Variable stars in the field of the globular cluster E3

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ABSTRACT

We present the results of a search for variable stars in the faint sparse globular cluster E3. We have found two variable stars: an SX Phe variable (V1) and a W UMa eclipsing binary (V2). We have applied period-luminosity and period-color-luminosity relations to the variables to obtain their distance moduli. V1 seems to be a blue straggler belonging to E3, based on its distance modulus and location on the CMD. V2 is probably located behind the cluster, in the Milky Way halo. We also present $V/B - V$ and $V/V - I$ color magnitude diagrams of E3.

1. Introduction

We present the results of a search for variable stars in the faint sparse globular cluster E3, located at $\alpha_{2000} = 9^h 20^m 59^s$, $\delta_{2000} = -77^\circ 16' 57''$. The cluster was discovered on the ESO B Schmidt Survey of the Southern Sky by Lauberts (1976). The first $BV$ photometry of the cluster was presented by van den Bergh, Demers & Kunkel (1980). Numerous candidates for blue stragglers were identified. The photoelectric photometry of Frogel & Twarog (1983) confirmed this finding. A subsequent study by Hesser et al. (1984) using $UBV$ photoelectric and photographic observations showed a sparsely populated subgiant branch in the color-magnitude diagram. The first CCD photometry for E3 in the $BV$ bands, obtained with the CTIO 4m telescope, was published by McClure et al. (1985). These observations suggested the presence of a second sequence of stars $\sim 0.75$ mag. above the cluster main sequence, interpreted as evidence for a significant population of binary stars in E3. The cluster was further studied by Gratton & Ortolani (1987), who provided new $BV$ CCD photometry from the 2.2m telescope at ESO.

2. Observations and Data Reduction

The data for this project was obtained with the Las Campanas Observatory 1.0m Swope telescope during two separate runs: from April 11 to 21, 1996 and from May 16 to 27, 1996. For
the first few nights of the April run the telescope was equipped with the TEK1 1024x1024 CCD camera giving a pixel scale of 0.70″/pixel. On the night of April 14 the camera was switched to the TEK3 2048x2048 CCD with a pixel scale of 0.61″/pixel. During the May run the FORD 2048x2048 CCD camera with a pixel scale of 0.41″/pixel was used.

The main observing target on both runs was the M4 globular cluster. Several exposures of E3 were taken at the beginning of most nights. A total of 121 long (400 ÷ 900 sec) exposures were taken in the V filter (33, 42 and 46 with TEK1, TEK3 and FORD, respectively), six short (35 ÷ 120 sec) exposures in V (2 with TEK1, 4 with FORD), two 600 sec exposures in I (TEK1) and two 480 sec exposures in B (TEK1).

The preliminary processing of the CCD frames was done with the standard routines in the IRAF-CCDPROC package. The images from the TEK3 camera were clipped to a size of 1024x1024 pixels² to cover roughly the same field as the TEK1 images. Due to the high degree of psf variability on the images taken with the FORD camera, only the central 800x800 pixel²

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1IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF
sections were used.

Photometry was extracted using the *Daophot/Allstar* package (Stetson 1987). A PSF varying linearly with the position on the frame was used. The PSF was modeled with a Moffat function. Stars were identified using the FIND subroutine and aperture photometry was measured with the PHOT subroutine. Approximately 40 bright isolated stars were initially chosen by *Daophot* for the construction of the PSF. Of those the stars with profile errors greater than twice the average were rejected and the PSF was recomputed. This procedure was repeated until no such stars were left on the list. The PSF was then further refined on frames with all but the PSF stars subtracted. This procedure was applied twice. The PSF obtained in the above method was then used by *Allstar* in profile photometry.

The image where the most stars were identified was chosen as the template. The template star list was then transformed to the \((X, Y)\) coordinate system of each of the frames and used as input to *Allstar* in the fixed-position mode. The output profile photometry was transformed to the common instrumental system of the template image and then combined into a database. The databases were created for the long \((400 - 900 \text{ sec})\) exposures in the \(V\) filter only.

### 3. Variable stars

We have followed the procedure for selecting variables given in Kaluzny et al. (1998), where it is described in detail. From the 1541 stars in the \(V\) database 11 variable star candidates were selected. After the rejection of stars with noisy and/or chaotic light curves we were left with two variables. Their periods were refined using the analysis of variance method, as described by Schwarzenberg-Czerny (1989). These two variables were confirmed with ISIS - the image subtraction package (Alard & Lupton 1998, Alard 1999). No other variables were detected using this method.

In Figure 2 we present the phased \(V\) light curves of the two variables. Table 1 lists the parameters of these variables: name, period, \(V\) magnitude \((\langle V \rangle\) for the pulsating variable, \(V_{\text{max}}\) for the eclipsing binary), the \(B - V\) and \(V - I\) colors. The variables are indicated by open circles on the finding chart in Figure 1.
V1 is a pulsating variable, most likely of the SX Phe type, judging from its short period (0.0853 days) and the shape of its light curve. V2 is an eclipsing binary with a period of 0.4490 days. Its light curve shows an absence of the constant light phase, indicating that it is a W UMa type variable.

We have used the period-luminosity calibration for SX Phe stars derived by McNamara (1997) to estimate the distance modulus to V1:

\[
M_V = -3.725 \log P - 1.933
\]

Adopting a value of reddening \(E(B-V)=0.30\) (Harris 1996) we obtain a distance modulus \((m_V - M_V)_0 = 14.46\). This value is in agreement with the distance moduli found in literature: 14.55 - van den Bergh et al. (1980), 14.4 - Frogel & Twarog (1983), 14.2 - Gratton & Ortolani (1987), indicating that V1 is located at the same distance as the cluster.

The following period-color-luminosity calibrations for W UMa type eclipsing binaries derived by Rucinski (2000) were applied to V2:

\[
M^B_V = -4.44 \log P + 3.03(B - V)_0 + 0.12
\]

\[
M^V_I = -4.43 \log P + 3.63(V - I)_0 - 0.31
\]

The fact that \(B - V\) and \(V - I\) colors were determined at random phase should not influence the outcome substantially, as in the case of contact binaries the color does not change significantly throughout the cycle. Using a value of \(E(V - I) = 1.28E(B - V)\) (Schlegel et al. 1997) we obtained a distance modulus of 15.42 mag. from the first calibration and 14.83 mag. from the second. The variable appears to be located behind the cluster, in the Milky Way halo.

4. Color-magnitude diagrams

To construct the color-magnitude diagrams we combined pairs of long exposures in the \(BVI\) filters. The transformation from instrumental magnitudes to the standard system was derived from the observations of the Landolt fields (Landolt 1992). The following relations were adopted:

\[
v = V - 0.0189 \times (B - V) + const
\]

\[
b - v = 0.9359 \times (B - V) + const
\]

Table 1: Variables in E3

| Name | \(P\) (days) | \(V\)  | \(B - V\) | \(V - I\) | Comments       |
|------|--------------|-------|-----------|-----------|----------------|
| V1   | 0.0853       | 17.48 | 0.60      | 0.86      | SX Phe         |
| V2   | 0.4490       | 18.17 | 0.66      | 0.96      | W UMa          |
Fig. 3.— The $V/B - V$ and $V/V - I$ color-magnitude diagrams of the inner 2′ of the E3 globular cluster. Variable V1 is denoted by an open circle and V2 by an open square.

$$v = V - 0.0182 \times (V - I) + \text{const}$$
$$v - i = 0.9843 \times (V - I) + \text{const}$$

We have compared our $BV$ photometry with that of McClure et al. (1985). The average differences in $V$ magnitude and $B - V$ color were computed for 6 selected stars in the range $15.5 \leq V \leq 19.25$ and were found to be $\Delta V = 0.02 \pm 0.014$ and $\Delta (B - V) = 0.04 \pm 0.080$.

The colors and magnitudes for variable stars were determined following a different procedure. For variable V1 its average magnitude $\langle V \rangle$ was used to place it on the CMDs. V2 was plotted with its magnitude outside of the eclipses $V_{\text{max}}$. To derive the colors we used the single $B$ and $I$ exposures and interpolated the $V$ magnitudes from the nearest exposures in $V$ to those epochs. The final values of $B - V$ and $V - I$ were taken as the average of two color determinations, with the average scatter of 0.04 mag.

The resultant $V/B - V$ and $V/V - I$ color-magnitude diagrams are shown in Figure 3 with the variable V1 denoted by an open circle and V2 by an open square. Only stars within 2′ of the cluster center are plotted. Both variables are located among candidate blue stragglers, although V2 appears to be located behind the cluster, based on the distance modulus determination in the previous section.

The cluster main sequence is apparent in both diagrams. It exhibits considerable scatter and there is some indication of a second sequence running above it, although not as clear as in Figure 3 of McClure et al. (1985). This would indicate that E3 could possess a significant population of binary stars. This is in agreement with the idea proposed by van den Bergh et al. (1980) that severe tidal stripping had depleted the cluster in single stars, leading to an increased binary
frequency.

A gap in the main sequence near the turnoff, at \( V \sim 19.5 \) is visible in both CMDs. This has been previously noted by McClure et al. (1985) and shown to be more of a visual effect, as no significant discontinuities are present in the cumulative luminosity function for stars on the main sequence (Figure 6 therein). This result is confirmed by our analysis.

The subgiant and lower giant branches are also discernible in the diagrams, although they show substantial scatter. This is regarded as a real feature of the cluster, as commented in literature (i.e. Hesser et al. 1984). A number of stars blueward of the turnoff are present, possibly blue stragglers belonging to the cluster, as first noted by van den Bergh et al. (1980).

5. Conclusions

Our variability search in E3 resulted in the discovery of two variable stars: an SX Phe variable (V1) and a W UMa eclipsing binary (V2). We have applied period-luminosity and period-color-luminosity relations to the variables to obtain their distance moduli. V1 seems to be a blue straggler belonging to E3, based on its distance modulus and location on the CMD. V2 is probably located behind the cluster.

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