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Three newly discovered globular clusters in NGC 6822

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ABSTRACT

We present three newly discovered globular clusters (GCs) in the Local Group dwarf irregular NGC 6822. Two are luminous and compact, while the third one is a very low luminosity diffuse cluster. We report the integrated optical photometry of the clusters, drawing on archival Canada–France–Hawaii Telescope/MegaCam data. The spatial positions of the new GCs are consistent with the linear alignment of the already known clusters. The most luminous of the new GCs is also highly elliptical, which we speculate may be due to the low tidal field in its environment.

Key words: galaxies: individual: NGC 6822 – galaxies: star clusters: general.

1 INTRODUCTION

In Λ cold dark matter (ΛCDM) cosmology, large galaxies are assembled as the result of the accretion and merger of smaller galaxies. If the globular cluster (GC) systems of large galaxies are also formed, at least in part, from the accretion of GCs from the smaller systems, then the GCs themselves can act as beacons of this process. Indeed, the seminal study of the Galactic GCs by Searle & Zinn (1978) was crucial for understanding the history of our own Milky Way (MW). Being compact and luminous, GCs are excellent probes when field star populations cannot be resolved. In our previous work (Mackey et al. 2010; Huxor et al. 2011), we have shown that the GC population of the outer halo of M31 arises largely from the accretion of dwarf galaxies. In many cases, one can identify the remnants of dwarf galaxies in the process of delivering their clusters into M31, where they are becoming part of its retinue of GCs. A similar process is also taking place in the MW, where the Sagittarius dwarf is most likely contributing its GCs to the MW halo (Bellazzini, Ferraro & Ibata 2003; Law & Majewski 2010). Recent work by Keller, Mackey & Da Costa (2012) also supports the view that many GCs found in the outer halo of the MW have been accreted alongside their (now disrupted) dwarf galaxy hosts. They conclude that the MW halo has experienced the accretion of some three Magellanic-like or equally up to 30 Sculptor-like dwarf galaxies, or some intermediate mix of both types. Knowledge of the characteristics of the types of GCs found in a range of dwarf galaxies will assist in determining which scenario may have occurred.

To use GCs as probes, it is essential to understand the properties of the GC systems of dwarf galaxies, the relationship of these properties to their host galaxies, and whether we can still identify these after they have been accreted into a more massive galaxy. Dwarf irregulars are particularly interesting in this regard as they are usually found in the field. Their relative isolation makes them ideal laboratories for studying the pristine properties of GC systems. This contrasts with dwarf spheroidal and elliptical galaxies which are usually found close to more massive galaxies, and thus they (and their GCs) will likely have been influenced by them. Motivated by our previous work in which wide-area searches yielded the discovery of many new clusters in M31 (Martin et al. 2006; Huxor et al. 2008), M33 (Huxor et al. 2009; Cockcroft et al. 2011), and the M31 satellite galaxies NGC 185 and NGC 147 (Veljanoski et al., in preparation), we decided to investigate the outer regions of the dwarf irregular NGC 6822 which benefits from extensive archival Canada–France–Hawaii Telescope (CFHT)/MegaCam imaging, and in which Hwang et al. (2011) have recently discovered four new extended star clusters.

NGC 6822 is a member of the Local Group and is not associated with either the MW or M31. We use an adopted distance of 472 kpc determined as the average of published values for which the error of the distance modulus is <0.2 mag (Górski, Pietrzyński & Gieren 2011). It has an absolute magnitude M_V of −15.2 (Mateo 1998) and an R_{25} of 465 arcsec (RC3.9 value, reported by NED[1]) equal to ∼1 kpc at our adopted distance. NGC 6822 possesses a number of interesting features including a ring of gas and stars which is almost perpendicular to the main body of the galaxy (de Blok & Walter 2000). The galaxy has also been found to have an extended stellar spheroid (Battinelli, Demers, & Kunkel 2006) (see Fig. 1). The central regions of NGC 6822 contain many young massive clusters (Chandar, Bianchi & Ford 2000); however, until very recently, it was believed that there was only one truly old GC in the system (Grebel

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[1] http://ned.ipac.caltech.edu/

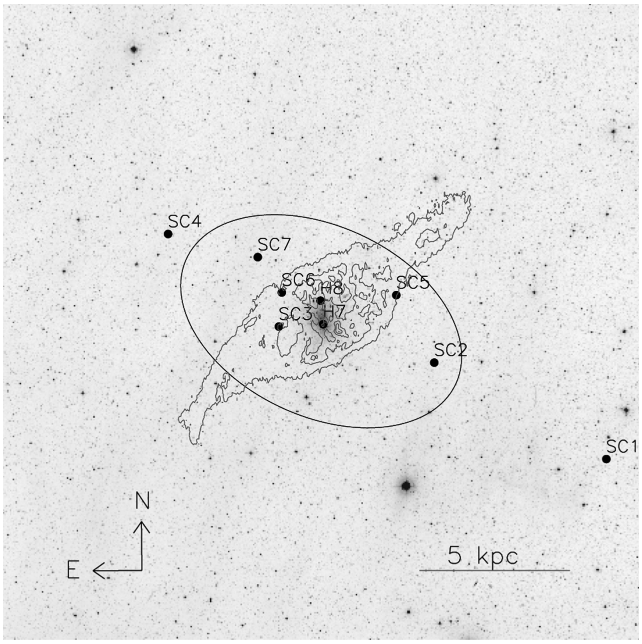

Figure 1. Image from the Digital Sky Survey (DSS) of NGC 6822 with locations of the new and previously known clusters shown, in filter GSS bandpass number 36. The image is 2°.57 × 2°.57. The ellipse shows the extent of the red giant branch stars of the spheroid where the halo is detected above the noise (Battinelli et al. 2006), with a semi major axis of 36 arcmin and an ellipticity of 0.36. Also shown are contours from the H I map of de Blok & Walter (2000).

2002), known as Hubble VII – one of his original lists of 'nebulae'[2] in NGC 6822 (Hubble 1925). Cohen & Blakeslee (1998) undertook a spectroscopic study of this object, reporting an age of 11 Gyr and [Fe/H] = −1.95 dex. Another of Hubble's candidates, Hubble VIII, has also been subjected to detailed study and appears to be a massive intermediate-age cluster. Using *Hubble Space Telescope*/Wide Field Planetary Camera 2 observations, Wyder, Hodge & Zucker (2000) derived an age of 1.5 Gyr; however, a spectroscopic study by Strader, Brodie & Huchra (2003) found it to be somewhat older at 3–4 Gyr. Both Chandar et al. (2000) and Cohen & Blakeslee (1998) derive spectroscopic [Fe/H] estimates for Hubble VIII, finding a value of about −2.0 dex.

In addition, NGC 6822 possesses four extended star clusters (SC1–SC4, shown in Fig. 1) that have been found beyond the main body of the galaxy (Hwang et al. 2011). These were discovered in a wide-field CFHT/MegaCam survey of NGC 6822 that covered a region of 3° × 3°. The clusters have half-light radii of 7.5–14 pc, and colour–magnitude diagrams that are consistent with a wide range of ages (2–10 Gyr) and metallicities (Z = 0.0001–0.004). These clusters are very similar to the extended clusters found in M31 (Huxor et al. 2005) and M33 (Stonkutė et al. 2008), with a couple of the clusters (SC1 and SC4) being very distant from NGC 6822 itself. Hwang et al. (2011) also noted that the extended clusters project on a line that is consistent with the major axis of the old stellar halo.

Drawing partly on the data from the Hubble clusters, Strader et al. (2003) suggest a view of NGC 6822 in which there has been a relatively constant star formation rate over time, with occasional stochastic outbursts that result in the formation of star clusters. A similar scenario has also been outlined by Colucci & Bernstein (2011).

2 THE SEARCH FOR NGC 6822 CLUSTERS

An initial study of the archives found that NGC 6822 had considerable and contiguous coverage in CFHT/MegaCam imaging (see Fig. 2). This is a wide-field camera at the CFHT with a 1° × 1° field of view and a pixel scale of 0.187 arcsec. We naturally use the same imaging as that of Hwang et al. (2011), but also include additional fields that extended the coverage and fill the gaps between the CCDs in their survey. In total, we searched 15 CFHT/MegaCam fields from the programmes2003BK03, 2004AC02, 2004AQ98 and 2005AK08, with observations taken over the period 2003 August–2006 August. Science exposures ranged from 660 to 1200 s in the g band, from 360 to 1000 s in the r band and from 150 to 460 s in the i band.

The images were visually inspected since star clusters at NGC 6822's distance are easily resolved in CFHT/MegaCam imaging, and indeed this is the optimal way to identify any additional examples of the extended clusters. We are only concerned with the outer regions of NGC 6822 and do not study the main body of the galaxy where many young clusters have already been documented (Krienke & Hodge 2004).

We also examined archival Subaru/Suprime-Cam imaging of NGC 6822. This instrument has a ∼0°.5 × 0°.5 field of view and a pixel scale of 0.20 arcsec, and the imaging was mainly concentrated on the inner regions of the galaxy. We utilized only those images for which the exposure was greater than 200 s. Those available in the archive were obtained in B-,V-, R- or I-band filters, and were taken for proposals o01422, o00005, o02419,o03147, o99005, o04151 and o05226. Although these pointings did not extend much beyond the main body of NGC 6822, many of the images were deeper than those from CFHT/MegaCam and they proved useful to

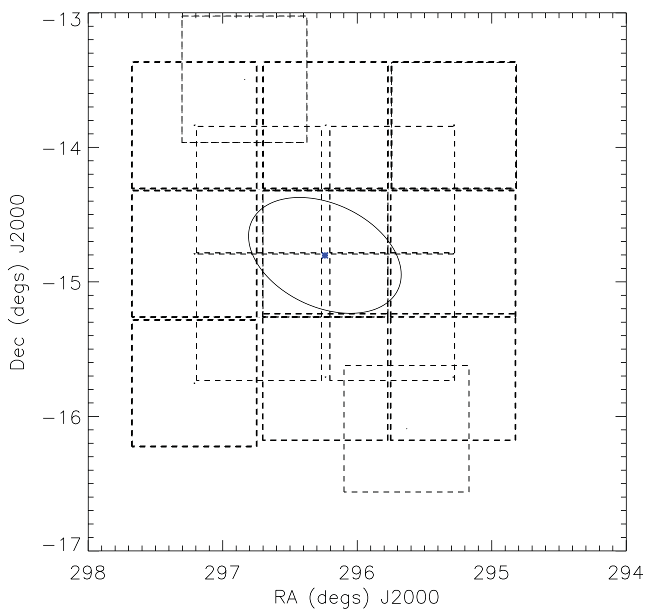

Figure 2. Locations of the CFHT/MegaCam fields studied. The centre of NGC 6822 is represented by the small solid square, and the ellipse is the same as that in Fig. 1.

[2] The majority of these are H II regions. Hubble VI is a young cluster and the nature of Hubble IX is still unclear.

confirm, or otherwise, candidate clusters found in the CFHT/MegaCam imaging.

3 THE NEW CLUSTERS

The search for new GCs found a total of three new clusters, in addition to rediscovering all those of Hwang et al. (2011). Two are luminous compact classical clusters, and one is very faint and appears extended in form. We continue the naming convention used by Hwang et al. (2011), and denote them as SC5, SC6 and SC7 (in order of right ascension). The coordinates of these objects and their projected distance from the centre of NGC 6822 are listed in Table 1. The two luminous clusters (SC6 and SC7) are clear examples of GCs (see Fig. 3). The new faint cluster (SC5) is, in contrast, much more diffuse. Although barely detected in a single exposure from the CFHT archive, SC5 can be seen more clearly in a stacked image available through the CFHT archive (Fig. 4, left-hand panel), and also in a deep archival Subaru/Suprime-Cam image (Fig. 4, right-hand panel). SC5 resolves into stars while SC6 and SC7 only do so in their peripheries.

Table 1. Locations of the new clusters and their projected distances ($R_{\rm proj}$) from the centre of NGC 6822 (RA = $19^{\rm h}\,44^{\rm m}\,57\overset{\rm s}{.}7$, Dec. = $-14^{\circ}\,48'\,12''$).

ID	RA (J2000)	Dec. (J2000)	$R_{\rm proj}$ (kpc)
SC5	$19^{\rm h}\,43^{\rm m}\,42\overset{\rm s}{.}30$	$-14^{\circ}\,41'\,59\overset{''}{.}7$	2.6
SC6	$19^{\rm h}\,45^{\rm m}\,37\overset{\rm s}{.}02$	$-14^{\circ}\,41'\,10\overset{''}{.}8$	1.6
SC7	$19^{\rm h}\,46^{\rm m}\,00\overset{\rm s}{.}85$	$-14^{\circ}\,32'\,35\overset{''}{.}4$	3.0

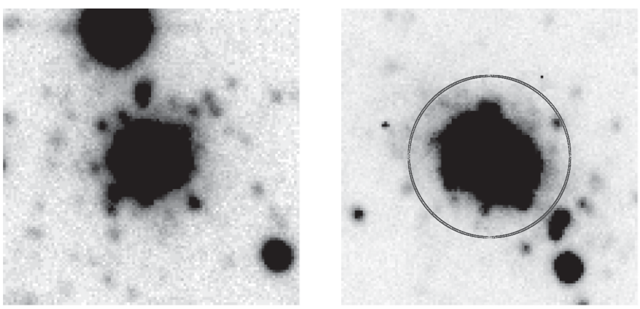

Figure 3. The two new compact GCs, SC6 (left) and SC7 (right) from CFHT/MegaCam *i*-band imaging. Each image is 20 by 20 arcsec. North is up and east is to the left. The circle overlaid on SC7 has a radius of 30 pixels (cf. Fig. 5).

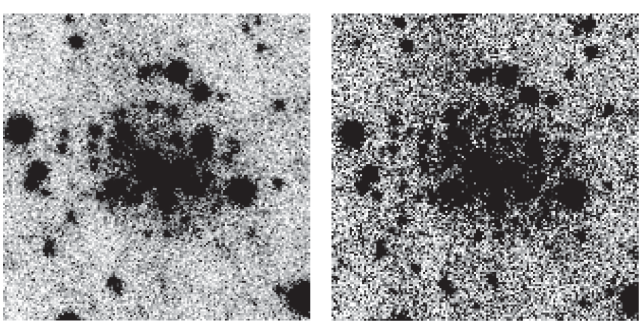

Figure 4. The new extended GC, SC5, from *r*-band CFHT/MegaCam (left) and Cousins *I*-band Subaru/Suprime-Cam (right) imaging, stretched to highlight the faint cluster. Each image is 30 by 30 arcsec. North is up and east is to the left.

Table 2. Photometric properties of the new clusters. Extinction corrections use values estimated from the extinction map of Schlegel et al. (1998). The *g, r* and *i* magnitudes are in the CFHT/MegaCam filter system. Photometric errors on the colours (derived for a inner aperture for SC6 and SC7 – see the text) are estimated at ±0.01 mag. The major source of error for the total magnitudes is the uncertainty of the memberships of cluster stars within the aperture, which are estimated at ±0.03 mag.

ID	g_0	r_0	i_0	V_0	$(V-I)_0$	M_{V0}	$E(B-V)$
SC5	–	19.43	–	–	–	–	0.219
SC6	15.55	15.01	14.79	15.28	0.84	−8.09	0.190
SC7	15.02	14.43	14.10	14.77	1.05	−8.60	0.207

3.1 Integrated photometry

Integrated photometry was undertaken for the two most luminous new clusters, using the archival imaging data available. The results are reported in CFHT/MegaCam filter magnitudes (which are similar but not identical to standard Sloan filters) in Table 2.

In our photometry we used large apertures that enclose the full extent of the cluster for the total magnitudes. As there is no evidence that GCs have strong colour gradients, we employed smaller apertures to obtain more reliable colours. Photometric calibration of the CFHT data was undertaken using the magnitudes derived for the one pointing taken in photometric conditions, and cross-calibrating the other data using stars common to both.

Photometry for the brightest cluster, SC7, proved problematic. In the archival CFHT/MegaCam data, the cluster is saturated in the *g* and *r* bands and photometry can only be undertaken in the *i* band. However, shorter exposures of cluster SC7 were also in the CFHT archive, taken for the purposes of photometric calibration. In these exposures, SC7 unfortunately lands on the edge of a CCD making measurements of the full cluster impossible. Hence, we use the central region of the shorter exposures to obtain the colours using an aperture radius of 1.5 arcsec. We then estimate the total magnitudes by using an aperture of radius 6 arcsec on the long *i*-band image and applying the colour measurements to obtain total *g*- and *r*-band magnitudes. For cluster SC6, no such problem arose: the apertures employed for the deriving the colour and total magnitude had radii of 2 and 4.7 arcsec, respectively.

The very faint cluster SC5 was also difficult to photometer. This object is visible in a long CFHT/MegaCam *r*-band stack (11 000 s) but the *g*- and *i*-band data, even when stacked, are too shallow to detect the cluster. The *r*-band stack was photometered with an aperture radius of 10 arcsec. SC5 was also found in archival Subaru data, confirming its status as a cluster.

Photometry in the CFHT/MegaCam filter set was also converted to Johnson–Cousins *V* and *I* for SC6 and SC7. This was achieved by using the colour transform equations given on the Sloan Digital Sky Survey (SDSS) webpages.[3] This was not possible for SC5 as we require photometry in more than the one filter for the transform equations.

Extinction is known to be a major issue with NGC 6822 due to its low Galactic latitude. Battinelli et al. (2006) use the stellar population of NGC 6822 to estimate the foreground reddening across the area discussed in this paper and find that it is not only significant, but also patchy. Specifically, $E(B-V)$ ranges from 0.19 to 0.30 (their fig. 2). We correct for this using the extinction maps – interpolated

[3] http://www.sdss.org/dr4/algorithms/sdssUBVRITransform.html

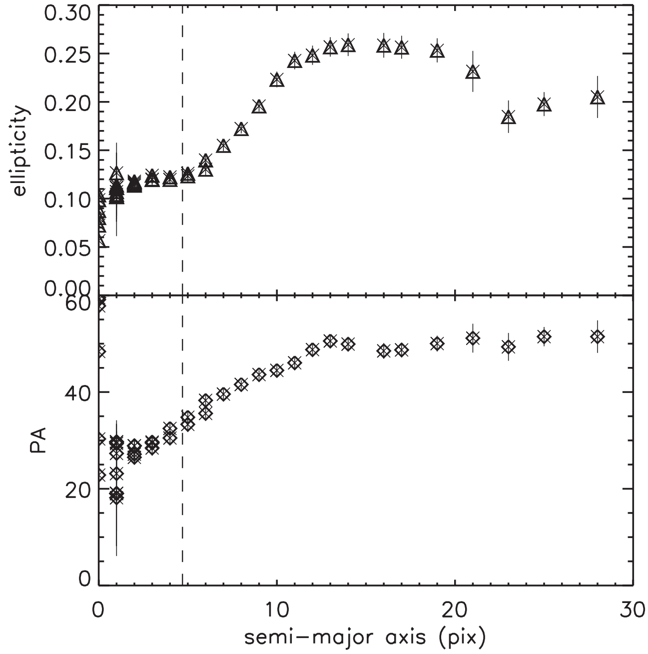

Figure 5. Ellipticity and PA as derived from IRAF/ELLIPSE for SC7. The PA is ∼50 ° over radii of ∼10–30 pixels (cf. circle on the left-hand panel of Fig. 3). The ellipticity has a value of ∼0.25 over a large range of radii. The FWHM of the image is 4.7 pixels (dashed vertical line).

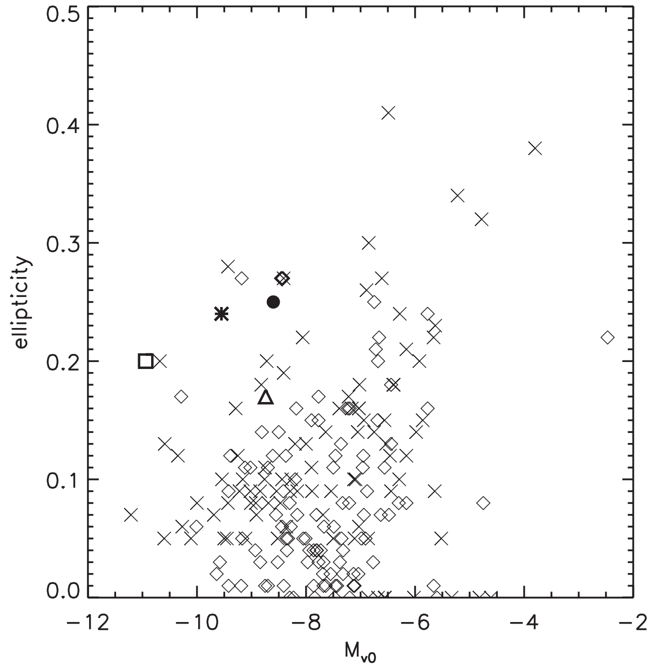

Figure 6. The location of SC7 (filled circle) in a plot of M_V versus ellipticity. Also shown are MW GCs (diamonds) taken from the McMaster MW GC catalogue (Harris 1996), M31 clusters taken from Barmby et al. (2007) (crosses) and G1 (Ma et al. 2007) (square), WLM-1 (Stephens, Catelan & Contreras 2006) (triangle), cluster 77 from Annibali et al. (2011) (asterisk) and NGC 121 (Glatt et al. 2009) (thick diamond), where the magnitude for NGC 121 is the mean of the values they derive for King and EFF fits to the profile. The most elliptical GC in the MW is M19, but this is known to be a result of differential reddening (van den Bergh 2008).

to the position of the new clusters – and relative extinction for the Sloan bandpasses from Schlegel, Finkbeiner & Davis (1998). NGC 6822 also has internal reddening and Massey et al. (1995) find values of up to $E(B - V)$ of 0.45 mag in the centre of the galaxy. However, the new clusters lie far from the centre of NGC 6822 and should be minimally impacted by internal reddening. We note, however, that patchy Galactic extinction may limit the accuracy our final photometry.

3.2 Ellipticity of SC7

Visual inspection reveals that cluster SC7 is significantly elongated. We used IRAF/ELLIPSE[4] to derive the ellipticity and position angle (PA) of the major axis of SC7 using a fixed centre, and the results are shown in Fig. 5. The PA beyond ∼12 pixels is 50° and the ellipticity has a value of ∼0.25 over the main body of the cluster. This high ellipticity is unusual for a GC and makes SC7 a clear outlier in a plot of M_{V0} versus ellipticity (Fig. 6).

4 DISCUSSION AND SUMMARY

The new clusters reported here substantially increase the number of classical GCs found in NGC 6822. If all the new massive clusters (excluding SC5, which is too faint to be found in comparable studies of local dwarfs) prove to be genuinely 'old' GCs, then the four clusters in Hwang et al. (2011) and the two in this work would increase the specific frequency of NGC 6822 to $S_N \sim 7$, comparable to the newly enlarged GC systems of NGC 147 and NGC 185 (Veljanoski et al., in preparation). This value is also consistent with values found for dwarf irregulars in the Virgo and Fornax galaxy clusters (Seth et al. 2004).

The cluster SC7 is of relatively high luminosity and SC6 is almost as luminous, with $M_{V0} \sim -8$ mag. The GC systems of M31 and the MW have median values of M_V of −7.9 and −7.3, respectively (Huxor et al. 2011), so both SC6 and SC7 are brighter than the turnover of the GC luminosity function for these galaxies. Previously, in Mackey et al. (2007) and Huxor et al. (2011), we found that M31 possesses a number of luminous GCs in its outer stellar halo, for which no counterparts exist in the MW (excepting the very unusual cluster NGC 2419). If, as seems likely, the accretion history of M31 was different from that of the MW, we may have a natural source of M31's luminous halo GCs in the accretion of systems such as NGC 6822. However, such events would have had to happen at an early epoch since there is no evidence for young populations – which dominate in galaxies like NGC 6822 – in the M31 halo today.

The origin of high ellipticities in GCs, such as that of SC7, has been the source of some debate. Kontizas et al. (1990) find that the ellipticity for young Small Magellanic Cloud star clusters is greater than for the clusters in the somewhat more massive Large Magellanic Cloud (LMC), and similar results lead Georgiev et al. (2008) to argue that the tidal field of the host galaxy is likely to be an important factor in determining cluster ellipticity. A scenario in which the SC7's ellipticity is a consequence of it being formed in a dwarf galaxy host is also consistent with the presence of the extended

[4] IRAF 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 National Science Foundation.

clusters in NGC 6822. Indeed, Hurley & Mackey (2010) argue that the formation and survival of extended clusters is a consequence of the more benign tidal fields in dwarf galaxies and the outer regions of massive galaxies. The origin of the high natal ellipticity, which a low tidal field preserves, may arise from a number of sources: rotation, galactic tides or anisotropy in the velocity dispersion between the major and minor axes. The latter was found to be the best explanation for the high ellipticity of the only GC known thus far in the dwarf galaxy WLM (Stephens et al. 2006).

It should be noted that an alternative scenario for the formation of luminous, elliptical GCs has also been proposed. In a study of the star cluster system of the Magellanic-type starburst galaxy NGC 4449, Annibali et al. (2011) found that the brighter clusters tend to be more elliptical. One of their clusters (cluster 77) is old, massive and highly elliptical (see Fig. 6), leading them to suggest that it may be the nucleus of a satellite galaxy that is currently being stripped (Annibali et al. 2012). A similar picture has also been proposed for G1, the most luminous GC in M31 (Meylan et al. 2001), and the anomalous Galactic GC ω Cen (e.g. Romano et al. 2007).

One last notable aspect of the newly discovered GCs is that they lie in the linear arrangement noted by Hwang et al. (2011). As we have surveyed the full area in Fig. 2, this distribution cannot be a result of incomplete areal coverage. Such a disc alignment would not be unusual – the cluster population of the LMC exhibits disc kinematics (Schommer et al. 1992; Grocholski et al. 2009) – but it would raise new questions about the formation of NGC 6822. If the GC system is found to exhibit disc-like kinematics, it might be hard to reconcile with a scenario where the galaxy formed via the merger of two similar mass gas-rich dwarfs (Bekki 2008). We have spectroscopic data for SC6 and SC7, and are currently obtaining data for other clusters in NGC 6822 to study the kinematics of the cluster system and address this question.

To summarize, we have presented the discovery of three new star clusters in the outskirts of NGC 6822 based on searches conducted with archival data sets. Two of these objects are massive compact GCs, very distinct from the extended clusters found by Hwang et al. (2011). The third is a very low luminosity diffuse cluster. We have measured integrated photometry for these objects, but additional characterization (e.g. structural parameters, stellar populations) will require deep high-resolution data. SC6 and SC7 are so compact that R_h is comparable to the full width at half-maximum (FWHM) in the data presented here. One of the clusters, SC7, is highly elliptical which we speculate could be due to the low tidal field it has experienced in the outer regions of a dwarf galaxy.

We note in closing that it is remarkable that SC6 and SC7 were not discovered earlier. These are high-luminosity GCs in a Local Group galaxy that has been studied very extensively. This underscores yet again how the outer regions of galaxies have the ability to surprise and provide important clues about their histories.

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