A proper motion study of the globular cluster M55

K. Zloczewski,1* J. Kaluzny1* and I. B. Thompson2*

1Nicolaus Copernicus Astronomical Centre, ul. Bartycka 18, 00-716 Warsaw, Poland
2The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101, USA

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ABSTRACT

We have derived the absolute proper motion (PM) of the globular cluster M55 using a large set of CCD images collected with the du Pont telescope between 1997 and 2008. We find \((\mu_\alpha\cos\delta, \mu_\delta) = (-3.31 \pm 0.10, -9.14 \pm 0.15)\) mas yr\(^{-1}\) relative to background galaxies. Membership status was determined for 16 945 stars with \(14 < V < 21\) from the central part of the cluster. The PM catalogue includes 52 variables, of which 43 are probable members of M55. This sample not only is dominated by pulsating blue stragglers, but also includes five eclipsing binaries, three of which are main-sequence objects. The survey also identified several candidate blue, yellow and red straggler stars belonging to the cluster. We detected 15 likely members of the Sgr dSph galaxy located behind M55. The average PM for these stars was measured to be \((\mu_\alpha, \mu_\delta) = (-2.23 \pm 0.14, -1.83 \pm 0.24)\) mas yr\(^{-1}\).

Key words: astrometry – binaries: eclipsing – blue stragglers – globular clusters: individual: NGC 6809 (M55) – galaxies: individual: Sagittarius dSph.

1 INTRODUCTION

M55 (NGC 6809) is a metal-poor globular cluster (GC) in the Galactic halo \((l = 9^\circ, b = -23^\circ)\), discovered by Nicholas Louis de Lacaille in 1752. Over 70 variable stars are known in the field of the cluster (Olech et al. 1999; Clement et al. 2001; Pych et al. 2001; Kaluzny et al. 2010, hereafter JK10). About half of these are located in the blue straggler (BS) region of the colour–magnitude diagram (CMD) and 13 are RR Lyr type pulsators. The cluster is close to us \([(m - M)_V = 13.87;\) Harris 1996\] and is relatively sparse. This makes it an ideal target for a measurement of the cluster proper motion (PM). Several authors have shown that for nearby GCs, ground-based CCD observations with temporal baselines of 3–5 yr are sufficient to efficiently separate member stars from field interlopers (Anderson et al. 2006; Yadav 2008; Bellini et al. 2009; Montalto et al. 2009).

In Section 2, we describe the observational data and methods used to prepare CCD images for the analysis. The procedures employed for the determination of relative PMs of individual stars and the absolute PM of the cluster are presented in Section 3. A discussion of our results is given in Section 4, and this is followed by a summary in Section 5.

2 DATA SELECTION AND PREPARATION

The images of M55 analysed in this paper were selected from the data collected by the Cluster AgeS Experiment (CASE; Kaluzny et al. 2005a) project during the period 1997–2008. Observations were made with the 2.5-m du Pont telescope at Las Campanas Observatory. All images were obtained with the same detector and the same set of filters. We used the 2K2 Tek#5 CCD camera with a scale of 0.259 arcsec pixel\(^{-1}\) and a field of view of 530 \(\times\) 530 arcsec\(^2\). CASE observed M55 as part of a programme to obtain follow-up photometric observations of specific variables and to survey the central part of the cluster for detached eclipsing binaries. For the present analysis, we selected four pointings, named F1–F4. The locations of these fields are shown in Fig. 1. The field centres are at the following (RA, Dec.) coordinates for Epoch 2000: F1 (294\(^{\circ}\) 9499, 30\(^{\circ}\) 30 9316), F2 (294\(^{\circ}\) 9668, 30\(^{\circ}\) 9621), F3 (294\(^{\circ}\) 9707, 30\(^{\circ}\) 9682), and F4 (294\(^{\circ}\) 9788, 30\(^{\circ}\) 9316). The set of frames selected for a given observing run and for a given pointing is called a ‘data set’. Each data set includes the V frames with the best seeing obtained for a given observing run. We considered only frames with seeing better than 1.1 arcsec and obtained at an air mass less than 1.1, avoiding observation obtained through clouds or with a bright sky. A summary of the final data sets is given in Table 1.

For each data set, we constructed an averaged, high signal-to-noise ratio (S/N) frame using the DIAPL\(^1\) package. In brief, individual frames were transformed to the coordinates of a chosen reference image. The point spread function (PSF) of each frame was also transformed to match the PSF of the reference image (i.e. the transformation kernel between a given frame and the reference image was derived). The best seeing frame from a given data set served

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\(^1\) DIAPL – Difference Image Analysis PL (available at http://users.camk.edu.pl/pych/DIAPL) developed by W. Pych.
3 PROPER MOTIONS

3.1 Proper motion measurements

Relative PMs of individual stars were derived from their positions measured at different epochs with respect to nearby cluster stars. This was done using a procedure resembling that described by Anderson et al. (2006). As a first guess, we selected cluster stars located along the main sequence and red giant and horizontal branches on the CMD. For this purpose, we constructed deep $V(I-V)$ CMDs for both the analysed fields, including only stars with high-quality photometry. The photometric quality was judged based on CHI and SHARP fit parameters returned by ALLSTAR. PM measurements were only made for stars with $V < 21.0$.

For any given star, we selected a set of ‘grid stars’ located inside a square of size $\sim 80 \times 80$ arcsec$^2$, centred on the star to be measured. Only likely cluster members were considered at this step. The median number of grid stars was equal to 203 for F1 and 202 for F2. The grid stars were used to calculate the local geometrical transformation between the appropriate master frame and a given average frame. This transformation was calculated using the IRAF$^2$ immatch.geomap and immatch.geoxytran tasks. We used a 2D third-order Chebyshev polynomial as the transformation function.

Subsequently, we calculated the expected coordinates $(X_C, Y_C)$ of the star on the average frame based on its $(X_0, Y_0)$ coordinates on the master frame. The relative motion was derived as the difference between the calculated and observed coordinates: $dx = X_C - X_0$ and $dy = Y_C - Y_0$. The shifts $dx$ and $dy$ were measured for all suitable average frames. Finally, the PM of a given star was calculated by a linear fit to $dx$ and $dy$ as a function of time. Fig. 2 shows as an example of the PM measurement for star #13300383.

Individual points were weighted by the amount of flux corresponding to a given ‘average frame’. In practice, this was done by summing fluxes measured for several bright isolated stars on individual frames before averaging. We then took the inverse value of the summed flux to compute the relative weight for each ‘average frame’. PM measurements were only attempted for objects with

\[ \text{as the reference image. The transformed frames were subsequently stacked by averaging to form what we later call an ‘average frame’. During this procedure the reference as well as the individual frames were divided into 16 overlapping subframes to reduce effects of PSF variability.}

We decided to obtain PMs for stars detected on the averaged frames of fields F1 and F2 for seasons 1997 and 1999, respectively. These frames are characterized by particularly good seeing and high S/N. We label these the ‘master’ frames. The observations of fields F1 and F2 span 9 and 11 yr, respectively. Fields F1 and F2 show significant overlap with fields F3 and F4. Therefore, most of the stars detected on F1-1997 and F2-1999 images are present on the remaining averaged frames. A master list of stars was extracted from frames F1-1997 and F2-1999 using the DAOPHOT/ALLSTAR package (Stetson 1987). The reductions were made on 16 overlapping subframes resulting from a $4 \times 4$ division of the respective averaged frames. A Moffat function with linear spatial variability was used to characterize the PSF. Due to crowding the photometry was extracted in an iterative way, gradually decreasing the detection threshold. An effort was made to avoid artificial splitting of bright stars which can happen when one uses an automatic procedure to detect missed objects in star-subtracted images. During the last iteration, the residual images were inspected by eye to find previously undetected stars. The master lists contained 47 333 and 42 725 objects for fields F1 and F2, respectively. In the next step, these lists were transformed to the coordinates of the averaged frames for different epochs. Profile photometry (as well as PSF modelling) was measured for these frames with ALLSTAR parameter set to $re = 1$. In this way, the positions of objects from the master lists have been redetermined for a given averaged frame. As before, we used a $4 \times 4$ mosaic of subframes for actual reductions.

\[ \text{Table 1. Summary of M55 observations used in this study.} \]

\begin{center}
\begin{tabular}{lllll}
Data set & (HJD - 245 0000) & $N$ & (Exp. time) & (Seeing) \\
& (yr) & & (s) & (arcsec) \\
F1-1997 & 1.65 & 12 & 60 & 0.80 \\
F1-2006 & 10.70 & 6 & 75 & 1.06 \\
F1-2007 & 11.86 & 8 & 40 & 1.08 \\
F1-2008 & 12.66 & 21 & 35 & 0.90 \\
F2-1999 & 3.68 & 23 & 120 & 0.83 \\
F2-2001 & 5.65 & 8 & 100 & 0.93 \\
F2-2003 & 7.58 & 18 & 85 & 0.86 \\
F2-2004A & 8.63 & 3 & 80 & 1.05 \\
F2-2004B & 8.78 & 17 & 50 & 0.89 \\
F2-2006A & 10.57 & 19 & 40 & 0.70 \\
F2-2006B & 10.64 & 15 & 60 & 0.87 \\
F2-2008 & 12.68 & 14 & 50 & 0.67 \\
F3-2006A & 10.71 & 8 & 65 & 0.82 \\
F3-2006B & 10.72 & 7 & 50 & 0.83 \\
F3-2007A & 11.70 & 4 & 60 & 0.95 \\
F3-2007B & 11.77 & 13 & 60 & 0.78 \\
F3-2008 & 12.73 & 14 & 85 & 0.89 \\
F4-2007 & 11.75 & 18 & 60 & 0.82 \\
\end{tabular}
\end{center}

\[ \text{\# IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation.} \]
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Figure 2. An example of PM determination for one of the fast-moving stars.

Figure 3. The rms of geometrical transformation versus time for field F1. Average seeing for a given frame is indicated.

3.2 Error estimates

Fig. 4 shows the difference in measured PMs for 11,398 stars measured on both fields F1 and F2. For 66 per cent of these stars, the difference is smaller than $\Delta \mu = 0.34$ mas yr$^{-1}$. This can be adopted as a robust estimate of the average error of a PM determination for the whole sample. For 95 per cent of the stars, the difference is smaller than $\Delta \mu = 0.94$ mas yr$^{-1}$.

Fig. 5 shows the dependence of $\log_{10} \sigma_{\mu}$ on $V$ magnitude. For stars with $V \approx 19.0$, the median value of $\sigma_{\mu}$ is equal to 0.47 mas yr$^{-1}$. A n increased scatter in $\sigma_{\mu}$ can be noted for $V < 14.5$. This arises from the saturation of bright stars on some frames resulting in fewer available epochs for the PM measurement. Note that the $\sigma_{\mu}$ values below $V \approx 17.5$ arise due to systematic effects and for fainter magnitudes are related to photon noise statistics. The spread of the $\sigma_{\mu}$ values may be due to the methodology of the reductions (fitting and coordinate transformations) and to the number of points used in the astrometric solutions.

3.3 Completeness

We assessed the completeness of our PM survey as a function of $V$ magnitude and radial distance from the cluster centre. Completeness was defined as the ratio of the number of stars with final PM measurements to the number of stars for which we attempted to make a PM measurement. The results are shown in graphical form in Figs 6 and 7. Only points with relative uncertainty smaller than 20 per cent were plotted. The completeness exceeds 70 per cent for $13 < V < 17$ and drops to 25 per cent at $V = 20.0$. As expected, the completeness increases with distance from the cluster centre.
flattening at a distance of about 4 arcmin. The larger incompleteness observed at the cluster centre is due to effects associated with crowding. The apparent peak at \( d = 4 \) arcmin, evident for all magnitude ranges, results from the fact that for more distant stars often only a few epochs were available. No attempt was made to estimate the completeness of the initial master list of stars detected in the studied field.

### 3.4 Cluster membership probabilities

A vector point diagram (VPD) including 16 945 stars with reliably derived relative PMs is presented in Fig. 8. Only 2.3 per cent (394 objects) of the measured objects have \( \mu > 3.0 \) mas yr\(^{-1}\) and these are likely field stars. To estimate the probability that a star is a cluster member, we use the ‘local-sample method’ described in Platais (1984) with further improvements proposed by Platais et al. (2003). In our case, however, field stars comprise only a very small fraction of the total sample.

We therefore decided to assign stars to one of the three groups based on location in the VPD diagram and on the error of the measured PM. All objects with a measured PM were divided into five subsamples in magnitude: 13 < \( V < 17 \) (\( N = 1048 \)), 17 < \( V < 18 \) (\( N = 2511 \)), 18 < \( V < 19 \) (\( N = 5140 \)), 19 < \( V < 20 \) (\( N = 5715 \)) and 20 < \( V < 21 \) (\( N = 2531 \)). For each bin, we selected stars with \( \mu < 1.8 \) mas yr\(^{-1}\) and calculated for these average values and standard deviations of \( \mu_\alpha \cos \delta \) and \( \mu_\delta \) (\( M_\alpha, M_\delta, S_\alpha, S_\delta \)). The total value of the standard deviation of the PM was then calculated as \( S = (S_\alpha^2 + S_\delta^2)^{1/2} \). Average values and standard deviations of the individual errors of \( \mu_\alpha \cos \delta \) and \( \mu_\delta \) were also calculated (\( ME_{\alpha,\delta} \), \( SE_{\alpha,\delta} \)). Subsequently, the total values \( ME = (ME_\alpha^2 + ME_\delta^2)^{1/2} \) and \( SE = (SE_\alpha^2 + SE_\delta^2)^{1/2} \) were calculated. The results are listed in Table 2. The histograms showing the distribution of both components of PM for the brightest and the faintest bin in \( V \) are shown in Fig. 9. Stars were assigned to three classes of membership. Those with \( M > 3.0 \times S \) are considered non-members (mem = 0; \( N = 379 \)). Possible members (mem = 1; \( N = 187 \)) are stars with \( M \leq 3 \times S \) but with \( \sigma_\mu > ME + 3.0 \times SE \). Objects with \( M \leq 3 \times S \) and \( \sigma_\mu \leq ME + 3.0 \times SE \) are considered PM members of the cluster (mem = 2; \( N = 16379 \)). The membership class defined as above is listed in the 12th column of Table 3.

### 3.5 Absolute proper motions

Among the objects remaining on the star-subtracted averaged frames, there are a number of relatively faint, unresolved galaxies. These were selected by visual inspection of both the averaged frames and averaged frames with stars subtracted. The sample includes a total of 70 galaxies from fields F1 and F2. 11 of these are undoubtedly relatively bright compact galaxies. Due to a crowding of the stellar field, we decided to extract photometry of the galaxies simultaneously with photometry of the nearby stars using the GALFIT 3.0 code (Peng et al. 2010). This was done on \( (30 \times 30 \text{ or } 60 \times 60 \text{ pixel}^2) \) subframes centred on a given galaxy and extracted from the relevant averaged frame.
Table 3. First few lines of the electronically available PM catalogue (see Supporting Information). Columns are as follows: (1) star ID (starting with 1 and 2 for fields F1 and F2, respectively); (2 and 3) equatorial coordinates ($\alpha, \delta$)$_{2000.0}$ for epochs 1997.41 and 1999.46 for F1 and F2, respectively; (4 and 5) XY pixel coordinates on reference frames; (6–9) PMs and their errors; (10) number of epochs used; (11) temporal baseline; (12) cluster membership (for explanation see Section 3.4) and (13) $V$ magnitude.

| ID   | $\alpha$ | $\delta$ | X     | Y     | $\mu_\alpha$ cos $\delta$ | $\sigma_{\mu_\alpha}$ cos $\delta$ | $\mu_\delta$ | $\sigma_{\mu_\delta}$ | N   | d$T$ | mem | V |
|------|----------|----------|-------|-------|-----------------------------|--------------------------------------|--------------|------------------------|-----|------|-----|---|
| 11100007 | 295.053729 | −30.902151 | 449.000 | 149.951 | 0.25                         | 0.22                                 | −0.51        | 0.29                   | 8   | 10.217 | 2   | 14.586 |
| 11100009 | 295.058880 | −30.928524 | 362.498 | 509.429 | −0.66                        | 0.22                                 | 11.84        | 0.19                   | 9   | 11.033 | 0   | 14.810 |
| 11100020 | 295.066402 | −30.924406 | 277.438 | 446.329 | −0.05                        | 0.17                                 | 0.65         | 0.21                   | 5   | 11.017 | 2   | 16.792 |
| 11100021 | 295.060880 | −30.928912 | 338.443 | 513.105 | −0.36                        | 0.32                                 | 1.24         | 0.16                   | 9   | 11.025 | 2   | 16.796 |
| 11100023 | 295.046117 | −30.915949 | 525.736 | 346.697 | 0.53                         | 0.52                                 | −0.31        | 0.79                   | 13  | 10.217 | 1   | 16.980 |
| 11100026 | 295.071004 | −30.916422 | 230.649 | 332.343 | 0.47                         | 0.20                                 | 0.06         | 0.20                   | 5   | 11.017 | 2   | 17.029 |
| 11100032 | 295.066432 | −30.905801 | 295.049 | 189.641 | 0.09                         | 0.14                                 | 0.15         | 0.22                   | 6   | 11.017 | 2   | 17.223 |
| 11100039 | 295.056244 | −30.921224 | 400.756 | 410.949 | −0.10                        | 0.11                                 | −0.20        | 0.11                   | 9   | 11.025 | 2   | 17.359 |
| 11100045 | 295.047850 | −30.924146 | 497.279 | 458.297 | −0.01                        | 0.06                                 | −0.22        | 0.14                   | 11  | 11.033 | 2   | 17.441 |
| 11100046 | 295.070611 | −30.926622 | 225.463 | 473.366 | −0.61                         | 0.15                                 | 0.88         | 0.07                   | 5   | 11.017 | 2   | 17.455 |

Figure 9. The distribution in $\mu_\alpha$ cos $\delta$ and $\mu_\delta$ for magnitude bins $V = 13–17$ and $20–21$. The right-hand panel shows a VPD for stars with PM < 1.8 mas yr$^{-1}$. Circles indicate $3 \times S$ which is defined in Section 3.4.

For every subimage, a PSF model was constructed using a few bright stars and IRAF’s DAOPHOT routines. All but two of the galaxies were modelled with a 2D Sérsic function. The fit included the closest stars, some of which were present in galaxy foreground. The sky background was also fitted. The coordinates of the galaxies derived this way were used to calculate their PMs relative to the cluster. This was done using the same procedure we applied earlier to stars. We excluded two galaxies from the sample since their $d_T$ was done using the same procedure we applied earlier to stars. We found that a proper motion study of the M55 field and M55-B1 is ($\mu_\alpha$ cos $\delta$, $\mu_\delta$) = ($−3.30 \pm 0.20, −9.14 \pm 0.17$) mas yr$^{-1}$. A VPD for these 10 objects is shown in Fig. 10. The point with the largest uncertainty corresponds to an edge-on galaxy. After dropping this object, we obtained ($\mu_\alpha$ cos $\delta$, $\mu_\delta$) = ($−3.31 \pm 0.10, −9.14 \pm 0.15$) mas yr$^{-1}$. This value was obtained assuming ($\mu_\alpha$ cos $\delta$, $\mu_\delta$) = (0.00, 0.00) mas yr$^{-1}$. Our value can be compared with the result of Dinescu et al. (1999) who obtained a PM for M55 of ($−1.57 \pm 0.62, −10.14 \pm 0.64$) mas yr$^{-1}$. Their measurement was obtained using wide-field photographic plates with a baseline of 25 yr.
4 DISCUSSION

4.1 Colour–magnitude diagram

Fig. 11 shows a $V/(B − V)$ CMD of M55 based on photometry from JK10. The left-hand panel includes about 10,000 stars with high-quality photometry. By selecting stars classified as certain PM members (mem = 2 in Table 3), we obtained the CMD shown in the right-hand panel of Fig. 11.

4.2 Binary stars

A clear sequence running parallel to the main sequence can be seen in the cleaned CMD. We interpret these objects to be binary stars in M55. The binary content of M55 was discussed at length by Sollima et al. (2007). These authors used the Hubble Space Telescope (HST)/Advanced Camera for Surveys (ACS) images centred on the cluster core. Our data show that a population of binaries with $q ≈ 1$ is also present in the more external parts of M55. The binary sequence crosses the cluster turn-off and then extends to the blue including several candidate BS stars. In addition to the BSs, we note the presence of candidate yellow and red straggler stars. These objects are located above the main-sequence turn-off on both sides of the lower part of the subgiant branch. A definitive determination of the membership status of these red/yellow/blue stragglers can be made based on measurements of their radial velocities. M55 has a large radial velocity, $V_{\text{rad}} = 174.8 \text{ km s}^{-1}$ (Harris 1996), and it should be easy to separate field stars from cluster members with high confidence.

4.3 Variable stars and blue stragglers

Our PM survey can be used to assign tentative membership for variables and other interesting objects from the cluster field. We compiled a list of variables and candidate BSs from Olech et al. (1999), Pych et al. (2001), Lanzoni et al. (2007) and JK10. Our PM catalogue includes 52 out of 71 known variables and 46 out of 65 candidate BSs. These stars are listed in Table 4. In Fig. 12, we present a CMD of M55 showing the upper main-sequence and BS regions. All variable BSs with available PMs turned out to be probable members of the cluster. The BS region contains some PM members of M55 not known to be variables. The light curves of these stars obtained by JK10 were re-examined in detail, but none of them showed any evidence for variability. Two of the variable BSs are eclipsing binaries. Variables which with high confidence do not belong to the cluster are V15, V49, V50 and V51. In addition the BSs BSS-7, BSS-27, BSS-31 and BSS-39 from Lanzoni et al. (2007) are probable field stars. Individual cases should be checked taking into account individual PM errors. Further radial velocity studies of all variable stars are needed to reliably establish their membership and evolutionary status.
### Table 4. Tentative membership status (mem) for variables and for BSs from Lanzoni et al. (2007; ID$_{LS}$).

| ID   | ID$_{PM}$ | mem | ID   | ID$_{PM}$ | mem | ID   | ID$_{PM}$ | mem |
|------|-----------|-----|------|-----------|-----|------|-----------|-----|
| V02  | 24300001  | 2   | V32  | BSS-21    | 2   | V62  | 23201072  | 2   |
| V04  | 12200014  | 2   | V33  | BSS-51    | 13400039 | 2   | V63  | 23300072  | 2   |
| V05  | 22405193  | 2   | V34  | BSS-61    | 12400077 | 2   | V64  | 23300099  | 2   |
| V06  | 12200010  | 2   | V35  | BSS-52    | 23200027 | 2   | V65  | 13300228  | 2   |
| V07  | 12220322  | 2   | V36  | BSS-53    | 23300087 | 2   | V67  | 14400131  | 2   |
| V08  | 22400024  | 2   | V37  | BSS-55    | 13300163 | 2   | V69  | 13400057  | 2   |
| V10  | 12100004  | 2   | V38  | BSS-20    | 13300141 | 2   | BSS-01 | 22300208 | 2   |
| V11  | 21300008  | 2   | V39  | BSS-61    | 12400077 | 2   | BSS-02 | 13200131 | 2   |
| V12  | 12300018  | 2   | V40  | BSS-61    | 23200027 | 2   | BSS-07 | 22300198 | 0   |
| V13  | 14400150  | 0   | V41  | BSS-20    | 13300141 | 2   | BSS-08 | 12300182 | 2   |
| V14  | BSS-56    | 2   | V42  | BSS-20    | 13300141 | 2   | BSS-09 | 12300182 | 2   |
| V15  | BSS-58    | 2   | V43  | BSS-61    | 12400077 | 2   | BSS-10 | 22300198 | 0   |
| V16  | BSS-59    | 2   | V44  | BSS-61    | 12400077 | 2   | BSS-11 | 22300198 | 0   |
| V17  | BSS-62    | 2   | V45  | BSS-61    | 12400077 | 2   | BSS-12 | 22300198 | 0   |
| V18  | BSS-63    | 2   | V46  | BSS-61    | 12400077 | 2   | BSS-13 | 22300198 | 0   |
| V19  | BSS-64    | 2   | V47  | BSS-61    | 12400077 | 2   | BSS-14 | 22300198 | 0   |
| V20  | BSS-65    | 2   | V48  | BSS-61    | 12400077 | 2   | BSS-15 | 22300198 | 0   |
| V21  | BSS-66    | 2   | V49  | BSS-61    | 12400077 | 2   | BSS-16 | 22300198 | 0   |
| V22  | BSS-67    | 2   | V50  | BSS-61    | 12400077 | 2   | BSS-17 | 22300198 | 0   |
| V23  | BSS-68    | 2   | V51  | BSS-61    | 12400077 | 2   | BSS-18 | 22300198 | 0   |
| V24  | BSS-69    | 2   | V52  | BSS-61    | 12400077 | 2   | BSS-19 | 22300198 | 0   |
| V25  | BSS-70    | 2   | V53  | BSS-61    | 12400077 | 2   | BSS-20 | 22300198 | 0   |
| V26  | BSS-71    | 2   | V54  | BSS-61    | 12400077 | 2   | BSS-21 | 22300198 | 0   |
| V27  | BSS-72    | 2   | V55  | BSS-61    | 12400077 | 2   | BSS-22 | 22300198 | 0   |
| V28  | BSS-73    | 2   | V56  | BSS-61    | 12400077 | 2   | BSS-23 | 22300198 | 0   |
| V29  | BSS-74    | 2   | V57  | BSS-61    | 12400077 | 2   | BSS-24 | 22300198 | 0   |
| V30  | BSS-75    | 2   | V58  | BSS-61    | 12400077 | 2   | BSS-25 | 22300198 | 0   |
| V31  | BSS-76    | 2   | V59  | BSS-61    | 12400077 | 2   | BSS-26 | 22300198 | 0   |

**Figure 12.** $V/(B-V)$ CMD showing the turn-off and BS regions of M55. Only likely cluster members are plotted. Circles – pulsating variables of SX Phe type; squares – eclipsing binaries.

### 4.4 Sagittarius dSph

The variable V15 has been found by Olech et al. (1999) to be an RR Lyr star belonging to the Sagittarius dSph galaxy. Part of this extended galaxy is present in the background of M55 (Ibata, Gilmore & Irwin 1994; Mateo et al. 1996). We measured the PM of V15 to be $(\mu_\alpha \cos \delta, \mu_\delta) = (1.14 \pm 0.31, 7.81 \pm 0.36)$ mas yr$^{-1}$. The variable is located on the VPD inside an apparent clump formed by a few dozen stars. We identify this group of stars as likely members of the Sagittarius dwarf. For 29 stars surrounding V15 on the VPD, we obtained a weighted mean absolute PM of $(\mu_\alpha \cos \delta, \mu_\delta) = (-2.23 \pm 0.14, -1.83 \pm 0.24)$ mas yr$^{-1}$. This position in the VPD was calculated iteratively with the PM of V15 as a starting point and using stars within a circle of radius of $r = 1$ mas yr$^{-1}$. The measured value of the average PM does not change beyond the quoted errors if this procedure is repeated for radii of 0.75 and 1.25 mas yr$^{-1}$. The positions of these stars on the cluster CMD are shown in Fig. 11. We conclude that this subsample is composed of upper main-sequence and subgiant stars from the Sagittarius dwarf galaxy. For a comparison, Pryor, Pieta & Olszewski (2010) determined the absolute PM of the Sagittarius dwarf to be $(\mu_\alpha \cos \delta, \mu_\delta) = (-2.75 \pm 0.20, -1.65 \pm 0.22)$ mas yr$^{-1}$ based on archival HST images. Their measurement was made at positions located 7.3° and 9.7° north-west from the centre of M55. Earlier determinations of the PM for the galaxy were reported by Dinescu et al. (2005) and Ibata et al. (1997).

### 5 SUMMARY

We have performed the first PM study of the GC M55 based on ground-based CCD images. Relative PMs were derived for 16,945 stars to $V < 21.0$ over a temporal baseline of up to 11 yr. We assigned a cluster memberships status for all stars with available PM measurements. The absolute PM of M55 was measured to be $(\mu_\alpha \cos \delta, \mu_\delta) = (-3.31 \pm 0.10, -9.14 \pm 0.15)$ mas yr$^{-1}$. The absolute PM was derived for a portion of the Sagittarius dSph galaxy located in the background of the cluster. The results of our survey allow a selection of cluster variables, as well as cluster blue/yellow/red stragglers, with high certainty.
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