

The first Δa observations of three globular clusters

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ABSTRACT

Globular clusters are main astrophysical laboratories to test and modify evolutionary models. Thought to be rather homogeneous in their local elemental distribution of members, results suggest a wide variety of chemical peculiarities. Besides different main sequences, believed to be caused by different helium abundances, peculiarities of blue horizontal-branch stars and on the red giant branch were found. This whole zoo of peculiar objects has to be explained in the context of stellar formation and evolution. The tool of Δa photometry is employed in order to detect peculiar stars in the whole spectral range. This three filter narrow band system measures the flux distribution in the region from 4900 to 5600Å in order to find any peculiarities around 5200Å. It is highly efficient to detect classical chemically peculiar stars of the upper main sequence, Be/Ae, shell and metal-weak objects in the Milky Way and Magellanic Clouds. We present Δa photometry of 2266 stars from 109 individual frames for three globular clusters (NGC 104, NGC 6205, and NGC 7099). A comparison with published abundances, for three horizontal-branch stars, only, yield an excellent agreement. According to the 3σ detection limit of each globular cluster, about 3% of the stars lie in abnormal regions in the diagnostic diagrams. The first observations of three widely different aggregates give very promising results, which will serve as a solid basis for follow-up observations including photometric as well as spectroscopic studies.

Key words: techniques: photometric – stars: chemically peculiar – stars: horizontal branch – globular clusters: individual: NGC 104 – globular clusters: individual: NGC 6205 – globular clusters: individual: NGC 7099.

1 INTRODUCTION

Globular clusters are extensively used to place constraints on key ingredients of canonical stellar evolution models, such as the mixing length parameter of convective energy transport theory (Ferraro et al. 2006). They are also rather “simple” stellar systems consisting of a distinct population, which is in dynamic equilibrium. Therefore, they are used for extensive N -body simulation in order to understand the formation and evolution of the Milky Way (Sippel et al. 2012).

It is now well known that several globular clusters have at least two main sequences (MS), which are explained by a different helium content (Piotto et al. 2007). In addition, different red giant (RGB) and sub-giant branches were also found (Piotto et al. 2012). A similar characteristic of the horizontal-branch (HB), namely at

least two different populations, was detected by Grundahl et al. (1998). There are different “jumps” in the blue HB (BHB) distribution in the V versus $(u - y)$ colour-magnitude diagram, which could be used to select apparent peculiar objects (Grundahl et al. 1999). Also, peculiar HB extensions, like the blue-hook were found (Brown et al. 2001). However, the cause of these phenomena is still not clear, but it is probably connected to the complex star formation history of the individual clusters (Valcarce et al. 2012).

Gratton et al. (2012) gave an excellent overview of all types of chemical peculiarities for members of globular clusters. Not only variations in light elements (Li, C, N, O, Na, Al, and Mg), but also of CN and CH were detected. Possible correlations and relations of the individual abundances for different elements were widely analysed in the context of stellar formation and evolution. In general terms, one has to distinguish, as for Population I type objects, between intrinsic and photospheric peculiarities.

An intriguing phenomenon, which triggered our study, was

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Table 1. The basic cluster parameters of the targets taken from Harris (1996, 2010 edition).

NGC	Name	$\alpha(2000)$ ($^{\circ}$)	$\delta(2000)$ ($^{\circ}$)	l ($^{\circ}$)	b ($^{\circ}$)	R_{\odot} (kpc)	R_{GC} (kpc)	$E(B-V)$ (mag)	[Fe/H] (dex)
104	47 Tuc	00 24 05.67	-72 04 52.6	305.89	-44.89	4.5	7.4	0.04	-0.72
6205	M13	16 41 41.24	+36 27 35.5	59.01	+40.91	7.1	8.4	0.02	-1.53
7099	M30	21 40 22.12	-23 10 47.5	27.18	-46.84	8.1	7.1	0.03	-2.27

first reported by Behr et al. (1999) who found large deviations in element abundances from the expected cluster metallicity for BHB stars in the globular cluster NGC 6205. For example, iron was found up to be a factor of 3 enhanced compared to the solar value, or about 100 times the mean cluster iron abundance. Later investigations confirmed such elemental abundance anomalies for stars of other globular clusters (Pace et al. 2006). Those authors already speculated that elemental diffusion in the stellar atmosphere will cause the phenomenon. Michaud et al. (2008) used stellar evolution models with self-consistent atomic diffusion to investigate the atmospheric effects in more detail. Indeed, they were able to reproduce the observational results, confirming the role of atomic diffusion driven by radiative accelerations in HB stars.

Such atmospheric effects are well known and studied for the classical chemically peculiar (CP) stars of the upper MS (Braithwaite et al. 2010). Those similarities encouraged us to exploit the capability to detect peculiar Population II stars with the tool of Δa photometry. Due to the typical flux depression in CP stars at 5200Å (full width at half-maximum, FWHM, of the corresponding filter is about 100Å), we are able to detect them in an economical and efficient way by comparing the flux at the centre (5200Å, g_2) to the adjacent regions (5000Å, g_1 and 5500Å, y). It has been shown that virtually all peculiar stars with magnetic fields have significant positive Δa values of up to +100 mmag, whereas Be/Ae and metal weak stars exhibit significantly negative ones (Paunzen et al. 2005). Furthermore, Khan & Shulyak (2007) investigated the contribution of individual elements on the 5200 Å flux depression. They concluded that Fe is mainly responsible for producing a positive Δa index, but also Cr and Si are contributors at least for lower effective temperatures.

Inspecting the spectral region around 5200Å, where the g_2 filter is centred, for RGB-, G- and K-type MS stars (Gray & Corbally 2009), we find strong Mg I (5167, 5173, and 5183Å) and MgH features. Those features vary strongly with the evolutionary status, i.e. for dwarfs and giants. Johnson et al. (2005) derived magnesium abundances for more than 100 RGB stars in each of the Galactic globular clusters NGC 5272 and NGC 6205. They found a wide spread of magnesium abundances within the individual aggregates (about 0.7 dex) and some significant outliers. So it might be possible to detect strongly deviating elemental abundances of magnesium and luminosity effects with Δa photometry.

A further motivation was its feasibility to detect CP stars in the Large Magellanic Cloud (Paunzen et al. 2006), because its global environment is also very different than in the Galactic disc.

In this paper we present the first photometric Δa observations of three, widely different, globular clusters NGC 104, NGC 6205, and NGC 7099. In this first observational pilot study, we test, if the Δa system is able to detect peculiar stars both at the HB- and RGB-, G- as well as K-type MS stars. We do not expect to find traces of the different star sequences due to the fact that helium does not contribute in the 5200Å region.

2 TARGET SELECTION, OBSERVATIONS AND REDUCTION

For this first case study, we selected three globular clusters with widely different overall metallicities, namely NGC 104, NGC 6205, and NGC 7099. Such a criterion guarantees to detect possible peculiar stars for various local environments. Table 1 lists the basic cluster parameters of the targets, taken from Harris (1996, 2010 edition).

The observations of the three globular clusters were performed at two different sites:

- 2 m Ritchey-Chretien-Coude telescope (Bulgarian National Astronomical Observatory, BNAO, Rozhen), direct imaging, SITE SI003AB 1024 × 1024 pixel CCD, 5' field of view, 1 pixel = 0.32'',
- 2.15 m telescope (El Complejo Astronómico El Leoncito, CASLEO), direct imaging with focal reducer, TEK-1024 CCD, 9'5 field of view, 1 pixel = 0.813''.

The observing log with the number of frames in each filter and the integration times is listed in Table 2. The typical seeing conditions were between 1 and 2 arc seconds. The observations were performed with two different filter sets, both having the following characteristics: g_1 ($\lambda_c = 5007$ Å, FWHM = 126 Å, $T_P = 78\%$), g_2 (5199, 95, 68) and y (5466, 108, 70).

The CCD reductions were performed with standard IRAF v2.12.2a routines. All images were corrected for bias, dark, and flat-field. The photometry is based on point-spread-function-fitting (PSF). For each image, we selected at least 20 isolated stars to calculate the individual PSFs. A Moffat15 function fitted the observations best. In the following, only stars were used which are detected on all frames. Because of instrumentally induced offsets and different air masses between the single frames, photometric reduction of each frame was performed separately and the measurements were then averaged and weighted by their individual photometric error. The used photometric errors are based on the photon noise and the goodness of the PSF fit as described in Stetson (1987).

For NGC 6205 three different, overlapping, fields around the centre were observed. No significant photometric offsets between the fields were detected. The most inner parts (radius of about 1'5) of NGC 104 and NGC 7099 were not used for the further analysis because of the severe crowding and the unresolved single star content.

The a -index is defined as

$$a = g_2 - \frac{(g_1 + y)}{2}. \quad (1)$$

Since this quantity is slightly dependent on temperature (increasing towards lower temperatures), the intrinsic peculiarity index (Δa) has to be defined as the difference between the a -value – individual measured a for studied star – and a_0 for non-peculiar star of the same colour. The locus of the a_0 -values is called normality line. Due to the reddening (Maitzen 1993), the a -values have to be corrected by $0.05E(b-y)$. Because there is no significant red-

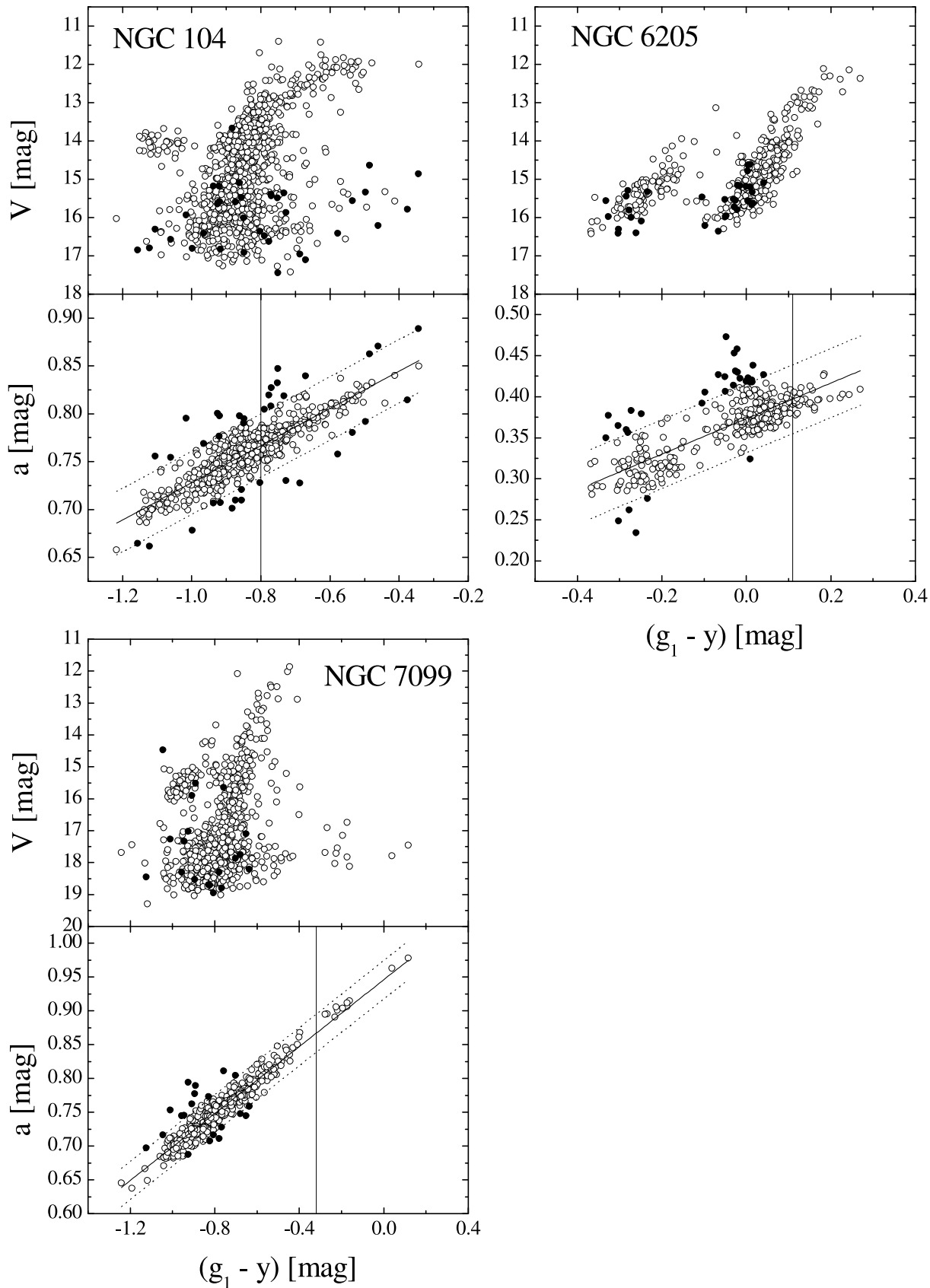


Figure 1. The photometric diagrams of the three globular clusters. The dotted lines are the 3σ upper and lower limits of the Δa detection sensitivity according to Table 3. The vertical lines are the locus of $(B - V)_0 = 1.0$ mag.

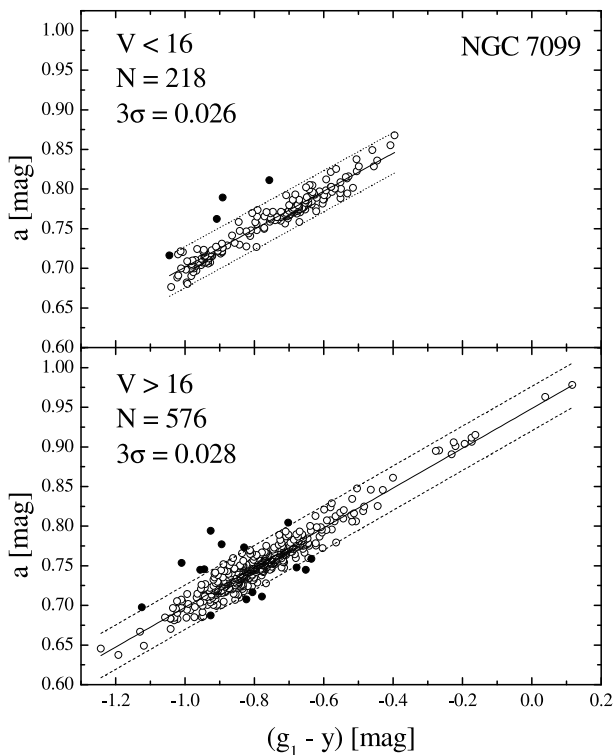
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Table 2. Observing log for the programme clusters. The clusters were observed by I.Kh. Iliev (II) and O.I. Pintado (OP).

Cluster	Site	Date	Obs.	# _{g1}	# _{g2}	# _y	t _{g1} (s)	t _{g2} (s)	t _y (s)
NGC 104	CASLEO	08.2001	OP	6	10	10	5x60, 1x120	5x60, 5x120	5x120, 5x300
NGC 6205	BNAO	07.2003	II	12	12	13	12x100	12x100	13x100
NGC 7099	CASLEO	08.2001	OP	15	16	15	10x60, 6x120	10x60, 5x120	10x60, 5x180

Table 3. Summary of results. The errors in the final digits of the corresponding quantity are given in parenthesis.

	NGC 104	NGC 6205	NGC 7099
$V = a + b(y)$	-3.23(21)/0.909(22)	-2.82(16)/0.965(9)	-5.10(19)/1.009(17)
Reference	Hesser et al. (1987)	Grundahl et al. (1998)	Alcaino et al. (1998)
$a_0 = a + b(g_1 - y)$	0.922(3)/0.194(4)	0.373(1)/0.217(9)	0.946(2)/0.248(3)
3σ (mag)	0.033	0.042	0.028
$n(\text{obj})$	1107	365	794
$n(\text{positive})$	21	28	12
$n(\text{negative})$	16	5	8
$n(\text{frames})$	26	37	46

**Figure 2.** The a versus $(g_1 - y)$ diagram of NGC 7099. The sample was divided into stars which are brighter (upper panel) and fainter (lower panel) than 16th magnitude.

dening towards our targets (see Table 1), we neglect this effect for the further analysis. Assuming that all stars exhibit the same interstellar reddening and metallicity, peculiar objects deviate from the normality line more than 3σ .

For the transformation of the instrumental y to V magnitudes,

we used the following references: Hesser et al. (1987, NGC 104), Grundahl et al. (1998, NGC 6205), and Alcaino et al. (1998, NGC 7099). We note that the zero-points for the measurements taken at BNAO and CASLEO are not the same due to different CCD gain and bias levels as well as extinction coefficients.

All results are summarized in Table 3. In total, 2266 stars on 109 frames are finally analysed. The complete photometric data (Table 4) together with the coordinates are available in electronic form.

3 DISCUSSION

The tool of Δa photometry measures any flux/spectral abnormalities in the 5200Å region. Employing the Δa photometric system on globular clusters aims primarily towards two widely different star groups:

- (i) Photospheric CP HB stars as found by Behr et al. (1999)
- (ii) Peculiar RGB-, G- and K-type MS stars (Gratton et al. 2012)

The first group shows enhancements of iron peak elements of up to three times solar, or 2 dex compared to the mean metallicity, whereas the latter could be detected by peculiarities of Mg I lines as well as MgH features around 5200Å. In addition, cool type dwarfs and giants can be sorted out by the different equivalent widths of their Mg features. However, such a distinction can also be easily done in the classical colour-magnitude diagram.

In Fig. 1, we present the results of our photometric observations. For each globular cluster, the V versus $(g_1 - y)$ and a versus $(g_1 - y)$ diagrams are shown. As expected, the colour-magnitude diagrams, especially the characteristics of the HB, of the three aggregates are widely different.

The slopes of the normality lines range from 0.194 to 0.248 (Table 3), which is perfectly in line with values found for Galactic open clusters (Netopil et al. 2007). We notice that there seems to be a correlation with $[\text{Fe}/\text{H}]$, i.e. NGC 104 with the highest metallicity exhibits the shallowest slope. However, with only three aggregates,

Table 4. The complete photometric data of the programme stars¹.

Id.	$\alpha(2000)$	$\delta(2000)$	$(g_1 - y)$ (mag)	$\sigma(g_1 - y)$ (mag)	a (mag)	σa (mag)	Δa (mag)	V (mag)	σV (mag)
NGC 104									
1	00:24:50.00	-72:05:15.2	-0.886	0.010	0.767	0.008	+0.017	15.047	0.005
2	00:24:49.69	-72:05:28.6	-0.904	0.004	0.768	0.003	+0.021	13.872	0.002
3	00:24:49.48	-72:05:46.4	-0.910	0.002	0.759	0.002	+0.013	14.049	0.002
4	00:24:49.41	-72:05:54.5	-0.838	0.001	0.762	0.002	+0.002	13.572	0.001
5	00:24:49.20	-72:05:38.5	-0.959	0.002	0.743	0.001	+0.008	14.722	0.002
6	00:24:48.58	-72:05:58.5	-0.869	0.001	0.745	0.002	-0.009	13.621	0.001
7	00:24:47.94	-72:04:55.5	-0.950	0.002	0.746	0.003	+0.008	14.851	0.002
...

¹A portion of the table is shown here for guidance. The complete table will be available online.

one has to be careful with such a conclusion. Further observations are clearly needed to prove this apparent correlation.

Due to the photon noise, fainter stars have, in general, larger photometric errors. Inspecting the a versus $(g_1 - y)$ diagrams in Fig. 1, no correlation of the 3σ detection limit with the a values is visible. For NGC 7099, the detailed analysis is shown in Fig. 2. The complete sample was divided in stars brighter and fainter than 16th magnitude. Both samples are rather different in terms of the number of stars and the range of $(g_1 - y)$. In comparison with the overall solution, only one object would not be detected as peculiar in the second sample with $\Delta a = +0.027$ mag which is just one mmag below the detection limit. In addition, we divided the other samples in different V subsamples and calculated the 3σ detection limit anew. All values agree within 1.5 mmag. Those tests justify using the sample as a whole for our analysis. This strong advantage of the Δa photometric system was already noticed before and is because for a given $(g_1 - y)$ value, a wide range of V values are sampled.

We also performed an artificial-star test to determine the completeness level of our sample which is very important when analysing crowded field photometry (Anderson et al. 2008). Normally, faint stars in very crowded regions are either lost in the saturated cores or have been detected against the high background of these bright star aureoles. Thus, the magnitude limits for the detection of faint stars and the undercount correction estimates are functions of both the stellar magnitude and the distance of the objects from the most crowded and therefore bright cluster centre. As mentioned before, the inner most core parts with a radius of about $1/5$ were not used for our analysis. For this purpose, we added artificial stars with the IRAF task ‘ADDSTAR’ to frames of each filter with the longest integration times. About 100 independent experiments, each consisting of 1000 artificial stars within a 1 mag interval randomly scattered throughout the image, were performed. These frames were then photometrically analysed the same way as the original ones. The detected fraction of artificial stars was determined in concentric annuli of $0/5$ width. Finally, a weighted average of the recovery fraction at each radius and magnitude interval was computed. For NGC 6205, we got almost a 99% completeness level for all bins because we observed fields quite far off the centre. Fig. 3 shows the artificial-star tests for NGC 104 and NGC 7099. The band width of the individual curves is about $\pm 3\%$. Since almost all regions and magnitude ranges are well above 90%, we are confident that the effect of undetected binary stars do not play a significant role for our analysis. As a further test, the differences of the a values from the artificial-star test and the observed ones were calculated. Fig.

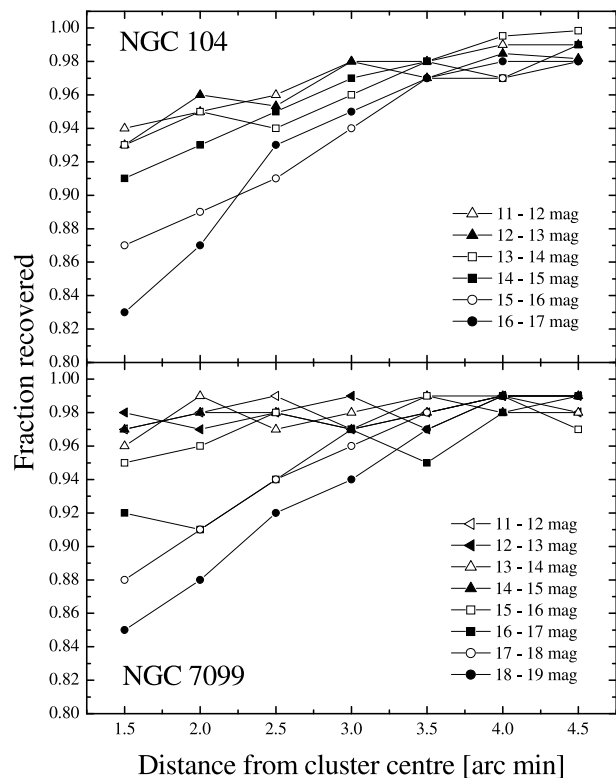


Figure 3. Results of the artificial-star tests for NGC 104 and NGC 7099. The inner most core parts with a radius of about $1/5$ were not used for our analysis.

4 shows these differences versus the V magnitude and the distance from the centre for the data of NGC 7099. Again, the distribution of the outliers does not significantly alter from the apparent normal type objects.

In total, photometric Δa values for 2266 stars were secured. According to the well established 3σ detection limit, 61 stars fall above, and 29 objects below the normality line. The latter can be also due to higher reddened background stars, which would shift these objects below the normality line. The only reliable distinction could be done via membership probabilities based on proper motions. However, such kinematic data are not available for our target sample. Indeed, such field stars are present in globular cluster areas (Sariya et al. 2012). Those field stars are clearly visible in the

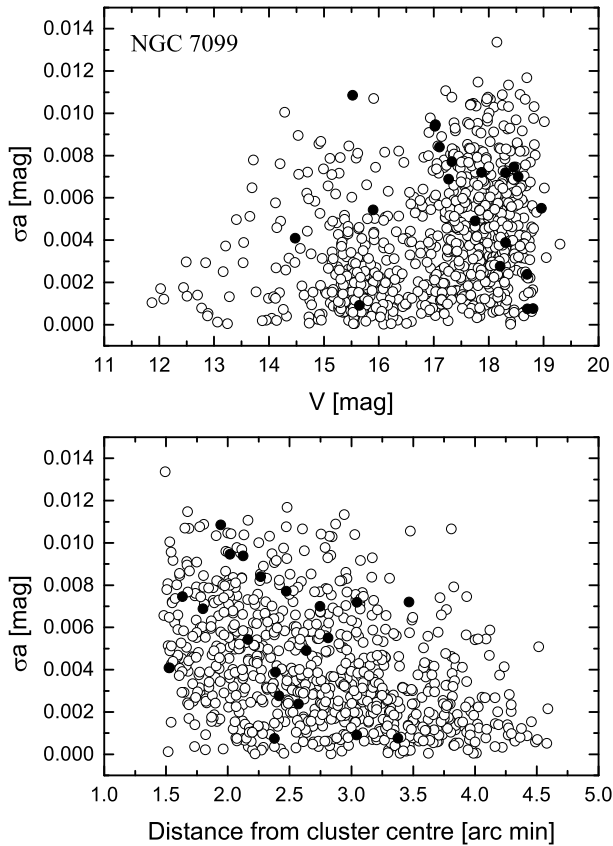


Figure 4. The differences of the a values from the artificial-star test and the observed ones (σa) versus the V magnitude (upper panel) and the distance from the centre (lower panel) for NGC 7099. The peculiar candidates (Fig. 1) are marked as filled circles.

right most upper panel of Fig. 5 in Sariya et al. (2012) where they exhibit redder ($V - I$) colours than the cluster members. In the Δa photometric diagram, such stars could lie below the normality line, but not above it. We also checked the possibility of the influence of undetected visual companions for the outliers. In general, applying PSF-fitting, already accounts for such cases. A comparison of ‘visual binaries’ among normal type objects and outliers shows no significant accumulation among the latter.

To estimate the a versus $(g_1 - y)$ diagram of background/foreground stars in the field of view of our targets, we used the theoretical Galactic model, TRILEGAL 1.6¹ described by Girardi et al. (2005). It includes the populations of the thin and thick disc as well as the Galactic halo but it is not able to simulate star clusters, yet. We have simulated fields of $12' \times 12'$ with the central coordinates as listed in Table 1. Up to now, the Δa photometric system is not included in the list of systems. As workaround, we used the synthetic Δa photometry taken from the Vienna New Model Grid of Stellar Atmospheres, NEMO² (Heiter et al. 2002). The TRILEGAL output includes T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$, and V for each object. First of all, we restricted the sample to the V magnitudes as deduced from Fig. 1. Then, for each star, we searched for the closest model from the NEMO data base and took the corresponding Δa photometry. Fig. 5 shows the observed and synthesized field

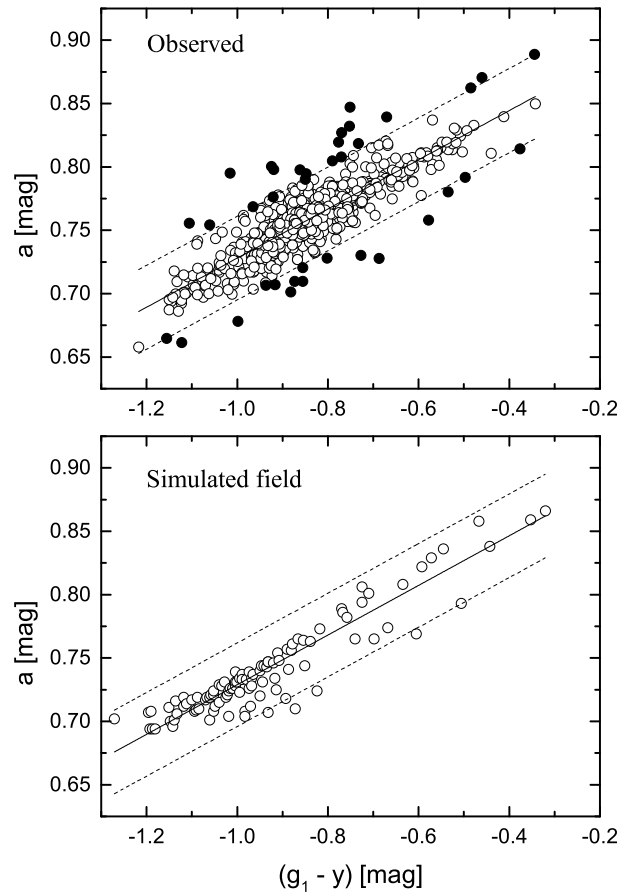


Figure 5. The simulated fore- and background population using the theoretical Galactic model, TRILEGAL (lower panel) and the observed one for NGC 104.

of NGC 104. The situation for the other two fields is similar. The slope for the normality line of the observational data is 0.194(4) whereas it is 0.196(5) for the synthetic data. There are a few stars below (see discussion above) but none above the normality line. We are, therefore, confident that fore- and background stars cannot mimic a statistically significant number of peculiar globular cluster members in the a versus $(g_1 - y)$ diagram. However, some negative outliers of NGC 104 and NGC 7099 (Fig. 1) can be caused by field stars.

NGC 104: no significant deviating Δa values for HB stars were found. About 10 outstanding objects are probable non-members and can be easily identified in the V versus $(g_1 - y)$ diagram.

NGC 6205: this is the most detailed investigated globular cluster among our targets. We measured three HB stars listed in Behr (2003), namely, WF2-820 (No. 147), WF-2692 (No. 227), and WF2-3035 (No. 74). The latter shows no chemical peculiarities, whereas the other two have large overabundances of almost all iron peak elements from 1 to 1.5 dex compared to the cluster metallicity. Our Δa values are perfectly in line with the abundances. For WF2-3035 we find an insignificant value of +8 mmag, whereas the other two stars were detected with +57 and +60 mmag. This lends to confidence that the Δa photometric system is indeed capable to detect CP HB stars. However, further observations of such objects have to prove this conclusion. There are also several BHB stars which are below the normality line. For none of these objects, membership probabilities are available in the literature (Johnson & Pilachowski

¹ <http://stev.oapd.inaf.it/trilegal>

² <http://www.univie.ac.at/nemo>

2012). We may speculate that this behaviour could be due to photometric variations. Such a behaviour is a common phenomenon for CP stars (Paunzen et al. 2011), but was never investigated for members of globular clusters, yet.

As next step, we investigated the RGB stars published by Johnson et al. (2005) among our sample. In total, we find 10 stars in common. The [Mg/Fe] values for those objects range from -0.15 to $+0.30$ dex. None of them exhibit a significant Δa value, probably because the effect of the Mg lines compared to Fe for such rather low peculiarities is too small in the 5200\AA region.

NGC 7099: there are no detailed elemental abundances for members in the literature available. There are three HB stars with a Δa detection, from which one object lies significantly above the HB in the V versus $(g_1 - y)$ diagram. If it is a member then this is probably a very interesting object for follow-up observations. The reasons why several fainter stars deviate from the normality line (as also seen for NGC 104), are not straightforward to determine without any additional observations. However, from our previous considerations one can think of non-members or very strong peculiarities of magnesium.

4 CONCLUSIONS AND OUTLOOK

We presented, for the first time, photometric Δa observations of three globular clusters. It measures the flux distribution in the region from 4900 to 5600\AA (Paunzen et al. 2014). This three filter narrow band system was originally developed to detect classical CP stars of the upper MS. Later on, it turned out that is also capable to detect underabundant, emission as well as shell type stars.

Another mile stone was its extension to field stars and clusters in the Large Magellanic Cloud. Even in this underabundant (compared to the Milky Way) global environment, we were able to detect CP stars, which were later confirmed spectroscopically (Paunzen et al. 2011).

In total, we present photometry of 2266 stars from 109 individual frames. According to the 3σ detection limit of each globular cluster, we find 61 objects with positive and 29 with negative Δa values. This corresponds to an upper limit of about 3% of apparent peculiar objects.

For NGC 6205, we were able to compare our results with abundance determinations from the literature. The Δa values of three HB stars, one without chemical peculiarities, listed in Behr (2003), are in perfect agreement. The peculiar objects were clearly detected with $+57$ and $+60$ mmag, whereas the non-peculiar object does not stand out. In addition, we analysed 10 RGB stars with [Mg/Fe] values from -0.15 to $+0.30$ dex, published by Johnson et al. (2005). None of them exhibit a significant Δa value, which means that the elemental peculiarity of magnesium has to be much larger to be detected.

Several future steps have to be still performed. First of all, further Δa observations of globular clusters and members with known elemental peculiarities are needed to test and establish the system and its results. The presented apparent peculiar objects should be analysed in detail, using high resolution spectroscopy and corresponding stellar atmospheres. However, Δa seems to be a very efficient way to preselect such very interesting objects by means of photometry. As last step, current available stellar atmospheres within the investigated astrophysical parameter space should be used to calculate synthetic colours for a comparison with the observations.

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