

No sign (yet) of intergalactic globular clusters in the Local Group

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Accepted 2016 April 19. Received 2016 April 18; in original form 2016 April 6

ABSTRACT

We present Gemini Multi-Object Spectrograph (GMOS) imaging of 12 candidate intergalactic globular clusters (IGCs) in the Local Group, identified in a recent survey of the Sloan Digital Sky Survey (SDSS) footprint by di Tullio Zinn & Zinn. Our image quality is sufficiently high, at ~ 0.4 – 0.7 arcsec, that we are able to unambiguously classify all 12 targets as distant galaxies. To reinforce this conclusion we use GMOS images of globular clusters in the M31 halo, taken under very similar conditions, to show that any genuine clusters in the putative IGC sample would be straightforward to distinguish. Based on the stated sensitivity of the di Tullio Zinn & Zinn search algorithm, we conclude that there cannot be a significant number of IGCs with $M_V \leq -6$ lying unseen in the SDSS area if their properties mirror those of globular clusters in the outskirts of M31 – even a population of 4 would have only a ≈ 1 per cent chance of non-detection.

Key words: globular clusters: general – Local Group.

1 INTRODUCTION

Globular clusters are observed in many Local Group galaxies – in abundance in the haloes of the Milky Way and M31, and in smaller numbers in roughly a dozen dwarf galaxies spanning a variety of morphological types. However, in the Local Group, no examples of intergalactic globular clusters (IGCs) are known. This is in stark contrast to the situation in denser environments, such as large galaxy clusters, where substantial populations of IGCs are seen (e.g. Gregg et al. 2009; Peng et al. 2011). It is unclear whether the local dearth of IGCs is a consequence of observational bias (due to a lack of dedicated searches, and, until quite recently, sufficiently deep and uniform all-sky imaging) or whether it reflects an intrinsic scarcity of such objects.

A thorough review of the reasons why a population of Local Group IGCs might plausibly be expected has recently been presented by di Tullio Zinn & Zinn (2015). They argue that there are two possible formation channels. The first posits that globular clusters are formed in galaxies, but that strong galaxy–galaxy interactions might subsequently lead to some fraction becoming unbound. This is thought to be the origin of the significant IGC populations observed in galaxy clusters, where close encounters between galaxies frequently lead to tidal disruption or stripping (e.g. West et al. 2011; Samsing 2015). It is well known that galaxy interactions, mergers and accretions have occurred in the Local Group. Numerous stellar streams and overdensities are observed in the halo of the

Milky Way (e.g. Belokurov et al. 2006; Martin et al. 2014; Grillmair & Carlin 2016), and indeed the Sagittarius dwarf is presently in the process of being accreted (Ibata, Gilmore & Irwin 1994). The stellar stream resulting from the tidal destruction of Sagittarius may be traced across the entire sky (e.g. Majewski et al. 2003), and this debris includes a number of globular clusters that were once hosted by the dwarf (Bellazzini et al. 2003; Law & Majewski 2010). In M31, an abundance of halo substructure is seen out to radii beyond 100 kpc in projection (McConnachie et al. 2009; Ibata et al. 2014), and many remote globular clusters are associated, both spatially and kinematically, with these features (Mackey et al. 2010b, 2013, 2014; Veljanoski et al. 2013, 2014).

The largest stream visible in the M31 halo is the Giant Stellar Stream, a signature of the most significant recent accretion event in the Local Group. This event involved an early-type progenitor which experienced an energetic, near head-on collision with M31 ~ 1 – 2 Gyr ago; prior to its disruption, this system was likely the fourth or fifth most massive galaxy in the Local Group (Fardal et al. 2013). Debris from this encounter can be traced to at least 100 kpc from the M31 centre. Moreover, there is strong evidence that the third most-massive Local Group galaxy, M33, has recently interacted with M31, as has the dwarf elliptical satellite NGC 147. In both cases, these interactions have been sufficiently strong so as to draw substantial stellar material from the inner parts of these galaxies into extended tidal tails (McConnachie et al. 2010; Crnojević et al. 2014). In the Milky Way sub-group, recent observations of the periphery of the Large Magellanic Cloud (LMC) have revealed a ~ 10 kpc stellar substructure (Mackey et al. 2016) that may be a result of tidal stripping by the Milky Way, or repeated close interactions

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between the LMC and its smaller neighbour the Small Magellanic Cloud (e.g. Besla et al. 2016).

While interactions between Local Group galaxies appear common, the dispersion of barycentric velocities is of the order of $\approx 50 \text{ km s}^{-1}$ (e.g. McConnachie 2012), such that the typical collision energy is likely much lower than in a dense galaxy cluster. Hence, it is plausible that IGCs arising due to close encounters between Local Group galaxies are quite rare.

The second, more speculative, formation channel advanced by di Tullio Zinn & Zinn (2015) is that IGCs might form *in situ*, within their own individual dark matter haloes (Peebles 1984). While no good evidence for dark matter in globular clusters has yet been observed (e.g. Lane et al. 2010; Ibata et al. 2013), this hypothesis has not been definitively ruled out. Perhaps the only place one might find ‘pristine’ globular clusters that formed in this way would be in intergalactic space; it is thought that clusters entering the dark matter halo of a large galaxy would have any of their own dark matter quickly stripped (e.g. Mashchenko & Sills 2005). The most isolated globular cluster known in the Local Group is MGC1, which sits ≈ 200 kpc from the centre of M31 (Mackey et al. 2010a). None the less, this is still well within the expected virial radius of the system (~ 300 kpc), and Conroy, Loeb & Spergel (2011) showed that the observed radial density profile of MGC1 precludes that this cluster resides within a dark matter halo of mass $\gtrsim 10^6 M_{\odot}$.

Motivated by these questions, di Tullio Zinn & Zinn (2015) recently conducted the first systematic large-area search for Local Group IGCs. The basis of their survey is the Sloan Digital Sky Survey (SDSS; York et al. 2000) Galaxy Catalogue, which spans $\sim 14\,500 \text{ deg}^2$, or roughly one-third of the entire sky. By combining the SDSS optical data with infrared photometry from the *Wide-field Infrared Survey Explorer* (WISE) satellite, and ultraviolet measurements from the *Galaxy Evolution Explorer* (GALEX) satellite, they attempt to select objects with spectral energy distributions matching those observed for globular clusters in Local Group galaxies. This technique is demonstrably successful – di Tullio Zinn & Zinn (2015) present the discovery of 22 clusters in the halo of M31 (see also di Tullio Zinn & Zinn 2013, 2014), many of which have independent verification from the Pan-Andromeda Archaeological Survey (Huxor et al. 2014). In addition to these objects, di Tullio Zinn & Zinn (2015) list another 12 candidates that pass their selection criteria but lie well away from M31 and all other Local Group galaxies. As such, they identify these objects as possible Local Group IGCs.

In this Letter, we present high-quality ground-based imaging of these 12 objects with the aim of assessing whether or not any of them are bona fide globular clusters.

2 OBSERVATIONS AND DATA REDUCTION

We obtained snapshot images of the 12 candidate IGCs listed by di Tullio Zinn & Zinn (2015) with the Gemini Multi-Object Spectrograph (GMOS) at the Gemini North telescope on Mauna Kea, Hawaii. The observations were carried out in queue mode as programme GN-2015B-Q-17 (PI: Mackey), between 2015 late July and early November. The data were collected during clear conditions and under excellent seeing ($\sim 0.4\text{--}0.7$ arcsec). Table 1 presents the observing log and the full list of targets.

For a given object, we obtained two frames of exposure duration 145 s each, with a 5 arcsec dither to fill in the GMOS inter-CCD gaps. All imaging was conducted through the GMOS i' filter. We reduced the data using standard procedures in the GMOS software package in IRAF. Bias and flat-field images were applied with the GIREDUCE task, the three CCD frames in a given exposure were

Table 1. Log of observations.

Target name	RA (J2000)	Dec. (J2000)	Date observed	Image quality (arcsec)
dTZZ-C01	00 54 27.3	+04 11 01.4	2015 July 26	0.41
dTZZ-C02	01 09 22.7	−05 54 57.5	2015 July 28	0.40
dTZZ-C03	02 05 30.4	+06 46 41.1	2015 August 27	0.44
dTZZ-C04	02 30 35.9	+46 19 11.9	2015 August 20	0.58
dTZZ-C05	06 48 36.5	−18 23 19.7	2015 October 08	0.56
dTZZ-C06	08 03 29.3	+13 04 38.3	2015 October 08	0.49
dTZZ-C07	10 09 37.0	+61 15 58.4	2015 November 07	0.55
dTZZ-C08	15 54 37.3	+12 55 13.4	2015 August 02	0.39
dTZZ-C09	16 40 17.9	+54 58 05.6	2015 July 26	0.51
dTZZ-C10	17 03 44.7	+38 47 50.2	2015 July 26	0.49
dTZZ-C11	20 55 18.0	+54 42 46.2	2015 October 08	0.70
dTZZ-C12	22 54 47.4	+17 26 21.4	2015 July 26	0.39

mosaicked into a single frame with GMOSAIC, and then the two frames for a given object were stacked together using IMCOADD.

3 RESULTS

Images of the targets are shown in Fig. 1. These are $1' \times 1'$ cut-outs from the final reduced GMOS frames. It is evident that all 12 of the IGC candidates are distant galaxies. Six exhibit distinct spiral arms (C02, C04, C05, C06, C07, and C12), while two have a more irregular morphology (C01 and C08). The remaining four (C03, C09, C10, and C11) appear to be early-type galaxies.

To provide insight on what we might expect IGCs in the Local Group to look like in this type of image, Fig. 2 shows examples of globular clusters in the outer halo of M31 observed with GMOS through the i' filter as part of programs GN-2008B-Q-22 and GN-2014B-Q-26 (PI: Mackey). Atmospheric conditions were very similar to those under which our IGC images in Fig. 1 were obtained; seeing was in the range $\sim 0.3\text{--}0.6$ arcsec. Long sequences of g' and i' -band images were taken in an effort to construct deep colour–magnitude diagrams for these clusters (as in Mackey et al. 2013); to ensure a fair comparison to our data for the IGC candidates, we selected and stacked only two random i' -band images for each object in Fig. 2. The total exposure times are longer than for the IGC candidates, but not by more than a factor of 2.

The clusters were chosen from the catalogues of Huxor et al. (2008, 2014) to span a representative range in luminosity ($-8.5 \lesssim M_V \lesssim -5.0$) and size ($3 \lesssim r_h \lesssim 25$ pc). The mean distance of the sample is approximately that of M31 – i.e. 780 kpc, corresponding to a distance modulus of 24.46 (Conn et al. 2012). However, because these objects sit in the outskirts of the M31 halo at projected radii in the range $45 \lesssim R_p \lesssim 90$ kpc, there could plausibly be line-of-sight distance variations from object to object of the order of ± 100 kpc about this value (see e.g. Mackey et al. 2010a). While the ‘edge’ of the Local Group is an ill-defined concept, a reasonable estimate would be that it is not much more than ≈ 1 Mpc from the mid-point of the vector connecting the Milky Way and M31 (e.g. McConnachie 2012). Thus, these clusters sit at distances comparable to those that might be expected for the IGC candidates in the case where any of these was a real cluster in the Local Group – recall that most fall well away from the direction of M31 on the sky.

Irrespective of their luminosity or physical size, all the globular clusters shown in Fig. 2 exhibit resolved stars. In the case of the more

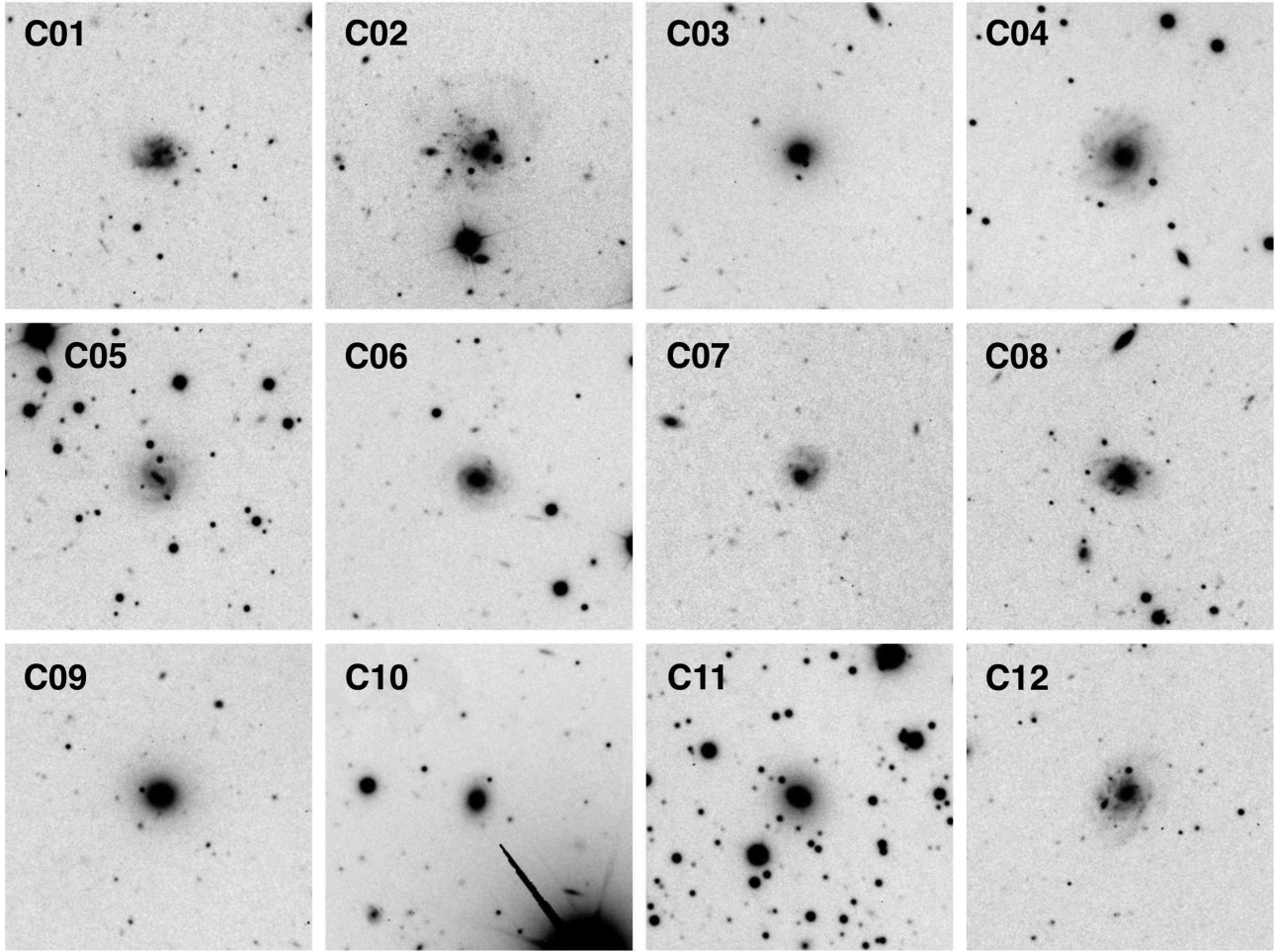


Figure 1. GMOS i' -band images of the 12 candidate IGCs. Each thumbnail is 1 arcmin \times 1 arcmin and oriented such that north is up and east to the left.

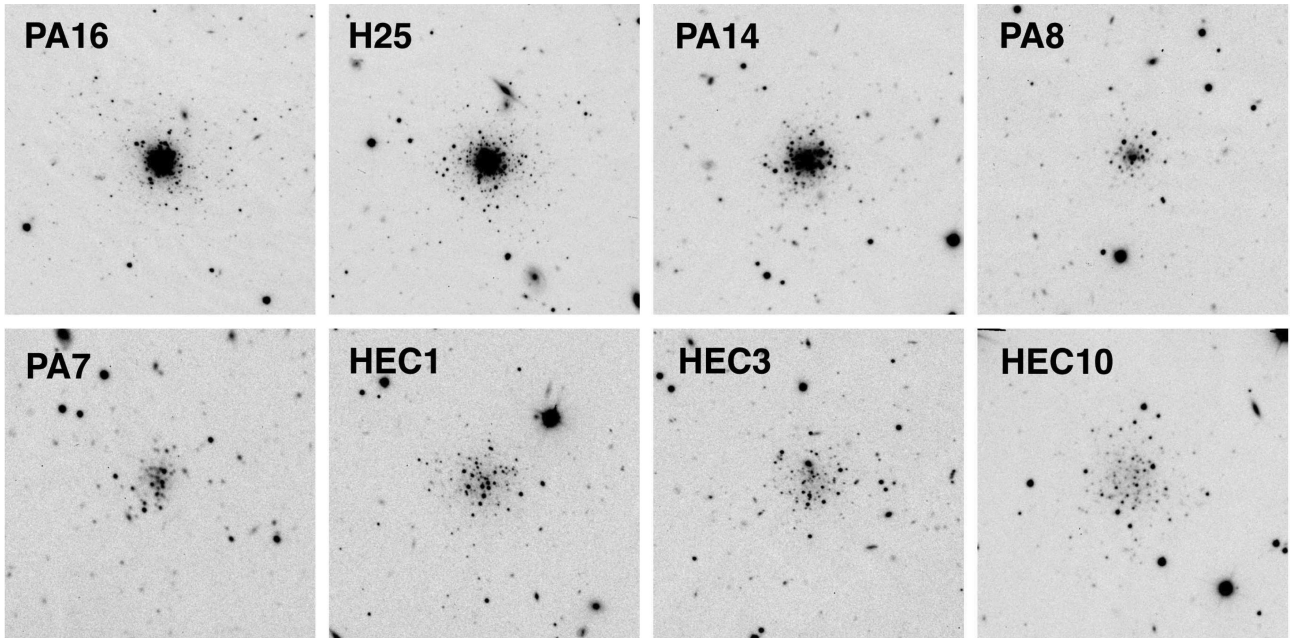


Figure 2. GMOS i' -band images of eight globular clusters in the outer M31 halo. These span luminosities of $-8.5 \lesssim M_V \lesssim -5.0$ and sizes $3 \lesssim r_h \lesssim 25$ pc, and sit at roughly the M31 distance of 780 kpc. As before, each thumbnail is 1 arcmin \times 1 arcmin and oriented such that north is up and east to the left.

compact clusters, these surround an unresolved core possessing an irregular appearance. None of the clusters displays anything akin to a feature that could be mistaken for a spiral arm. Similarly, none of them exhibits a diffuse, unresolved component similar to the irregular morphology of C01 or C08, or the much smoother morphology of C03, C09, C10, and C11.

On the basis of this simple comparison, we are confident that none of the objects shown in Fig. 1 is a star cluster.

4 DISCUSSION AND CONCLUSIONS

The fact that there are no globular clusters amongst the 12 candidates from di Tullio Zinn & Zinn (2015) suggests that IGCs in the Local Group are intrinsically rare, although it is difficult to quantitatively assess the meaning of ‘rare’ in this instance. di Tullio Zinn & Zinn (2015) provide the following information about the efficiency, and limitations, of their detection algorithm.

(i) The search area spans roughly one-third of the sky, although a few regions (e.g. towards the Galactic plane) are affected by extinction and crowding.

(ii) They are only sensitive to clusters more luminous than $M_V \sim -6$ out to the edge of the Local Group (i.e. ≈ 1 Mpc from the mid-point of the vector connecting the Milky Way and M31).

(iii) They are only sensitive to relatively compact clusters; objects like some of those in Fig. 2 that might be mostly resolved into stars in SDSS images do not appear in their base catalogue.

(iv) By passing data for known Local Group globular clusters through their selection criteria, they show that their detection completeness is ≈ 85 per cent for objects in the range of size and luminosity to which the algorithm is sensitive.

Given these constraints, we can ask how likely it is that a population of IGCs falls within the SDSS footprint but was not detected by the di Tullio Zinn & Zinn (2015) search procedure. To proceed, we make the assumption that the putative IGCs have the same luminosity function and size distribution as globular clusters observed in the outer halo of M31 at projected radii in the range $25 \leq R_p \leq 150$ pc. We choose M31 because (i) it has many more globular clusters at such radii than does the Milky Way, so the population statistics are sounder; and (ii) perhaps surprisingly, the census of remote globular clusters is likely more complete in M31 than in the Milky Way – as evidenced by the continuing discovery of moderately luminous clusters in the Milky Way periphery (e.g. Belokurov et al. 2014; Laevens et al. 2014, 2015).

From Huxor et al. (2014), we see that, for M31 clusters with $R_p \geq 25$ kpc, the distribution of sizes depends weakly on luminosity. We assume, conservatively, that the di Tullio Zinn & Zinn (2015) search algorithm is sensitive to objects with $r_h \leq 10$ pc, but does not see objects with sizes larger than this. At luminosities brighter than $M_V \approx -7.5$, all clusters in the M31 sample have $r_h \leq 10$ pc; however, for luminosities in the range $-7.5 \leq M_V \leq -6$, approximately 40 per cent of clusters have $r_h > 10$ pc. Out of the clusters with $M_V \leq -6$, half have $M_V \leq -7.5$, and half have $-7.5 \leq M_V \leq -6$.

Armed with this information, we see that the chance that a cluster is detectable (i.e. the probability that it has $r_h \leq 10$ pc given that its luminosity is $M_V \leq -6$) is 0.8. Applying the 85 per cent success rate stated by di Tullio Zinn & Zinn (2015) then implies that, for any given cluster, the total chance of detection is 0.68. Hence, the probability that for a population size N , there will be no detections is $(1 - 0.68)^N$. For $N = 2$, the likelihood is only ~ 10 per cent; for $N = 4$, it has fallen to ≈ 1 per cent. Thus, the fact that we did not

observe any genuine clusters in the target sample suggests that there is almost certainly not more than ~ 4 Local Group IGCs with $M_V < -6$ to be found across the SDSS footprint. Of course, it is possible to hide any number of objects fainter than this because the di Tullio Zinn & Zinn (2015) algorithm cannot find them; if we continue to base our assumptions on the outer halo of M31, then we might expect roughly one cluster fainter than $M_V = -6$ for every two clusters brighter than this level.¹

It is difficult to scale these limits to the whole sky because we do not know how IGCs might be distributed within the Local Group. The simplest assumption of an isotropic distribution on the sky leads to a scale factor of ≈ 3 ; however, the distribution is almost certainly not isotropic due to our vantage point away from the Local Group barycentre, and because the processes that might form IGCs very likely do not distribute them uniformly in any case – strong galaxy–galaxy interactions tend to create streams and arcs, while small dark matter haloes tend to cluster around larger dark matter haloes. Thus, while it is improbable that a substantial population of relatively luminous IGCs might remain undetected in the SDSS footprint, it would still be very worthwhile to execute similar searches to that conducted by di Tullio Zinn & Zinn (2015) on extant and future large-area data sets covering different regions (e.g. those from PS1, DES, SkyMapper, LSST, etc.).

ACKNOWLEDGEMENTS

The authors are grateful to the organisers of the Lorentz Center workshop Globular Clusters and Galaxy Haloes in February 2016, where this collaboration was established. ADM acknowledges support from the Australian Research Council through Discovery Projects DP1093431, DP120101237, and DP150103294. MAB was supported by the Programa Nacional de Astronomía y Astrofísica from the Spanish Ministry of Economy and Competitiveness, under grants AYA2013-48226-C3-1-P, AYA2013-48226-C3-2-P, AYA2013-48226-C3-3-P. RL acknowledges funding from the Natural Sciences and Engineering Research Council of Canada PDF award.

This Letter is based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), Ministério da Ciência, Tecnologia e Inovação (Brazil) and Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina). These observations were obtained under programmes GN-2008B-Q-22, GN-2014B-Q-26, and GN-2015B-Q-17.

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¹ Although the PAndAS sample starts to become incomplete below $M_V \approx -6$, with 50 per cent completeness at $M_V \sim -4.1$ (Huxor et al. 2014).

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