. All exposures are centered on the cluster center itself. The reason for the rather large number of observing runs with relatively few epochs per run (compared with the other clusters in our sample) is the equatorial location of both M10 and M12. Consequently, neither cluster is ever located closer to the zenith than 30° from MDM, as well as from LCO. As a result, the clusters were observed for only up to ~2 hr each per night when seeing conditions were good, with the rest of the time dedicated to other clusters in our sample.

### 2.2. Data Processing and Reduction

The details of the IRAF<sup>2</sup> processing, as well as the basic data reduction of the 1998 May data are described in BM01,

<sup>2</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF.

TABLE 2  
M12 OBSERVATIONS

Date	Telescope	Field-of-View Size <sup>a</sup>	Number of Epochs <sup>b</sup>
1995 Jun .....	MDM 1.3 m	10.6	60
1996 Apr .....	MDM 1.3 m	14.9	4
1997 May .....	LCO 1 m	23.5	28
1997 Jun .....	MDM 1.3 m	14.9	39
1997 Aug <sup>c</sup> .....	LCO 1 m	23.5	18
1998 May .....	LCO 1 m	23.5	22
1998 Aug .....	MDM 1.3 m	17	16
1998 Aug .....	LCO 1 m	23.5	8
1999 May .....	MDM 1.3 m	17	10

<sup>a</sup> In units of arcminutes on the side.

<sup>b</sup> This number of 600 s exposure time epochs is more or less evenly divided between *V* and *I*.

<sup>c</sup> During this run, we took additional 10 s exposures to complete the CMD in brighter regions. These shorter exposures were not used to look for variables.

§ 2.1. The IRAF processing of the other data sets was performed in the same manner. All data were reduced using DoPHOT (Schechter, Mateo, & Saha 1993) in fixed-position mode after aligning every image to a deep-photometry template image consisting of the best seeing frames for each filter from every run (see BM01). Aperture corrections and a variable PSF were fitted to the 1998 May data as second-order polynomials in  $x$  and  $y$ . Our astrometric solutions for both cluster fields, based on approximately 120 US Naval Observatory (USNO) reference stars (Monet et al. 1996), respectively, produced linear fits in  $x$  and  $y$  with a random mean scatter of around  $0''.2$ , consistent with the USNO precision. Photometric calibration of the 1998 May data is described in BM01.

All other data were shifted to the coordinates and the photometric system of the 1998 May 600 s exposures, including the shorter exposures. In the process of combining the 10 s exposures with the deep data, we fitted for a zero point and color term to match the two sets, thereby effectively treating the deep data as photometric standards. Whenever we had two measurements for the same star, we kept the one with the lower photometric error associated with it (in most cases, this was the 600 s measurement). The division between the two photometry sets occurs around  $V \sim 17\text{--}17.5$ . We note that we are sensitive to variable detection to a magnitude as bright as  $V \sim 16.5$ , since the CCDs we used have different quantum efficiencies and some of the observations were taken through thin layers of clouds.

Photometric results for every star, weighted by the inverse square of the DoPHOT photometric error for the respective measurement, were averaged with the only requirement that a star appear<sup>3</sup> in approximately 20% or more of the epochs. This condition is much less stringent than its corresponding counterpart in the analysis of NGC 3201 (see BM01 and BM02) for which we set this threshold to 75%. The reason for the difference lies in the varying field sizes of the CCDs used for M10 and M12 (see Tables 1 and 2). A larger field (LCO data) will obviously include more stars than a smaller one, whereas a higher spatial resolution (MDM data) allows us to get closer to the GC center with our reductions.

### 2.3. Photometry Results and Comparison to Previous Studies

Our photometry results are presented, in the form of CMDs, in Figures 1 (M10) and 2 (M12). Based on similarities between the underreddened CMDs of NGC 3201 (presented in BM01) and M10, it appears that M10 suffers from differential reddening across the field of view, as previously suggested by, e.g., Kennedy, Bates, & Kemp (1996). M10's main sequence is broad, especially around the MSTO, where the reddening vector (Cardelli, Clayton, & Mathis 1989; Schlegel, Finkbeiner, & Davis 1998; hereafter SFD) is approximately perpendicular to a hypothetical isochrone fit to this particular region. Its subgiant branch, giant branch, and horizontal branch (HB) display the same feature, whereas the fainter region of the main sequence ( $V > 20$ ), where the reddening vector is almost parallel with an iso-

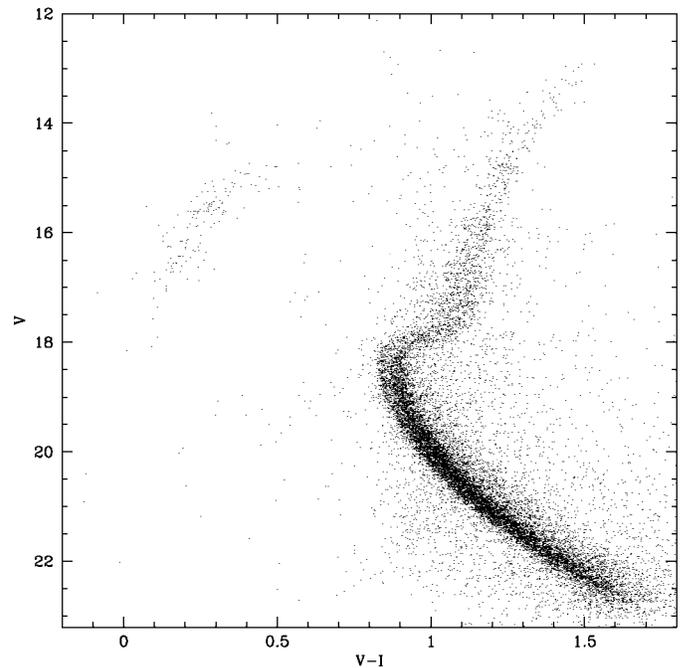


FIG. 1.—CMD of M10 before applying any extinction correction. The typical symptoms of differential extinction across the field are present: main sequence appears relatively tight where it is approximately parallel to the reddening vector (at  $V$  fainter than  $\sim 20$ ), whereas regions more or less perpendicular to the reddening vector, such as the MSTO, the subgiant and giant branches, and the blue HB, appear broad. As part of the process of combining 600 s and 10 s exposure data, we set the division at around  $V \sim 17\text{--}17.5$  where saturation of the deep data sets in.

chrone fit to the region, appears tighter. This behavior clearly rules out any sort of photometric error as the reason for the broadness of the CMD features, since, in that case, one would observe well-defined MSTO and subgiant branch regions and a main sequence that would flare up at fainter magnitudes. M12's CMD does not display the signature of differential extinction as strongly as M10, indicating that the effects of differential reddening across its field are small, despite the fact that the two clusters are separated by less than  $3^\circ$  in the sky.

In our photometry, we estimate the MSTO of M10 to be around  $(V-I)_{\text{MSTO}} \sim 0.88$  and  $V_{\text{MSTO}} \sim 18.5$  (Fig. 1), and the one of M12 to be at  $(V-I)_{\text{MSTO}} \sim 0.84$  and  $V_{\text{MSTO}} \sim 18.35$  (Fig. 2). Two recent  $VI$  studies present themselves as a means for photometry comparison: the extensive  $VI$  GC-CMD catalog of Rosenberg et al. (2000), RB00 hereafter, and the *Hubble Space Telescope* (*HST*) study of M10, M22, and M55 of Piotto & Zoccali (1999), PZ99 hereafter. For M12, we find excellent agreement with RB00 for our photometry for both  $(V-I)_{\text{MSTO}}$  and  $V_{\text{MSTO}}$ . For M10, our MSTO is slightly bluer and brighter than that of RB00 [ $(V-I)_{\text{MSTO}} \sim 0.92$  and  $V_{\text{MSTO}} \sim 18.6$ ]. We attribute this to the fact that the region of M10 observed by RB00 lies to the east of the cluster center where we find higher differential extinction compared with the rest of the cluster field (see § 3.1, and Figs. 3 and 5). Plotting our data that fall into the R00 field results in a location of the MSTO within 0.02 mag of the R00 MSTO, which approaches the limits of the random mean scatter of the photometry.

The agreement between our M10 results and the *HST* photometry of PZ99, however, is not as good, since their

<sup>3</sup> A detection of a star occurs when a subcluster of pixels with a signal sufficiently high above the sky background is filtered through a DoPHOT stellar model profile (based on the parameters  $x$ ,  $y$ , central intensity, and three shape parameters) and the object under investigation is classified as a star.

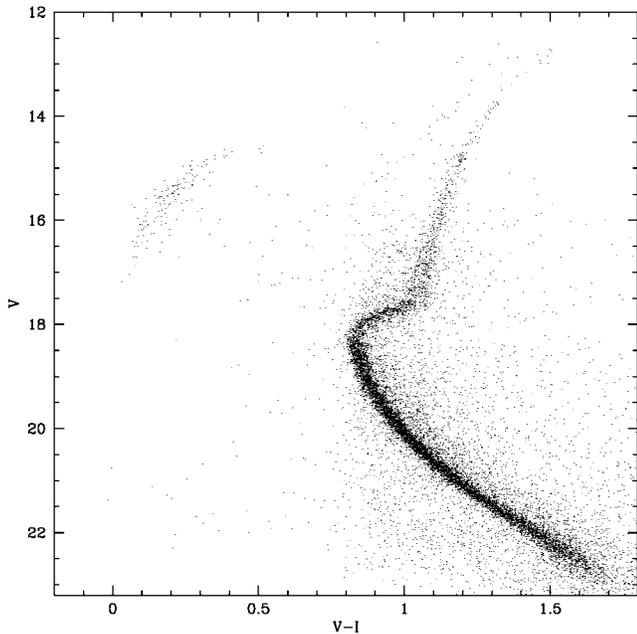


Fig. 2.—CMD of M12 before applying any extinction correction. The signatures of differential reddening are much less visible than in M10 (see Fig. 1). The division between the deep (600 s) and shallow (10 s) photometry data is located around  $V \sim 17\text{--}17.5$ .

MSTO is at  $(V-I)_{\text{MSTO}} > 1$ . As one can see in Figure 1, the range in our data does not extend to values redder than  $(V-I)_{\text{MSTO}} \sim 0.95$ . Since a direct star-by-star comparison between our data and PZ99 is not possible, we cannot give a good explanation for this discrepancy. One possible reason, however, might be a zero-point drift in the *HST* photometry, which has been noticed in studies such as Gallart et al. (1999), especially since PZ99’s photometry zero point is based on *HST* data.

In addition, we compared our MSTO magnitude to two *BV* studies of M10 (Hurley, Richer, & Fahlman 1989) and M12 (Sato, Richer, & Fahlman 1989). The  $V_{\text{MSTO}}$  for both M10 and M12 is estimated to be at 18.4, in good agreement with our results.

### 3. DEREDDENING

#### 3.1. Differential Extinction

As mentioned above, the calibrated CMDs in Figures 1 and 2 show the effects of differential reddening across the respective field of view. In order to get precise magnitudes and intrinsic colors for potential GC member binaries in the clusters, we created differential extinction maps for M10 and M12 from our data for these clusters. The method we used is outlined in detail in BM01, § 2.2, and Figures 1–4. We will briefly review the most important steps here and outline the difference between the method used for NGC 3201 (BM01) and the one used here.

For each cluster, we chose a fiducial region in which little differential reddening occurred, whose overall extinction is low compared with the rest of the field, and which contained a sufficient number of stars to fit a polynomial to the main sequence for stars with  $18.5 < V < 21$  and  $0.7 < (V-I) < 1.4$ . The field of view of each cluster was then divided into subregions of different sizes such that the number

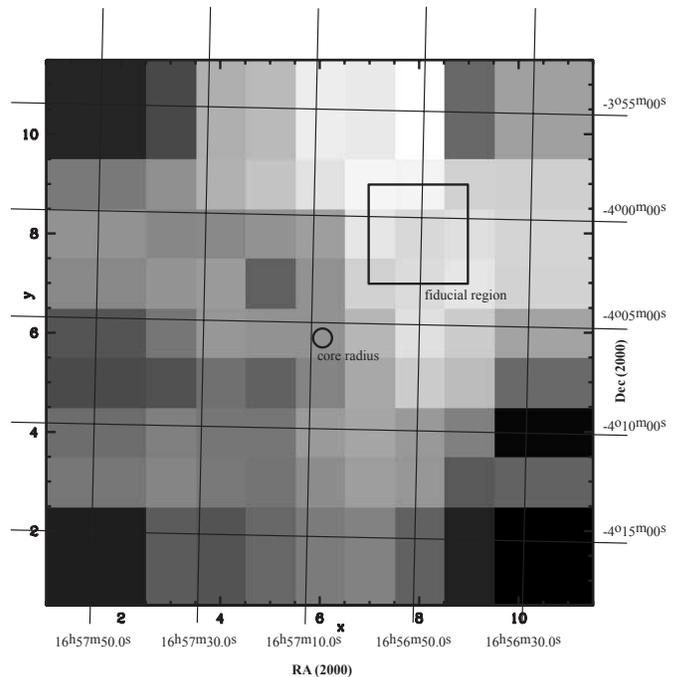


Fig. 3.—Extinction map for M10. North is up, east is to the left. The size of the entire field is  $25^{\circ}9$  on the side. The darker the color of a subregion, the more extinction is occurring in it (see Fig. 5) relative to the fiducial region whose position is shown on the map along with the core radius around the location of the center of the cluster. The coordinate axes  $x$  and  $y$  correspond to the ones in Fig. 5. The average reddening with respect to the fiducial region is  $E_{V-I} = 68 \pm 41$  mmag for the entire field and  $E_{V-I} = 49 \pm 28$  mmag for the inner part of the field (see Fig. 5). The size of one pixel in this map ( $\Delta x = 1$  or  $\Delta y = 1$ ) is  $\sim 140''$ .

of stars in each of the subregions was large enough to produce a statistically significant result. For each of the subregions, an average offset between its stars and the polynomial fit along the reddening vector with slope 2.411 (Schlegel et al. 1998, Table 6, col. [4] for Landolt filters) was calculated after  $1 \sigma$  outliers were deleted with an iteration. This calculated average offset corresponds to the differential  $E_{V-I}$  of each star in the subregion with respect to the fiducial region, i.e., how much more extinction the stars in the subregions suffer than the ones in the fiducial region.

The slope of the reddening vector for the analysis of NGC 3201 in BM01 was 1.919, calculated using Table 3 in Cardelli et al. (1989). The central wavelength of the *I* filter in Cardelli et al. (1989) is around 9000 Å, whereas the filter used during the 1998 May LCO observing run has a  $\lambda_{\text{central}} \sim 8100$  Å, closer to the value given in Table 6 of Schlegel et al. (1998) for Landolt filters. As a result, the conversion between  $E_{B-V}$  to  $E_{V-I}$  changes to  $E_{V-I} = 1.375E_{B-V}$ , and the slope of the reddening vector changes to  $A_V/E_{V-I} = 2.411$ . We comment on the implications of this change in § 3.2.4.

We present our results for M10 and M12 in the form of differential extinction maps in Figures 3 (M10) and 4 (M12). North is up, and east is to the left (see coordinate grid on the figure included for reference). Dark corresponds to regions of higher extinction relative to the fiducial region. For reference, we show the approximate locations of the cluster center and core radii (from Harris 1996), as well as the fiducial regions of the clusters. The sizes of the pixels in these maps vary with stellar density from  $\sim 140''$  on the side toward the





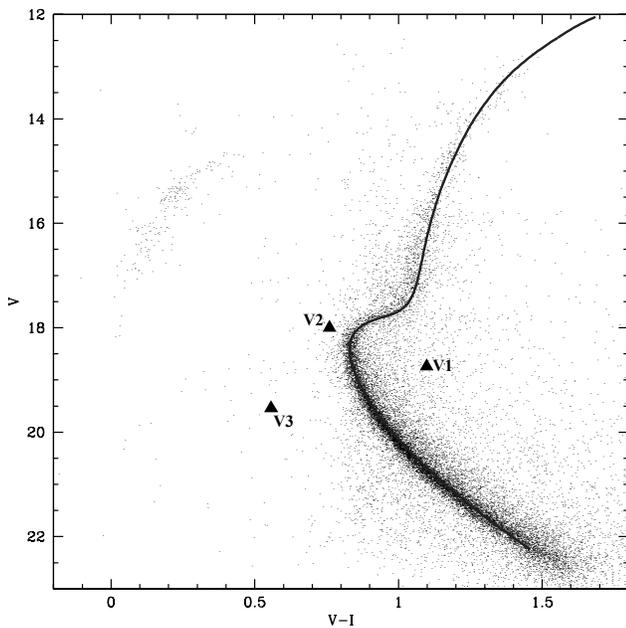


FIG. 9.—Differentially dereddened CMD of M10 with overlain VDB best-fit isochrone and locations of variable stars. For this fit,  $[\text{Fe}/\text{H}] = -1.54$ , the age is 16 Gyr,  $d = 5.1$  kpc, and the  $E_{V-I}$  zero point, to which any differential extinction has to be added, is 0.23. All CMD features are well traced out by the VDB isochrone. The 16 Gyr isochrone produced the better fit than the 18 Gyr one, but from the appearance of the CMD, it seems that perhaps a 17 Gyr VDB isochrone, if it were available, would produce an even better fit than the one shown here. We also show in this figure the locations of the variable star candidates in the CMD of M10. The data presented, including the variable stars, are dereddened to the M10 fiducial region. No reddening zero point is applied. The variables are plotted at maximum brightness. From this figure alone, it seems that none of the variables we found in the field of M10 are members of the cluster. It should be noted that since we only use our 600s data for binary detection, we are not sensitive to variables brighter than  $V \sim 16.5$ .

well traced out by the VDB isochrone. The 16 Gyr isochrone produced a slightly better fit than the 18 Gyr one, but from the appearance of the CMD, it seems that perhaps a 17 Gyr VDB isochrone, if it were available, would produce an even better fit than the one shown here. The value for  $[\text{Fe}/\text{H}]$  is similar to the Harris (1996) one of  $-1.52$ , whereas our distance estimate of 5.1 kpc is slightly higher than the Harris (1996) one of 4.4 kpc.

### 3.2.1.2. M12

Since M12's underreddened CMD is very similar to the one of M10, apart from the much lower differential reddening, it is no surprise that the parameters for the VDB isochrone fit shown in Figure 10 are almost identical to the ones used for M10:  $[\text{Fe}/\text{H}] = -1.54$ , the age is 16 Gyr,  $d = 4.9$  kpc ( $V_0 - M_V = 13.46$ ), and the  $E_{V-I}$  zero point is 240 mmag. Again, all features of the CMD, including the subgiant branch and the red giant branch (RGB), are very well traced out. The only minor deviation between the loci of the data points and the isochrone fit occurs at  $V \sim 21.5$ . The above isochrone parameters agree with the values for M12 in Harris (1996).

### 3.2.2. Using SFD Maps

A second option in the determination of the reddening zero point is to simply calculate the average offset between our maps and the SFD dust maps. If the two maps trace out

similar dust features, the offset between the maps should approximately be constant everywhere in the field. This average offset then corresponds to the estimate of the reddening zero point based on the comparison between our extinction maps and the SFD maps (based on dust emissivity).

We show the pixel-interpolated SFD maps of our fields of view of M10 and M12 in Figures 11 and 12. The orientation and field sizes of Figures 11 and 12 are identical to the ones in Figures 3 and 4, respectively. As before, darker regions correspond to regions of higher extinction. We added the location of the fiducial region for reference in each figure. For M10, the average reddening of the SFD map is  $E_{V-I} = 387 \pm 17$  mmag for the whole field and  $389 \pm 16$  mmag for the inner region (see Fig. 5). The errors represent the standard deviation about the mean. For M12, these values are  $E_{V-I} = 254 \pm 8$  mmag for the whole field and  $250 \pm 7$  mmag for the inner region. Note that these numbers are estimates for the full extinction along the line of sight, i.e., they contain a reddening zero point. The SFD estimates agree well with Harris (1996), who quotes  $E_{V-I} = 382$  mmag for M10 and  $E_{V-I} = 258$  mmag for M12.

As a first step in the calculation of the average offset between the two independent reddening estimates, we subtracted our extinction maps from the SFD maps of the corresponding regions. The resulting images are shown in Figures 13 (M10) and 14 (M12). As in BM01, Figure 7, darker regions correspond to areas where our maps indicate

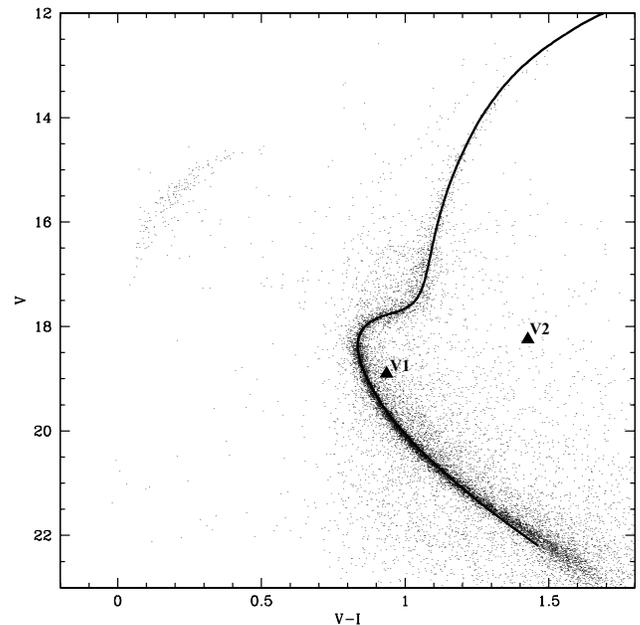


FIG. 10.—Differentially dereddened CMD of M12 with overlain VDB best-fit isochrone and locations of variable stars. For this fit,  $[\text{Fe}/\text{H}] = -1.54$ , the age is 16 Gyr,  $d = 4.9$  kpc, and the  $E_{V-I}$  zero point is 0.24. All features of the CMD, including the subgiant branch and the RGB, are very well traced out. The only minor deviation between the loci of the data points and the isochrone fit occurs at  $V \sim 21.5$ . The above isochrone parameters agree with the values for M12 in Harris (1996) and the SFD  $E_{V-I}$  estimates for this region. Also shown are the locations of the variable star candidates in the CMD of M12. The data presented, including the variable stars, are dereddened to the M12 fiducial region. No reddening zero point is applied. The variables are plotted at maximum brightness. From this figure alone, it seems that the variable V1 is a cluster member, whereas V2 is not. It should be noted that since we only use our 600 s data for binary detection, we are not sensitive to variables brighter than  $V \sim 16.5$ .

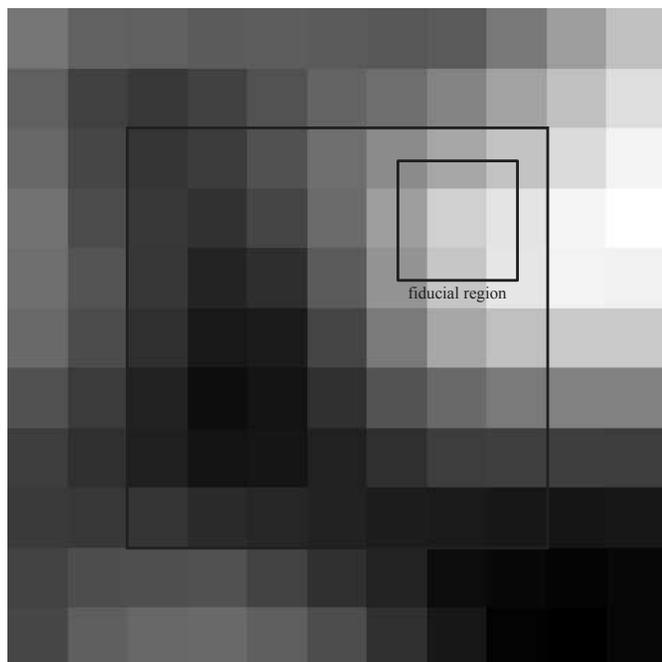


FIG. 11.—Graphical representation of the SFD map in the region of M10. The location of the fiducial region is given for reference. Orientation, size, and pixel sizes are the same as in Figs. 3 and 5. Darker regions correspond to higher extinction. The extinction ranges from  $E_{V-I} = 344$ –411 mmag. The average reddening is  $E_{V-I} = 387 \pm 17$  mmag for the entire field and  $E_{V-I} = 389 \pm 16$  mmag for the inner part of the field.

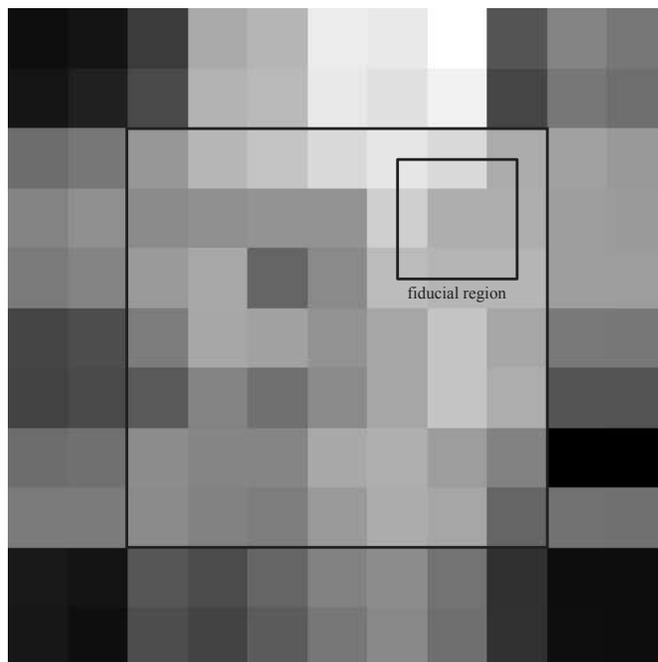


FIG. 13.—Graphical representation of the difference between our extinction map for M10 (Fig. 3) and the SFD map of the same region (Fig. 11). The location of the fiducial region is given for reference; the orientation, size, and pixel sizes are the same as in Figs. 3 and 5. Darker regions correspond to areas where our maps indicate more differential extinction (relative to the fiducial region) than the SFD map. It is obvious that especially the inner region is featureless, indicating good spatial agreement between the two maps. The pixels toward the edges of the map contain fewer cluster stars, causing any calculated differential reddening to have a higher associated random mean scatter error that results in the “noisy” appearance of the ring around the inner region. The average reddening of the whole field is  $E_{V-I} = 319 \pm 35$  mmag and  $E_{V-I} = 340 \pm 16$  mmag for the inner region.

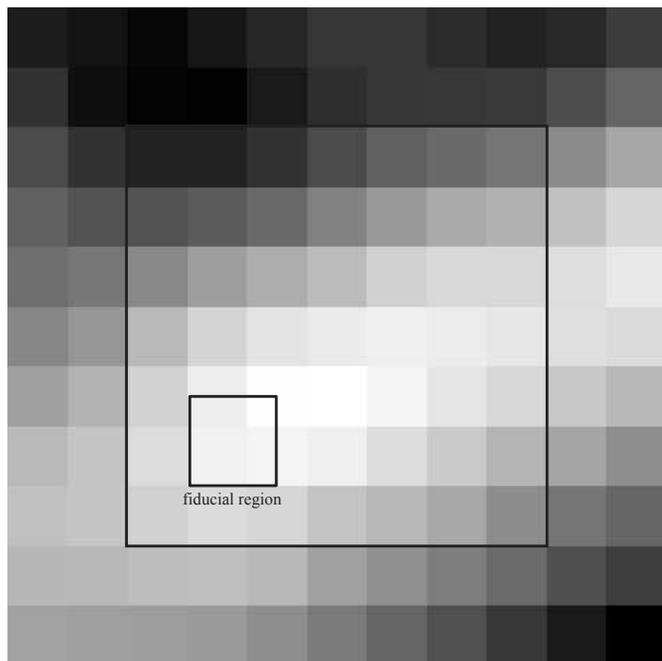


FIG. 12.—Graphical representation of the SFD map in the region of M12. The location of the fiducial region is given for reference. Orientation, size, and pixel sizes are the same as in Figs. 4 and 6. Darker regions correspond to higher extinction. The extinction ranges from  $E_{V-I} = 241$ –271 mmag. The average reddening is  $E_{V-I} = 254 \pm 8$  mmag for the entire field and  $E_{V-I} = 250 \pm 7$  mmag for the inner part of the field.

more differential extinction (relative to the fiducial region) than the corresponding SFD map. We show the locations of the fiducial regions, as well as the border between inner and outer regions (see above) for reference.

### 3.2.2.1. M10

The difference map for M10 (Fig. 13) indicates that our extinction map and the SFD map for M10 spatially agree quite well, particularly in the inner region of the image, which basically shows no residual features at all. The determination of the differential extinction toward the edges of the map is less precise because of the lower number of cluster stars in these regions (see Fig. 5) and thus appears more noisy. The average reddening of the whole field of Figure 13 (the difference map) is  $E_{V-I} = 319 \pm 35$  mmag, whereas for only its inner region, it is  $E_{V-I} = 340 \pm 16$  mmag. It is worth noting that for the inner region, the random mean scatter of this difference map of 16 mmag is smaller than the random mean scatter of our extinction map (28 mmag; see Fig. 3) and equal to the random mean scatter of the SFD map for M10 (16 mmag; see Fig. 11), indicating that the features traced out by both maps are correlated.

The value 340 mmag corresponds to our estimate for the reddening zero point as determined by using the SFD maps. We were simply unable, however, to produce an isochrone that resulted in a fit to our data using this estimate of  $E_{V-I}$ , even when widely varying the values for distance, age, and [Fe/H] (see § 3.2.3 for discussion). We therefore adopt our

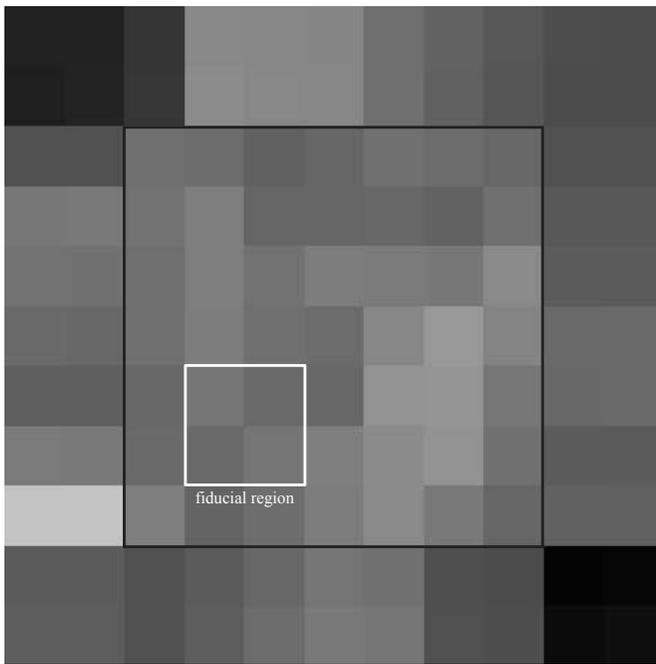


FIG. 14.—Graphical representation of the difference between our extinction map for M12 (Fig. 4) and the SFD map of the same region (Fig. 12). The location of the fiducial region is given for reference, the orientation, size, and pixel sizes are the same as in Figs. 4 and 6. Darker regions correspond to areas where our map indicates more differential extinction (relative to the fiducial region) than the SFD map. The difference map is featureless, except in the regions toward the corner of the image, which is evidence for the good spatial agreement between the two maps. The average reddening of the whole field is  $E_{V-I} = 214 \pm 53$  mmag, whereas for only the inner region, it is  $E_{V-I} = 241 \pm 11$  mmag.

estimate of 230 mmag, as determined by the VDB isochrones, as the reddening zero point for M10 (see previous subsection).

### 3.2.2.2. M12

Similar to M10, the two maps for M12 (Figs. 4 and 12) agree well, resulting in a difference image (Fig. 14) that is featureless except in the regions toward the corner of the image. The average reddening of the entire difference map (Fig. 14) is  $E_{V-I} = 214 \pm 53$  mmag, whereas for only its inner region, it is  $E_{V-I} = 241 \pm 11$  mmag. The value 11 mmag as the random mean scatter is comparable to the random mean scatter of the SFD map (7 mmag; see Fig. 12)

and lower than the random mean scatter for our extinction map (15 mmag; see Fig. 4), again indicating positive correlation between the features present in both maps. We calculate 241 mmag to be our estimate for the reddening zero point, as determined by using the SFD maps. This value agrees very well with our results from the VDB isochrone fitting method (240 mmag; see above).

### 3.2.3. Comments on the Adopted Reddening Zero Point

The two independent estimates we obtain for an average  $E_{V-I}$  (zero point plus differential) for each cluster are 389 mmag (by adding the SFD zero point to the average level of our extinction map) and 279 mmag (by using the VDB isochrone) for M10 and 250 mmag (using SFD zero point) and 249 mmag (using VDB isochrones) for M12. The reddening estimates in the literature for the two clusters vary more for M10 than for M12. Our results, along with some recent  $E_{V-I}$  values for M10, are presented in Table 3, and for M12 in Table 4. It should be noted that all the literature values in Tables 3 and 4 were obtained by converting their cited  $E_{B-V}$  values to  $E_{V-I}$  by using  $E_{B-V} = 0.7273E_{V-I}$  and an  $R_V = 3.1$  reddening law (Schlegel et al. 1998).

As mentioned above, we were not able to fit an isochrone to our data using the SFD reddening zero point for M10, even when lowering the metallicity to  $-2.31$  (limit of the isochrones) and changing the values for the age of the isochrone or the distance of the cluster. In order to avoid the possibility of multiple factors conspiring against us (such as incorrect aperture corrections and/or calibration zero points), we compared our DoPHOT photometry results for 10 isolated stars (no close neighbors) with IRAF's QPHOT magnitudes for the same stars. Within random mean scatter photometry errors, the results were identical, such that we found an average offset between  $I_{\text{DoPHOT}} - I_{\text{QPHOT}} \sim 0.034$  and  $V_{\text{DoPHOT}} - V_{\text{QPHOT}} \sim 0.005$ .

We will therefore adopt 230 mmag as the reddening zero point for M10. Compared with literature values, we are thus below the SFD, Hurley et al. (1989), and Harris (1996) estimates and slightly above the values in Burstein & Heiles (1982) and Arribas et al. (1990). For M12, our reddening estimate agrees very well with the SFD and Harris (1996) values but is slightly higher than the Burstein & Heiles (1982) and slightly lower than the Sato et al. (1989) estimates.

The similarity in our  $E_{V-I}$  values for the clusters may be somewhat unexpected because of the strong presence of differential reddening across the field of M10, which is not

TABLE 3  
SELECTED RECENT AVERAGE  $E_{V-I}$  ESTIMATES FOR M10

$E_{V-I}$ (mmag)	Reference	Method
214.....	Burstein & Heiles 1982	H I/galaxy count maps
426.....	Reed, Hesser, & Shawl 1988	Integrated light
371.....	Hurley, Richer, & Fahlman 1989	$UBV$ two-color diagram
234.....	Arribas et al. 1990	Infrared photometry
382.....	Harris 1996	Compilation of selected previous results
389 <sup>a</sup> .....	Schlegel, Finkbeiner, & Davis 1998	Dust IR emissivity maps
279.....	This work	VDB isochrone fitting

NOTES.—All listed literature reddening estimates were obtained by converting  $E_{B-V}$  values to  $E_{V-I}$  by using  $E_{B-V} = 0.7273E_{V-I}$  and a  $R_V = 3.1$  reddening law (Schlegel et al. 1998).

<sup>a</sup> This value also corresponds to our estimate using the SFD maps.

TABLE 4  
SELECTED RECENT AVERAGE  $E_{V-I}$  ESTIMATES FOR M12

$E_{V-I}$ (mmag)	Reference	Method
127.....	Burstein & Heiles 1982	H I/galaxy count maps
317.....	Sato et al. 1989	<i>UBV</i> two-color diagram
258.....	Harris 1996	Compilation of selected previous results
250 <sup>a</sup> .....	Schlegel et al. 1998	Dust IR emissivity maps
249.....	This work	VDB isochrone fitting

NOTES.—All listed literature reddening estimates were obtained by converting  $E_{B-V}$  values to  $E_{V-I}$  by using  $E_{B-V} = 0.7273E_{V-I}$  and a  $R_V = 3.1$  reddening law (Schlegel et al. 1998).

<sup>a</sup> This value also corresponds to our estimate using the SFD maps.

observed in M12. On the other hand, the two observed (underreddened) CMDs of the clusters are extremely similar to each other (confirmed also in Hurley et al. 1989; Sato et al. 1989; Rosenberg et al. 2000). Given the small difference between the values of [Fe/H] for M10 and M12, it therefore appears quite sensible that the estimates for age, distance, and reddening should be very similar for the two GCs.

### 3.2.4. Comments on the BM01 Reddening Zero Point for NGC 3201

As we mentioned in § 3.1, we changed the value for the slope of the reddening vector from  $A_V/E_{V-I} = 1.919$  in BM01, based on Cardelli et al. (1989), to 2.411 for this work, based on Schlegel et al. (1998). The central wavelength for the *I* filter used to establish the Cardelli et al. (1989) conversions is 9000 Å, whereas the filter used for the SFD conversions peaks closer to 8100 Å. Any instrumental *I* magnitude will suffer higher extinction with shorter *I* filter central wavelengths. Since reddening is not calculated until after the transformation to standard magnitudes is performed, the slope of the reddening vector has to be chosen according to the characteristics of the *I* filter. The *I* filter used during the LCO 1998 observing run has a central wavelength around 8200 Å, closer to the one used in SFD.

A recalculation of the reddening maps based on this “new” slope, however, produced results that were identical to the previously calculated ones. The values in the individual pixels of the extinction map grid (such as in Figs. 5 and 6) changed by only a few millimagnitudes from the values calculated in BM01. Similarly, refitted isochrones produced an identical reddening zero point. We therefore conclude that our reddening results for NGC 3201 (BM01)

do not change as a result of this different slope of the reddening vector.

As another consequence of adopting a different central wavelength for the *I* filter, however, the conversion between  $E_{B-V}$  and  $E_{V-I}$  changes from  $E_{B-V} = 1.546E_{V-I}$  for  $\lambda_{\text{central}} \sim 9000$  Å to  $E_{B-V} = 1.375E_{V-I}$  for  $\lambda_{\text{central}} \sim 8100$  Å. Thus, literature  $E_{B-V}$  values will correspond to  $E_{V-I}$  values that are different from the ones quoted in BM01. We show these updated literature values in Table 5. Qualitatively, the conclusions we reached in BM01 remain the same. Quantitatively, the agreement between our estimate for  $E_{V-I}$  and the corresponding literature values is better than we stated in BM01. Our value falls less than 1  $\sigma$  below the Cacciari (1984) and Harris (1996) values (we quoted 1.5  $\sigma$  in BM01).

## 4. THE SEARCH FOR VARIABLE STARS

The starting point for our analysis of the photometry data with respect to finding binaries and determining their periods were two databases. One contained the data on approximately 70 observational epochs per filter for M10 (600 s exposure time each) of 20,000 stars per image, the other the equivalent data for M12 consisting of about 100 600 s epochs per filter with  $\sim 14,000$  stars per image. Our data are sensitive to variables as bright as  $V \sim 16.5$ , slightly brighter than the previously mentioned division between 600 s and 10 s data in the CMDs, since observing conditions and CCD quantum efficiencies may vary between epochs or observing runs. Finally, we note that the variability detection and the period determination of variable stars are

TABLE 5  
SELECTED RECENT AVERAGE  $E_{V-I}$  ESTIMATES FOR NGC 3201

$E_{V-I}$ (mmag)	Reference	Method
285.....	Cacciari 1984	RR Lyrae colors
285.....	Harris 1996	Compilation of selected previous results
336 <sup>a</sup> .....	Schlegel et al. 1998	Dust IR emissivity maps
240.....	von Braun & Mateo 2001	VDB isochrone fitting

NOTES.—All listed literature reddening estimates were obtained by converting  $E_{B-V}$  values to  $E_{V-I}$  by using  $E_{B-V} = 0.7273E_{V-I}$  and a  $R_V = 3.1$  reddening law (Schlegel et al. 1998;  $\lambda_{\text{central}} \sim 8100$  Å). They represent the updated values from BM01 where we calculated  $E_{B-V} = 0.6468E_{V-I}$ , based on Cardelli et al. (1989),  $\lambda_{\text{central}} \sim 9000$  Å.

<sup>a</sup> This value also corresponds to our estimate using the SFD maps.

entirely independent of the differential dereddening described in § 3.

#### 4.1. Variability Detection

The criteria we set in order to extract variable star candidates from the list of stars in our database were described in detail in BM02, § 3.1. We will only briefly reiterate them here and mention any differences between BM02 and this work:

1. The  $\chi^2$  per degree of freedom, calculated based on the assumption that every star is a nonvariable, has to be greater than 3.0. We furthermore set a  $\sigma > 0.05$  mag threshold for a star to be taken into consideration as a variable candidate, where  $\sigma$  represents the variability in the light curve.

2. The star under investigation must appear in at least 40% of the epochs. The reason why this number is considerably lower than it was set in the analysis of NGC 3201 (BM02) is the same as in § 2.2: the MDM data, which comprise a large fraction of the epochs (see Tables 1 and 2), were taken with CCDs with smaller field sizes than the LCO data.

3. The detected variability should not be due to only a few outliers (3%–5% of the data points) causing the high  $\chi^2$ . Care was taken to avoid deleting possible detached eclipsing systems at this stage as we outlined in BM02, § 3.1.

4. The star under investigation should display a brightness variation in both filters, and the variability signal should be correlated in both filters (this algorithm is very similar to the one described in Welch & Stetson 1993; Stetson 1996).

Any measurement of stellar magnitude was weighted by the square of the inverse photometric error associated with it.

#### 4.2. Period Determination

The final decision as to whether a star is a true variable candidate (and if so, what kind of variable star it is) was based on the inspection of the data phased by the correct period (the photometry light curve). A variety of algorithms to determine periods are used in astronomy, many of which are based on similar principles. Generally, a test statistic is defined as a function of the observations (random variables) and of a trial period (parameter of the statistic) by which the real-time observations are folded. For each trial period and a given set of observations, the test statistic returns a single number. One may therefore plot the value of the test statistic against trial period (or its corresponding frequency) in what is called a periodogram (Schwarzenberg-Czerny 1989). Periodic oscillations in the observations will show up as features (resembling spectral lines) in the periodogram.

The initial estimates of the periods of all our variable star candidates that survived the steps outlined in the previous subsection were determined by two independent algorithms:

1. The minimum string length method, based on a technique by Lafler & Kinman (1965) and described in Stetson (1996). The test statistic in this method is the length of a hypothetical piece of string connecting consecutive data points in a magnitude versus phase plot. For an incorrect period estimate, the data points will most likely be scattered, resulting in a long string length. When the trial period is very close to the true period, however, the string length will

be short, since any two data points consecutive in phase will be very close to each other in magnitude.

2. The analysis of variance (AoV) method, described in detail in Schwarzenberg-Czerny (1989).<sup>4</sup> The basic code for this algorithm was supplied to us by Andrzej Udalski (1998, private communication). For this method, the entire data set is folded by a test period and then divided into bins in phase. The test statistic is the ratio of two variances. The numerator is the variance of the averages of the bins about the mean of the entire data set, which obviously is high if a star is a variable. The denominator is the sum of variances within the individual bins, which is small if the test period is the correct period. For a pure noise signal, this ratio (the AoV statistic) is 1. For a periodic signal, its value is small for incorrect trial periods and large for the correct trial period.

A final tweaking of the precision in the period for a candidate was then done by hand whenever necessary, based on the appearance of the light curve.

As in BM02, we note that we did not systematically address the issue of completeness in our analysis. The choice of parameters for the steps outlined above was made mainly based on hindsight (e.g., all of our candidates'  $\chi^2$  values are well in excess of 100)<sup>5</sup> or trial and error (e.g., the analysis of a set of phased light curves before and after a reduction criterion was applied). Any assessment of incompleteness due to other effects, such as period, phase, or duty cycle, is difficult to make as it sensitively depends on the windowing function created by the times of the observational epochs. If the period of a variable star is less than about an hour or higher than 5 days, we will most likely not detect the system, since our exposure times are 600 s long and observing runs generally last between 1 and 2 weeks. If the phase is such that the variable will only undergo changes in its brightness during the daytime, we will obviously also not find it. Very low duty cycles make it hard to detect the variable, since it spends so little time in an eclipse and otherwise appears as a nonvariable star. The lower the duty cycle, the more likely it is that a combination between the windowing function and the phasing of the binary would cause us to not detect it. However, the timing of our observing should enable us to find all variables with a period of up to around a day with fairly high duty cycles (30% or higher), since we perform repeated observations of the same cluster over the course of hours throughout many nights (especially for NGC 3201, see BM02).

### 4.3. Results

#### 4.3.1. Locations of Variable Stars in Field and in CMD

Table 6 gives the basic information about the variable stars we detected in the fields of M10 and M12.  $V_{\text{bright}}$  and  $I_{\text{bright}}$  are the  $V$  and  $I$  magnitudes at maximum light. Figures 15 and 16 show the locations of the respective variable stars in the fields of M10 and M12. Figures 9 and 10 indicate where the variables fall within the CMDs of the two clusters. The data shown in Figures 9 and 10 are differentially dereddened to the fiducial region within the respective cluster, as

<sup>4</sup> This method is quite similar to the phase dispersion minimization method.

<sup>5</sup> Reasons for high  $\chi^2$  values of nonvariable stars are very low signal and crowding.

TABLE 6  
VARIABLE STARS IN THE FIELDS OF M10 AND M12

Var. No.	Type	R.A. (J2000.0)	Decl. (J2000.0)	Period (days)	$V_{\text{bright}}$	$I_{\text{bright}}$
M10-V1 .....	W UMa	16 57 39.15	-04 16 03.9	0.263366(28)	18.890(17)	17.620(19)
M10-V2 .....	RR Lyrae	16 57 41.57	-04 08 24.8	0.61438(23)	18.170(14)	17.650(19)
M10-V3 .....	SX Phe	16 56 48.63	-03 58 35.9	0.0637(41)*	19.538(18)	19.013(33)
M12-V1 .....	W UMa	16 47 22.89	-01 55 35.8	0.243183(15)	18.818(19)	17.949(19)
M12-V2 .....	W UMa	16 47 32.58	-02 03 10.1	0.25212(25)*	18.238(12)	16.750(19)

NOTES.—(1) Errors in parentheses indicate the uncertainty in last two digits. (2) Photometry errors are the result of adding in quadrature the DoPHOT photometry error for the instrumental magnitude and the random mean scatter of the standard star solution (see BM01). (3) The random error in the period corresponds to the full width at half-maximum of the peak in the AoV power spectrum corresponding to the correct frequency. For the determination of this error, only  $V$  data were used. For the variables M10-V3 and M12-V2, the peak in the power spectrum corresponding to the correct period was assigned essentially the same power as the directly neighboring peak (i.e., it would be hard to pick “by eye” which one is the correct one). In these instances, we estimated the period random mean scatter to be the distance between these two neighboring peaks. The two cases are marked by an asterisk.

described above. No reddening zero point is applied. The magnitudes and colors of the variables correspond to the values at maximum brightness.

#### 4.3.2. Phased Photometry Light Curves

The phased light curves for the variable stars are presented in Figures 17–21. In particular, Figure 17 shows the light curve of M10-V1 (period = 0.263366 days), which is a W UMa-type contact binary system. M10-V2 is a background RR Lyrae (*ab* type) variable with a period of 0.61438 days; its light curve is displayed in Figure 18. M10-V3 appears to be a field  $\delta$  Scuti or an SX Phoenicis-type (SX Phe) variable with a period of 0.0637 days. These stars are rapidly pulsating Population I ( $\delta$  Scuti) or Population II (SX Phe) stars, which are commonly found toward the faint end of the instability strip in the CMD (Rodríguez, López-González, & López de Coca 2000). M10-V3’s light curve is

shown in Figure 19. M12-V1, another W UMa binary, seems to be the only variable in our data set that is physically associated with its respective parent GC (based on its CMD location). Its period is 0.243183 days, and its light curve is displayed in Figure 20. M12-V2, another W UMa binary but not associated with M12, has a period of 0.25212 days; its light curve is in Figure 21. In all of these figures,  $V$  data are in the bottom panel,  $I$  data in the top panel. The error bars represent the DoPHOT photometric errors associated with that particular measurement of the star’s magnitude. No reddening correction was applied to the light curves.

#### 4.3.3. Variable Stars: Distances and Cluster Membership

##### 4.3.3.1. W UMa Binaries (in M10 and M12)

As indicated in § 4.3.2, all the binary systems we detect in the fields of M10 and M12 are of the W Ursa Majoris type.

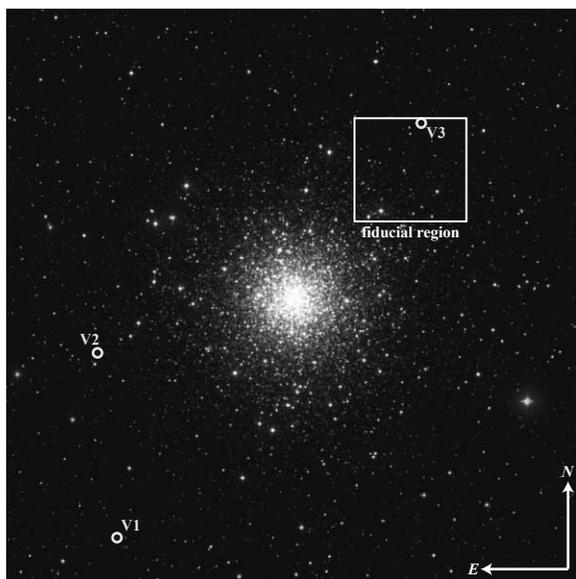


FIG. 15.—CCD field of view of M10 with the locations of the variables. The fiducial region is shown for reference. The size of the field of view is 81% (23/5 on the side) of the area shown in Figs. 3, 5, 11, and 13. [See the electronic edition of the *Journal* for a color version of this figure.]

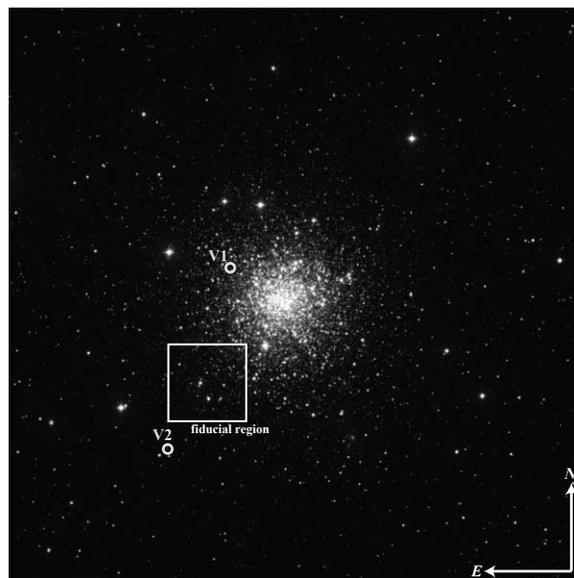


FIG. 16.—CCD field of view of M12 with the locations of the variables. The fiducial region is shown for reference. The size of the field of view is 81% (23/5 on the side) of the area shown in Figs. 4, 6, 12, and 14. [See the electronic edition of the *Journal* for a color version of this figure.]

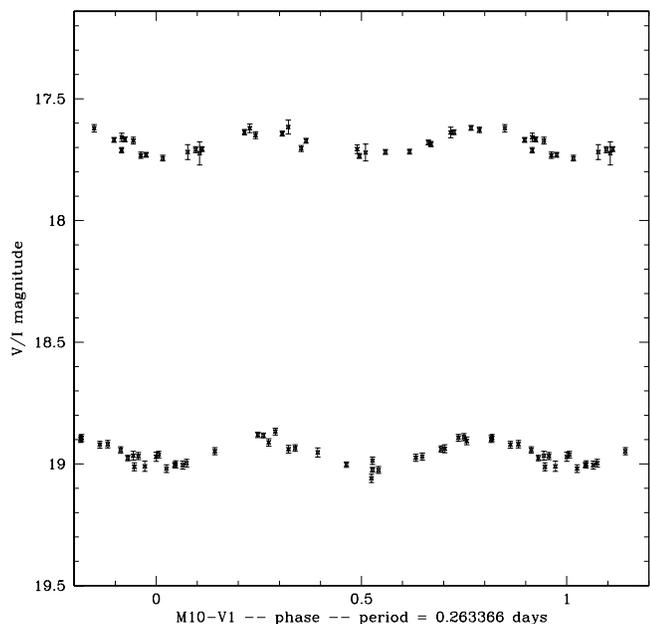


FIG. 17.—V1 in the field of M10, a W UMa binary system with a period of 0.263366 days. *I* data are plotted above the *V* data. No reddening correction is applied to the light-curve data. M10-V1 is not a member of M10.

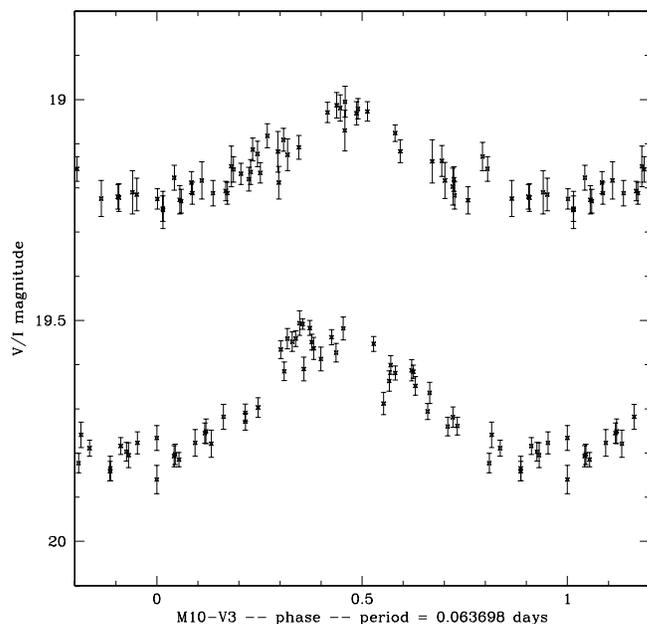


FIG. 19.—V3 in the field of M10, an SX Phe pulsating variable with a period of 0.0637 days. *V* data are plotted below the *I* data. No reddening correction is applied to the light-curve data. M10-V3 is a background field star (distance is  $\sim 16$  kpc).

W UMa binaries are systems in which the two components are in physical contact with their Roche equipotential lobes and at their inner Lagrangian point (see, e.g., Rucinski 1985a, 1985b; Mateo 1993, for more detailed description of W UMa systems). The fact that the total brightness of the system is constantly changing by up to  $\sim 0.75$  mag makes them easy to detect. Due to the good thermal contact between the two components, the two stars have similar surface temperatures. The absolute magnitude of the system

can therefore be defined as

$$M_V = -4.43 \log P + 3.63(V - I)_0 - 0.31, \quad (1)$$

where  $M_V$  is the absolute *V* magnitude,  $P$  is the period in days, and the  $(V - I)_0$  color is reddening-free. The empirically determined standard deviation in this relation is  $\sigma \sim 0.29$ , corresponding to about 13% in distance. See

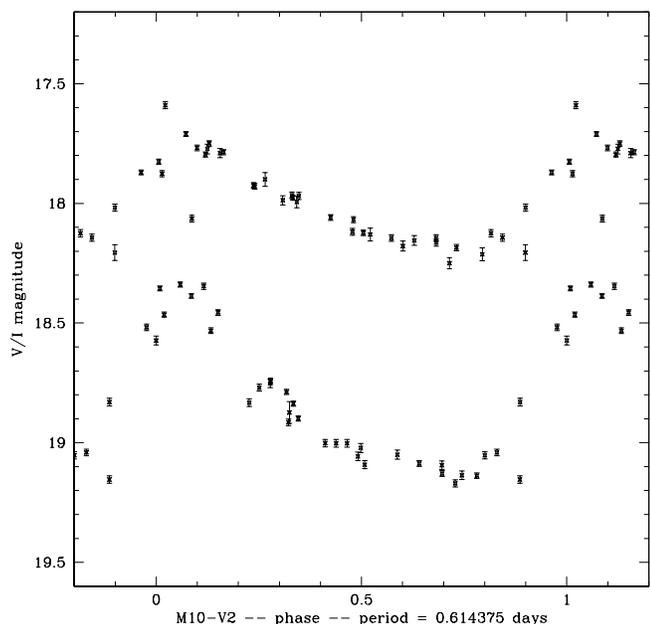


FIG. 18.—V2 in the field of M10, an RR Lyrae system with a period of 0.61438 days. *I* data are on top. No reddening correction is applied. The variable is a background star (40 kpc).

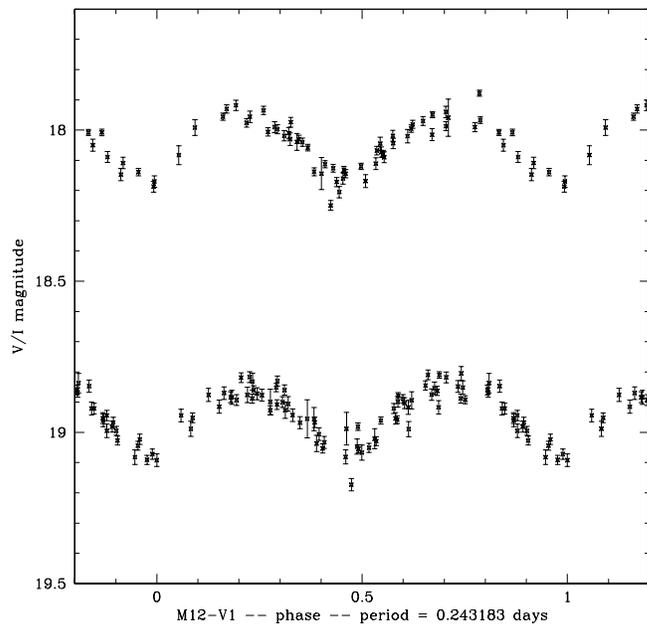


FIG. 20.—V1 in the field of M12, a W UMa binary system with a period of 0.243183 days and the only variable that is most likely physically associated with a GC. *I* data are above the *V* data. No reddening correction is applied to the light-curve data.

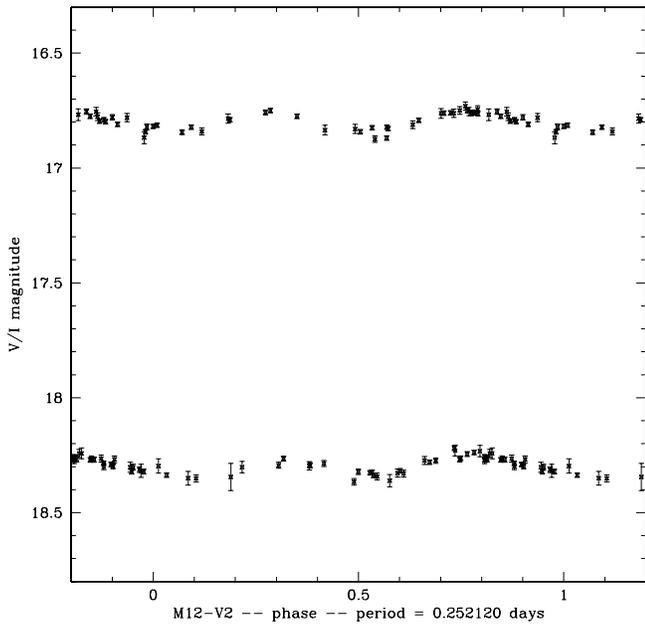


FIG. 21.—V2 in the field of M12, a W UMa binary system with a period of 0.25212 days.  $I$  data are plotted above the  $V$  data. No reddening correction is applied to the light-curve data.

Rucinski (2000) and BM02 for a more detailed derivation of the above equation.

Table 7 shows the absolute magnitudes and distance moduli for the W UMa binaries in the fields of M10 and M12 based on the above relation. The distances to the clusters were calculated in § 3.2.2 to be 5.1 kpc (M10) and 4.9 kpc (M12). The corresponding true distance moduli (apparent distance moduli corrected for extinction) are  $V_0 - M_V = 13.55$  and 13.46, respectively. We note that the absolute magnitudes and distance moduli in Table 7 were calculated under the assumption that the W UMa system under investigation is suffering the full extinction between us and the cluster. Since the Rucinski magnitudes for some

of the variables indicate that they are foreground stars, this assumption might be incorrect in some cases. That is, for some of the nonmembers, the color might not be the correct, reddening-free value.

A first indication of whether an EB star system in the field of a GC is associated with that cluster is, of course, its location with respect to the cluster center (we note that we cannot study the very center of the cluster because of crowding). The tidal radii of M10 and M12 are 21'48 and 17'6, respectively (Harris 1996). Thus, all the binary systems we find are well within the tidal radii. A more powerful membership criterion is a binary's location in the CMD. Based on the CMDs of M10 and M12 (see Figs. 9 and 10), M10-V1 and M12-V2 are not associated with their respective parent cluster. M12-V1, however, appears to be a cluster member from its location in M12's CMD. The estimates of distance moduli to the various W UMa binaries in Table 7 confirm what the GC CMDs suggest: M10-V1 and M12-V2 are foreground stars, but M12-V1 is most likely a member of M12 (it falls well within one  $\sigma_{\text{Rucinski}}$  of the calculated distance to the GC).

4.3.3.2. Pulsating Variables (in M10)

The two pulsating variable stars we detected in M10 are M10-V2, an *ab*-type RR Lyrae star, and M10-V3, either a  $\delta$  Scuti or an SX Phe star. From their locations in M10's CMD, it is apparent that neither of them is associated with the cluster.

Since the “expected” location of any GC member RR Lyrae is on the HB, M10-V2 is clearly a background star. If one assumes that  $M_V \sim 0.7$  for RR Lyrae stars, M10-V2's distance is around 40 kpc, putting it into the Milky Way halo beyond the bulge.

As mentioned above, SX Phe stars represent the Population II counterparts to the Population I  $\delta$  Scuti variables (Rodríguez & López-González 2000). GC member SX Phe stars are typically found in the blue straggler region of the CMD. Since M10-V3 is not inside this region, we conclude that it is not a member of the GC. Instead, the photometry results for M10-V3 ( $\Delta V \sim 0.32$ ,  $P \sim 0.064$  days,  $(V-I)_0 \sim$

TABLE 7  
RUCINSKI MAGNITUDES AND DISTANCE MODULI FOR W UMa-TYPE BINARIES IN THE FIELDS OF M10 AND M12

System	Period (days) <sup>a</sup>	$E_{V-I}$ <sup>b</sup>	$(V-I)_{0,\text{bright}}$ <sup>c</sup>	$M_{V(\text{Rucinski})}$ <sup>d</sup>	$V_0 - M_V$ <sup>e</sup>
M10-V1 .....	0.263366(28)	0.323(07)	0.947	5.695	12.576
M12-V1 .....	0.243183(15)	0.249(04)	0.620	4.661	13.679
M12-V2 .....	0.25212(25)	0.259(03)	1.229	6.802	10.939

NOTES.—Rucinski quotes the scatter in his relation (Rucinski 1994, 1995) to be 0.29 mag in the calculation of the absolute  $V$  magnitudes (corresponding to an uncertainty of approximately 13% in distance). Since this uncertainty is far larger than the quadratic sum of all our random errors, we refrain from a detailed error analysis for the Rucinski magnitudes and distance moduli.

<sup>a</sup> As in Table 3, errors in parentheses indicate the uncertainty in last two digits. The period errors are the same as in Table 3.

<sup>b</sup>  $E_{V-I}$  contains the reddening zero points for the two clusters, calculated in § 3.2.1. As mentioned above, this value assumes that the binary suffers the full extinction along the line of sight to the GC (which is not necessarily correct if the binary is not a cluster member). The errors for  $E_{V-I}$  are the random errors in the determination of the *differential reddening*. That is, any possible systematic error in the determination of the reddening zero point is not included in this estimate.

<sup>c</sup>  $(V-I)_{0,\text{bright}}$  is the dereddened color at maximum light.

<sup>d</sup>  $M_V = -4.43 \log P + 3.63(V-I)_0 - 0.31$  (see § 4.3.3).

<sup>e</sup> The true distance modulus to M10 is  $V_0 - M_V = 13.55$  and the one to M12 is 13.46. These values represent the apparent distance moduli corrected for extinction.

0.29)<sup>6</sup> quite exactly correspond to the modes in the distributions of the catalogue of field  $\delta$  Scuti and SX Phe stars of Rodriguez et al. (2000); see their Figures 1, 3, and 4. Since the number of known field SX Phe stars is very low (Rodriguez et al. 2000; Rodriguez & López-González 2000; Jeon et al. 2001), we cannot say for sure whether M10-V3 is a field  $\delta$  Scuti or SX Phe variable (see, e.g., Fig. 5 in Jeon et al. 2001). Since M10-V3 is a background variable, however, and thus located in the halo, we will assume that it is an SX Phe variable. Using the appropriate  $P-L$ -[Fe/H] relations in Nemeč, Nemeč, & Lutz (1994) and Nemeč et al. (1995) with an assumed [Fe/H]  $\sim -1.5$ , we obtain a distance to M10-V3 of approximately 16 kpc.

## 5. SUMMARY AND CONCLUDING REMARKS

The GCs M10 and M12 were monitored for the existence of photometrically variable stars in the magnitude range of approximately  $16.5 < V < 20$  and for periods between roughly 0.05 and 5 days. Observations were conducted over a span of about 4 yr, with only relatively few epochs per observing run because of the equatorial locations of the clusters.

During the search for variables, we noticed strong differential reddening effects across the field of M10 (Fig. 1) and a similar, but weaker signature across M12 (Fig. 2). We correct for this differential reddening by creating extinction maps (Figs. 3 and 4). The features visible in these maps are similar to the ones detected by SFD in their dust emissivity maps of the same regions (Figs. 11 and 12). Applications of our differential extinction maps to our data significantly improves the appearance of the CMDs of the GCs (Figs. 7 and 8), especially in the case of M10.

The  $E_{V-I}$  zero points for M10 and M12, which need to be added to the differential  $E_{V-I}$  values in the grids of Figures 5 and 6, are 0.23 and 0.24 mag, respectively, determined by fitting VDB isochrones to the differentially dereddened data. Since previous reddening estimates for these two GCs vary, especially for M10, our results agree with some literature values but not with others. Specifically, our reddening estimate for M12 agrees well with the SFD maps, whereas our value for M10 falls below the one quoted in SFD ( $E_{V-I} \sim 0.389$ ) but produces, by far, the best VDB isochrone fit.

Reddening studies like the one presented here may be useful in determining properties of the interstellar medium, such as a dependence of  $R_V$  upon position in the field of view. In addition, they may give insight into the properties and the distribution of the dust along the line of sight. One may argue, for instance, that M10 and M12, since they are so close to each other in the sky, lie behind a common, larger scale “layer” of dust that accounts for the practically identical reddening zero point. M10 seems to fall behind another dust ridge (suggested by, e.g., Kennedy, Bates, & Kemp 1996), causing the additional differential reddening, which varies on arcminute scales by tenths of a magnitude. Furthermore, reddening maps such as the ones presented here and in BM01 can give a sense of how small a scale differential extinction in general may vary on, and by how much, perhaps as a function of position in the sky or Galactic lati-

tude. We hope to shed some light on this matter with a similar analysis of the remaining GCs in our sample.

Our search for variable stars in M10 and M12 produced five candidates. In M10, we detected a W UMa binary, an RR Lyrae, and an SX Phe field variable. None of these three systems appears to be physically associated with M10, given their locations in the CMD (Fig. 9) and their estimated distances (Table 7 and § 4.3.3). In M12, we detected two W UMa binary systems, one of which (M12-V1) is most likely a cluster member. Again, we base this estimate on CMD location (Fig. 10) and calculated distance moduli (Table 7).

As in the case of NGC 3201 (BM02), we detect a number of foreground and background variables but only one (likely) GC member binary. Both M10 and M12 are at higher Galactic latitude ( $\sim 25^\circ$ ) than NGC 3201 ( $\sim 8^\circ$ ), so the disk contamination is not as significant. The number of total stars that were monitored was only slightly different (27,000 for NGC 3201 and 34,000 for M10 and M12 combined), but in the case of NGC 3201, we found 14 variables (11 binaries, one member), whereas in this work we find five variables (three binaries, one probable member). In both studies, cluster member stars outnumber nonmember stars, as may easily be seen in the CMDs of the clusters. Yet the number of nonmember binaries we find is much higher than the number of member binaries.<sup>7</sup> It will be interesting to see whether this trend continues in the rest of the GCs in our sample, which will be analyzed using the same methods as outlined in this work, BM01, and BM02, or whether NGC 3201, M10, and M12 are merely “special cases.”

Finally, we have shown that we are able to detect binaries of very low amplitude ( $\sim 0.07$  mag; BM02) and duty cycle (0.1; BM02) and of short ( $\sim 0.13$  days;<sup>8</sup> this work) and long periods (2.85 days; BM02), even when using very different observing techniques for the clusters. Using our existing 1 m class telescope photometry data set of the rest of the GCs in our sample, we should be able to identify binaries and other variables in these clusters (provided they exist) and determine their periods. With the spectroscopic capabilities of modern 8 m class telescopes for follow-up observations, we can determine cluster membership for these variables in the near future.

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<sup>6</sup> From comparison with the CMD of M10 by Hurley et al. (1989), this approximately corresponds to  $(B-V)_0 \sim 0.3$ , i.e., a spectral type of about F0.

<sup>7</sup> It should be noted that we are not sensitive to cluster member pulsating variables, since almost all of them are saturated in the data we analyze for the existence of binaries. A comparison between GC member and nonmember pulsating variables is therefore not meaningful.

<sup>8</sup> M10-V3 actually has a period of just above 0.06 days, but only has one maximum per period. Were it a binary star, it would have two maxima, and its period would consequently be around 0.13 days.

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