Cluster AgeS Experiment (CASE): Detection of a dwarf nova in the globular cluster M55

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ABSTRACT

We report the detection of a dwarf nova (DN) in the core region of the globular cluster M55. Six outbursts were observed during 8 observing seasons spanning the period 1997-2004. The variable has an X-ray counterpart detected on images taken with the ROSAT telescope. Although we cannot offer proof of cluster membership, one can see that both the position on the H-R diagram and the X-ray flux are consistent with a bright DN at the cluster distance. According to our outburst statistics, no more than one similar DN could remain undetected in our field of view, centred at the cluster core.

Key words: stars: dwarf novae - novae, cataclysmic variables – globular clusters: individual: (M55, NGC 6809)

1 INTRODUCTION

It is well established on theoretical grounds that close binary stars can have a significant impact on dynamical evolution of globular clusters (Hut et al. 1992). At the same time, the theory predicts that large numbers of white/red dwarf binaries should form in the cores of globular clusters via two-body tidal capture or three-body exchange capture (Fabian, Pringle & Rees 1975; Hut & Paczynski 1984). According to expectations, some of these systems would be in orbits sufficiently tight to become cataclysmic variables (CVs) at some point in their evolution. For example, di Stefano and Rapaport (1994) estimate that there should be several thousand CVs in the galactic globular clusters (GCs). Numerous ground-based surveys for CVs in GCs yielded the identification of surprisingly few objects (e.g. Shara et al. 1994). Besides the two classical novae (Sawyer 1938; Hogg & Wehlau 1964) observed in M14 and M80, a dwarf nova was detected in M5 (Oosterhoff 1941; Margon, Downes & Gunn 1981). Several dozen candidate CVs have been reported over the last few years in observations collected with the \textit{Chandra} and XMM-

\textit{Newton} observatories (Grindlay et al. 2001; Gendre, Barret & Webb 2003) and with the \textit{Hubble Space Telescope} (e.g. Edmonds et al. 1999; Knigge et al. 2003). However, at present there are just a few spectroscopically confirmed CVs in GCs (Margon et al. 1981; Grindlay et al. 1995; Edmonds et al. 1999; Knigge et al. 2003). Similarly, the list of objects with observed dwarf nova type outburst is rather short: V101 in M5 (Shara, Potter & Moffat 1987), DN in NGC 6624 (Shara, Zurek & Rich 1996), CV1 in M22 (Anderson, Cool & King 2003), V1 in M15 (Charles et al. 2002), CV1 in M15 (Shara et al. 2004) and V2 in 47 Tuc (Paresce & de Marchi 1994).

We note parenthetically that at least 3 CVs have been identified so far in open clusters, including one certain DN (Kaluzny et al. 1997; Gilliland et al. 1991). Recently Mochejska et al. (2004) detected a very likely CV in the field of the open cluster NGC 2158. All 4 objects were discovered by chance and one may expect the detection of more CVs, even in close open clusters, if a systematic survey is undertaken.

We have started a systematic search for erupting dwarf novae in GCs by taking advantage of the rich photometric data base collected by the CASE collaboration. The CASE project is focused on the determination of ages and distances to nearby GCs using observations of detached eclipsing binaries (Kaluzny et al. 2005). To identify suitable binaries we conducted an extensive photometric survey of a dozen GCs. The data obtained during the survey can be used to search for various types of variable objects and, in particu-
Table 1. \textit{UBVI}_{C} observations of M55.

| Date            | Filter | Exposure (s) | Seeing (arcsec) |
|-----------------|--------|--------------|-----------------|
| 1997 June 2     | V      | 5×45         | 0.75            |
| 1997 June 2     | B      | 6×65         | 0.82            |
| 1997 June 2     | V      | 7×35         | 0.73            |
| 1997 June 2     | I      | 3×25         | 0.61            |
| 1997 June 2     | U      | 5×360        | 0.81            |
| 1997 June 2     | V      | 8×35         | 0.81            |
| 2003 May 11     | V      | 2×30         | 0.99            |
| 2003 May 11     | I      | 2×20         | 0.83            |
| 2003 May 11     | U      | 2×120        | 1.20            |
| 2003 May 11     | B      | 2×50         | 1.13            |
| 2003 May 11     | V      | 2×35         | 1.25            |

lar, for optical transients in the fields of the clusters being monitored. This paper presents results obtained for M55, which was the first cluster searched by us for the presence of possible dwarf novae.

2 OBSERVATIONS

The CASE project is conducted at Las Campanas Observatory. For the survey we used the 1.0-m Swope telescope, equipped with a 2048 × 3150 pixel SITE3 CCD camera\footnote{The actual size of the CCD is 2048 × 4096 pixels, but rows above 3150 are unusable for photometry.}. With a scale of 0.435 arcsec/pixel, the usual field of view is about 14.8 × 23 arcmin\textsuperscript{2}. However, a large fraction of images for the M55 cluster were taken with a smaller subraster covering a field of 14.8 × 11.6 arcmin\textsuperscript{2} (longer axis aligned in the E-W direction). In the present search for CVs all of the analysed frames were trimmed to this smaller size. The cluster core was located approximately at the centre of the subraster field.

The cluster M55 was monitored during 8 observing seasons spanning years 1997-2004. A total of 3795 images were taken through the V filter, with exposure times ranging from 100s to 480s, while exposure times for a further 313 images taken in the B filter ranged from 100s to 420s. The number of V-band frames taken per night ranged from a few to 90. The median seeing was 1.44 and 1.51 arcsec for the V and B bands, respectively. The cluster was also observed during the 1997 and 2003 seasons with the TEK5 direct CCD camera attached to the 2.5-m du Pont telescope. The field of view was 8.8 × 8.8 arcmin\textsuperscript{2} at a scale of 0.259 arcsec/pixel. The time series photometry through \textit{BV} filters was obtained on a total of 6 nights in May-June 1997 and on 3 nights in May 2003. In addition, exposures with \textit{UBVI}_{C} filters were collected on the nights of 1997 June 2 and 2003 May 11. The journal of observations used to extract \textit{UBVI}_{C} photometry discussed in Sec. 3 is listed in Table 1.

3 SEARCH FOR DWARF NOVAE

The search for possible DNe in M55 was conducted on the V filter images collected with the Swope telescope. We used a slightly modified version of the \textsc{isis}-2.1 image subtraction package (Alard & Lupton 1998; Alard 2000) to detect the variable objects and to extract their photometry. Our procedure followed that described in detail by Mochejska et al. (2002). A reference image was constructed by combining 19 individual frames with \textit{T}_{exp} = 120s taken during dark time on the night of 2001 July 12/13. The seeing for the resultant reference image was \textit{FWHM} = 1.00 arcsec and the limiting magnitude corresponding to a 3σ detection level was \( V \approx 23.0 \).\footnote{This limiting magnitude only applies to the least crowded part of the analysed field.} Subsequently we selected the nights for which at least two V images with seeing better than 1.6 arcsec were available. There were 145 such nights and for 113 of them it was possible to select at least 5 images fulfilling the above condition. The data sets consisting of 2-5 images were then combined to form an average image for each of the 145 nights. Use of the combined frames to search for erupting variables is advantageous not only because of the S/N issue but also because the combined images are free from defects caused by cosmic rays. The combined images were remapped to the reference image coordinate system and subtracted from the point spread function (PSF) convolved reference image using programs from the \textsc{isis} package. The resultant frames were searched with \textsc{daophot} (Stetson 1987) for presence of any subtraction residuals with stellar PSF profiles. We omitted from the search regions which corresponded to the location of saturated stars or to known variables (Clement et al. 2001; Pych et al. 2001; a more extended list based on CASE results will be published elsewhere). In addition, to avoid too many false alarms we set a high detection threshold, at a total residual flux equivalent to that of a constant star with \( V = 20.5 \). In other words, such a star would be marginally detected if it doubled its flux. The apparent distance modulus of M55 is \( (m-M)_{V} = 13.87 \) (Harris 1996). At this distance our variability limit in terms of excess flux corresponds to the constant flux produced by a star of \( M_{V} = 6.6 \).

Our analysis yielded the identification of just one certain erupting object, which we shall call CV1. Its equatorial coordinates are: \( \alpha_{J2000} = 19^h 40'm 08.59's, \delta_{J2000} = -30^\circ 58.51'.1 \). The external accuracy of these coordinates is about 1.0\text{".\footnote{The external accuracy of these coordinates is about 1.0\text{".}}

For further analysis, the \textit{BV} light curves of the variable were extracted with \textsc{isis}, using individual images rather than the combined frames. In the case of the \textit{B}-band photometry, the reference image was constructed by combining the 15 best seeing exposures from the 1998 season. The reference image has \textit{FWHM} = 1.1 arcsec and the limiting magnitude is \( B \approx 23.2 \). The instrumental photometry was transformed to the standard \textit{BV} system using a set of secondary standards present in the M55 field (Stetson 2000). Specifically we used a total of 49 standards with 0.07 < \( B - V < 1.04 \).

4 PROPERTIES OF CV1

Our observations of the variable CV1 recorded 6 outbursts. The combined light curve in the \textit{V}-band is presented in Fig. 4 while Fig. 2 shows two selected outburst light curves.
On individual out-of-outburst images collected with the 1.0-m Swope telescope, the CV1 variable is, in fact, below or close to the detection limit. In Figs. 1 and 2 the data points corresponding to the out-of-outburst images are plotted assuming $V = 22$. The variable in its low state is still detectable on the reference images, but even then the exact measurement of its magnitude is difficult because of crowding problems and relatively poor sampling of the PSF. Photometry of the variable in quiescence is much easier on the images collected with the du Pont telescope. We have used the data listed in Table 1 to measure magnitudes and colours of CV1 in its low state (1997 June 2) and on the rising branch of an outburst (2003 May 11). The close companion visible south-east of CV1 is located at an angular distance of 0.94 arcsec from the variable and has $V = 20.15$ and $B - V = 0.465$. The following magnitude and colours of the variable were derived from the images taken on June 2, 1997: $V = 21.88 \pm 0.06$, $B - V = 0.63 \pm 0.08$, $U - B = -0.83 \pm 0.09$ and $V - I = 1.18 \pm 0.09$. For the night of May 11, 2003 we obtained: $V = 18.98 \pm 0.02$, $B - V = 0.13 \pm 0.02$, $U - B = -0.66 \pm 0.03$ and $V - I = 0.26 \pm 0.03$. The instrumental photometry was transformed to the standard system using observations of several Landolt (1992) fields. The 1σ uncertainties quoted only reflect internal errors and do not include the uncertainties of the zero points of the photometry. To check the external errors we have compared our photometry against standard stars visible in the cluster field.

Observations collected with the du Pont telescope show the variable at $V \approx 20.7$ on 2003 May 4 and at $V \approx 19.9$ on 2003 May 10.
(Stetson 2000). For 28 stars found in common the average differences for $V$, $B-V$ and $V-I$ amount to 0.022, 0.022 and 0.033 mag, respectively. No such comparison was possible for the $U-B$ colour as no Stetson photometry is available for the $U$ band. The data obtained with the Swope telescope give the median colour of the variable during outburst as $B-V = 0.12$.

The nature of the variability of CV1 along with its observed colours indicates that it is a cataclysmic variable of dwarf nova type. According to Warner (1976), most DNe at maximum outburst have unreddened colours in the range $(B-V)_0 = 0.0 \pm 0.10$ and $(U-B)_0 = -0.80 \pm 0.15$. It appears that the colours displayed by CV1 during outburst fall within the above ranges, especially if we take into account the reddening of M55, which amounts to $E(B-V) = 0.08$ (Harris 1996).

In Fig. 4 we show the location of CV1 in three different luminosity stages on the colour-magnitude diagram of the cluster. It is worth noting that in the low state the variable is located close to the cluster main sequence on the $V/B-V$ and $V/V-I$ planes, although it is still very blue in the $U-B$ colour. There are several examples of DNe from GCs and open clusters which show relatively red optical colours in quiescence (Kaluzny & Thompson 2003; Kaluzny et al. 1997; Anderson, Cool & King 2003). Hence, CV1 is hardly exceptional in that respect (see also Bruch & Engel 1994). Out of a total of 193 nights, CV1 was seen in outburst on 23 nights, yielding an average duty cycle of $\rho = 23/193 = 0.119 \pm 0.025$. Due to telescope scheduling and weather, the available nights were not distributed randomly and tend to clump, however, both the numerator and denominator should be affected in a similar way without any systematic effect on the duty cycle. The best-covered outburst lasted $t \approx 10$ days. Each outburst was on average covered by 4, not necessarily consecutive, nights. Hence we estimate that, to within 30 percent accuracy, the above duration $t$ is typical for all outbursts. This yields the average outburst cycle length $T = t/\rho \approx 84$ days with a similar 30 percent error. These results might be used to deduce the average accretion rate and evolution time of the binary, a subject outside our present scope.

We are not in a position to determine from our observations the total number of close binary stars in the cluster core, an important number for its dynamical evolution. However, we can try to estimate the maximum number of DNe in the cluster which would still be consistent with our observations. Let us assume that in our field there is another DN with properties identical to CV1. For as small a duty cycle as $\rho = 0.12$, its outburst should, to a good approximation, obey the Poisson distribution $P(r \leq k; \lambda)$, with the average number of outbursts $\lambda = 6$ from CV1. However, we did not observe any outbursts from a star other than CV1 ($k = 0$), an occurrence of probability $P(r \leq 0; 6) = 0.0025$ or $2.4\sigma$ significance. As a conservative estimate, we assume that a single outburst per star could be misinterpreted as an artefact and overlooked; thus we obtain a probability $P(r \leq 1; 6) = 0.0003$ for the presence of as many as 2 undetected DNe in our field. Therefore, the hypothesis that M55 contains as many as 3 DNe including CV1 has to be rejected at the $3.7\sigma$ confidence level. Furthermore, the peak outburst magnitude of CV1 is around $V = 18.0$. However, in our photometry, outbursts as faint as $V \approx 19.8$ mag would stand out. Hence we can be confident of our conclusion on the lack of 3 DNe in the cluster with outburst magnitude $M_V < 5.9$.

The available data do not allow us to establish with confidence the cluster membership status of CV1. However, we note that the range of observed luminosities of the variable, $18 < V < 21.8$, is consistent with the assumption that it is a dwarf nova belonging to M55. The cluster has an apparent distance modulus $(m-M)_V = 13.87$ (Harris 1996) which yields a variability range in absolute magnitudes of $4.3 < M_V < 7.9$ for CV1 under the assumption of cluster membership. Such a range would be normal for a bright, non-magnetic DN.

The X-ray observations conducted with the ROSAT PSPC detector led to the detection of 18 sources in the field of M55 (Johnston, Verbunt & Hasinger 1996) of which one, namely object #9, is a very likely counterpart of CV1. For that object the ROSAT Source Catalog of Pointed Observations with the HRI (ROSAT Team, 2000) gives $\alpha_2000 = 19^h 40^m 08.4^s$ and $\delta_2000 = -30^\circ 58' 52''$ with a positional error of 2 arcsec. The optical coordinates of CV1 listed above fall within the error circle of the ROSAT source M55-#9. The X-ray to optical luminosity ratio $L_x/L_o \approx 0.3$ would be higher than average for DN but consistent with that for SS Cyg, assuming CV1 was in quiescence during ROSAT observations.

5 BLUE STARS IN THE CLUSTER FIELD

There are several classes of CVs which do not show any pronounced outbursts on a time-scale of years or even decades. For example, old novae or AM CVn stars typically show variability on the level of a few tenths of a magnitude in the optical domain and on time-scales ranging from seconds to years. However, most CVs show very blue $U-B$ and $U-V$ colours (Bruch & Engel 1994). Hence, one may search for candidate CVs in globular clusters by looking for blue stars located below the horizontal branch on the $U-B/V$ or $U-V/V$ colour-magnitude diagram. We have constructed such diagrams for M55 using the data collected with the du Pont telescope on the night of 1997 June 2. The photometry was extracted from the following combined images: $U 5 \times 360s$, $B 6 \times 65s$, $V 40 \times 35s$, $V 5 \times 10s$. The resultant colour-magnitude diagrams are shown in Fig. 4 We considered seven blue objects with measured $U-B < -0.6$ to be candidate CVs (CV1 was dropped from the list). Not one of the X-ray sources detected in the M55 field by the ROSAT PSPS detector (ROSAT Team, 2000) is located within 10 arcsec of any of these blue stars. Examination of time series photometry based on the data from the Swope telescope allowed us to detect variability for only one of candidates. This object, which we call M55-B1, is seen at $V = 20.40$ and $U-B = -0.65$ in Fig. 5 and its equatorial coordinates are: $\alpha_2000 = 19^h 39^m 49.8^s$, $\delta_2000 = -30^\circ 53' 19.6$. It exhibits season to season changes of the mean V luminosity on a level of a few tenths of a magnitude. The light curve for the period 1997-2004 is shown in Fig. 5 In order to search for possible short term variability of blue star candidates for CVs we have examined their time series photometry extracted with ISIS 2.1 (Alard 2000) from the data collected with the du Pont telescope in 1997. A total of 592 V images
Figure 4. Location of CV1 on colour-magnitude diagrams of M55, in quiescence ($V = 21.8$; 1997 June 2), on the rise to maximum ($V = 19.0$; 2003 May 11) and at maximum ($V = 17.9$; 1998 Aug 19).

Figure 5. Colour-magnitude diagrams of M55. Stars with $U - B < -0.6$ are marked with triangles. The open symbol corresponds to the variable M55-B1.

with exposure times ranging from 30 s to 120 s were taken during the period 1997 May 31 – 1997 June 7. Time series photometry was extracted from individual images as well as from 64 combined images formed by averaging 5-10 consecutive frames. We failed to detect any significant variability for any of the blue candidates marked in Fig. 4. In particular, the light curve of variable M55-B1 based on combined images was flat, with $<V> = 20.40$ and $rms = 0.014$ mag. We conclude that none of the selected blue stars is a likely candidate for a CV. The blue colours and long time-scale low-amplitude variability of M55-B1 make it a likely candidate for a quasar.

We conclude this section by noting that a large fraction of stars with $V > 18.5$ visible to the blue or below the main-sequence of M55 in Fig. 4 are members of the Sagittarius dwarf galaxy which is located in the background of the cluster (Mateo et al. 1996). It is feasible that some of blue stars considered above belong to the extended blue horizontal branch of the Sagittarius dwarf.
6 SUMMARY

We report the results of a search for DN outbursts in an extensive photometric survey of the globular cluster M55 obtained within the scope of the CASE collaboration. Using a total of 3795 V-band images taken over 8 seasons centred on the cluster core we were only able to detect 6 outbursts, all from the newly discovered DN star CV1. As we relied on a median combination of several images and on subtraction of the PSF matched templates using the ISIS technique, our survey is quite deep and sensitive down to the very crowded cluster core. Our outburst statistics are consistent with the absence of any further undetected DNe similar to CV1 in the investigated field, and we reject at the 3.7σ confidence level the hypothesis that there are 2 additional undetected DNe with outbursts similar to CV1 or fainter, down to $M_V \approx 5.9$. While most bright field DNe located at the distance of M55 would be detected in our survey, we caution that DNe are in general heterogeneous class of objects and cluster CVs differ in metallicity, so that some rather exotic faint DNe and/or with rare outbursts could perhaps have escaped our scrutiny. However, the deficit of DNe in globular clusters appears to be real. Generally, any dynamical evolutionary scenario of cluster cores would thus have to address the issue of the slow creation of DNe and/or destruction of the existing ones.

The outbursts of CV1 last about 10 days and recur every 85 days, on average. Its position appears to coincide with a ROSAT point source. Although we do not offer proof of the cluster membership of CV1, its characteristics – position in quiescence on the colour-magnitude diagram and X-ray flux – are entirely consistent with a fairly bright dwarf nova $M_V(\text{min}) = 7.9$ located at the distance of M55.

In addition, we searched our deep multicolour photometry obtained with the du Pont telescope for the presence of any blue objects. Apart from CV1, we discovered another blue object showing variability between seasons with no evidence of short time scale variability. Its properties suggest that it is quite likely to be a background quasar.

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