

The Faint Globular Cluster in the Dwarf Galaxy Andromeda I

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Abstract

Observations of globular clusters in dwarf galaxies can be used to study a variety of topics, including the structure of dark matter halos and the history of vigorous star formation in low-mass galaxies. We report on the properties of the faint globular cluster ($M_V \sim -3.4$) in the M31 dwarf galaxy Andromeda I. This object adds to the growing population of low-luminosity Local Group galaxies that host single globular clusters.

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1 INTRODUCTION

Globular clusters (GCs) have long been used as luminous tracers of the star-formation histories, chemical enrichment, and gravitational potential of their host galaxies, especially in the stellar halos where the density of stars is low (Brodie & Strader 2006). GCs in dwarf galaxies are of particular interest; for example, in recent years, they have been used to provide evidence that some dark matter halos have central cores rather than cusps (e.g., Goerdt et al. 2006) and to constrain the extreme mass loss from GCs predicted in some models of the formation of multiple stellar populations (Larsen, Strader, & Brodie 2012). The presence of GCs also hints at active early star formation in dwarfs, as measurements in the local universe suggest that the fraction of stars formed in bound clusters and the maximum mass of star clusters correlates strongly with the star formation rate density (e.g., Goddard, Bastian, & Kennicutt 2010; Cook et al. 2012; Kruijssen 2012; Johnson et al. 2017).

Most dwarfs in the Local Group do not host GCs, especially among the less massive galaxies. The least luminous Local Group galaxy known to have a GC is the recently discovered dwarf Eridanus II. This galaxy has $M_V = -7.1$ and hosts a GC with $M_V = -3.5$, which by itself makes up 4% of the luminosity of its host (Koposov et al. 2015; Crnojević et al. 2016a). Contenta et al. (2017) and Amorisco (2017) argue that the survival of this GC against dynamical friction, despite its projected location close to the galaxy centre (offset by only ~ 45 pc), is evidence for a cored dark matter halo in Eridanus II: If

a standard cuspy halo were present, the GC would have been very unlikely to have survived to the present day. Amorisco (2017) makes a similar argument for the M31 satellite Andromeda XXV, which hosts a faint extended star cluster near its centre, though the precise offset is not well-determined as the galaxy centre itself is poorly constrained (Cusano et al. 2016). These conclusions are important as it is unclear whether galaxies with such low luminosities can effectively transform cuspy dark matter profiles to cored ones through central bursts of star formation (e.g., El-Badry et al. 2016; Read, Agertz, & Collins 2016), and the presence of cores could provide evidence for self-interacting dark matter rather than standard cold dark matter (e.g., Robles et al. 2017).

Here we present a discussion of another faint Local Group galaxy with a GC: the M31 satellite Andromeda I (And I). The existence of this GC, which we term And I–GC1, was briefly noted in a conference proceeding many years ago (Gebel, Dolphin, & Guhathakurta 2000) but the basic data of the cluster have not been discussed in the subsequent literature, and it has not been included in lists of Local Group dwarfs that host GCs (e.g., Mackey 2015).

2 BACKGROUND, DATA REDUCTION, AND ANALYSIS

Gebel et al. (2000) noted the presence of a faint GC in the archival *Hubble Space Telescope* (HST)/WFPC2 imaging of And I published in da Costa et al. (1996). This GC is

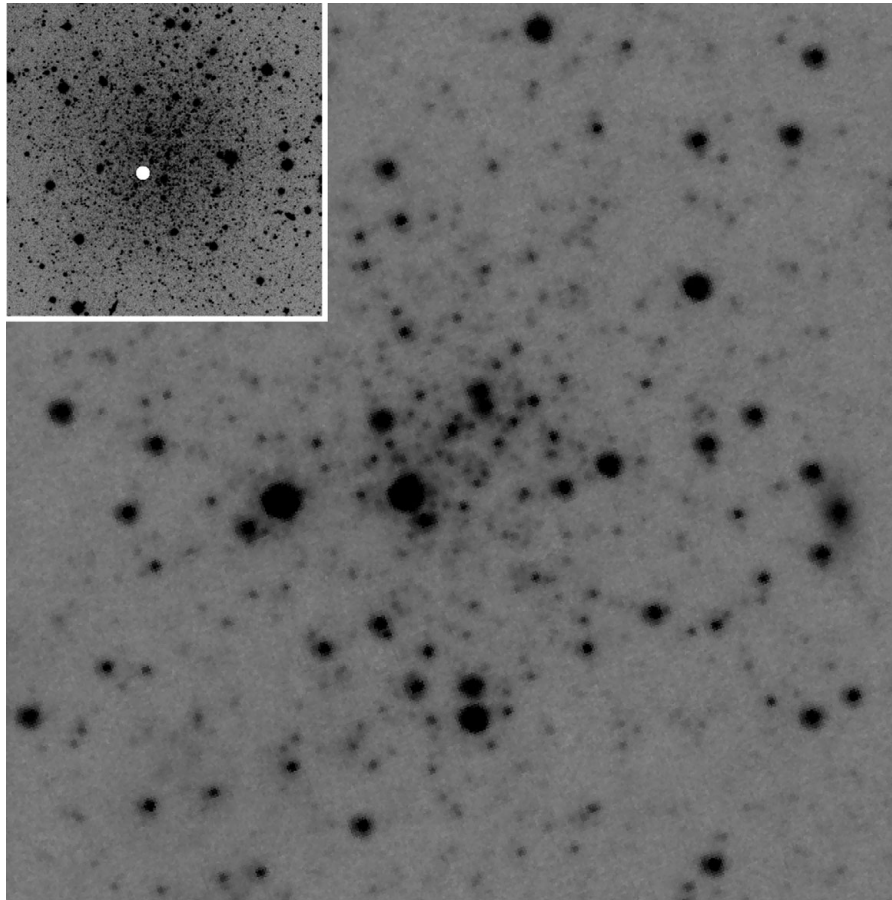


Figure 1. A log-scaled *HST/ACS F814W* image of And I-GC1, 10 arcsec (38 pc) on a side. An insert shows the entire And I galaxy, from a ground-based image. This has a width of 7.2 arcmin (1.6 kpc). The location of the GC within the dSph is indicated by the white spot.

located at a J2000 degree position (R.A., Dec.) = (11.42881 +38.03162), calculated from our own images discussed below. This position is located ~ 207 pc from the centre of And I (we use a distance of 745 kpc; McConnachie 2012). As the half-light radius of And I is 672 ± 69 pc (McConnachie 2012), the GC sits well within the central regions of the galaxy. New, deep *HST/ACS* observations of And I have been obtained as part of programme GO-13739 (Skillman et al. 2017), which fortunately include the GC (see Figure 1). These data comprise a total exposure time of approximately 29 ks in *F475W* and 23 ks in *F814W*. We retrieved the individual CTE-corrected exposures from the *HST* archive then processed the data using *DrizzlePac*. The relative exposure offsets were determined using *TweakReg* and then drizzled together with *AstroDrizzle* to a pixel scale of 0.03 arcsec.

Using an isophote fitting programme, we determined integrated magnitudes of the GC out to a radius of 3 arcsec (100 pixels or 11 pc), the radius at which light from the GC could not be distinguished from the background. As the cluster is faint and there are a few likely contaminating stars in the field, we masked pixels 4σ above the local isophote. The integrated

Vega magnitudes of the cluster are $F475W = 21.7 \pm 0.1$ and $F814W = 20.3 \pm 0.1$. These photometric uncertainties represent only the shot noise in the masked profile. If the bright stars are not masked, the cluster is brighter by about 0.5 mag in *F814W* and 0.3 mag in *F475W*, which should be taken as a qualitative estimate of the systematic uncertainties in the integrated photometry. We note that even in the case of perfect measurements, there are substantial stochastic fluctuations in the absolute magnitudes and colours of low-mass clusters due to sparse sampling of the stellar mass function and the short lifetimes of bright post-main sequence stars (e.g., Fouesneau et al. 2014).

To reference these measurements to the commonly used *V* band, we used Padova single stellar population models (Bresnan et al. 2012) for a 13 Gyr population to convert *F475W* to *V*, finding $V \sim 21.1$, equivalent to $M_V \sim -3.4$ (-3.7 if the bright stars are not masked). The luminosity of And I GC would rank among the lowest of confirmed M31 GCs, though most GC searches have not been complete to this depth (e.g., Huxor et al. 2014).

To empirically derive a metallicity for the cluster, we corrected the magnitudes for foreground reddening using the

maps of Schlafly & Finkbeiner (2011) and then converted them to AB g and i , again using the Padova models. These values are $i_0 = 20.7 \pm 0.1$ and $(g - i)_0 = 0.70 \pm 0.11$. As a check on this value, we also calculated integrated colours within the half-light radius (see below), for which we might expect the relative effect of contaminating stars to be lower. This value is $(g - i)_0 = 0.73$, well within the uncertainty on the total colour. Peacock et al. (2011) publish observed $(g - r)$ and $(r - i)$ colour vs. $[\text{Fe}/\text{H}]$ plots for M31 GCs; We combine these data to estimate a rough conversion between $(g - i)$ colour and metallicity. Using the value $(g - i)_0 = 0.70$, we find an estimated photometric metallicity of $[\text{Fe}/\text{H}] = -1.5 \pm 0.4$, suggesting the GC is metal poor, but not remarkably so: its metallicity is typical of the typical of the metal-poor GC populations in the Milky Way and M31. This metallicity is also consistent with the overall low metallicity of And I itself ($[\text{Fe}/\text{H}] \sim -1.5$; Kalirai et al. 2010).

We also estimated a rough half-light radius via integrated light, finding a value of 4.2 ± 0.4 pc (the individual $F475W$ and $F814W$ measurements were 4.3 and 4.1 pc, respectively). This implies a half-mass relaxation time of ~ 360 Myr assuming a mean stellar mass of $0.6 M_\odot$ (Koposov et al. 2007). The evaporation time will be approximately 10 times longer than the relaxation time, though the actual mass loss rate depends on the current stellar mass function (including remnants), the true galactocentric distance, and the mass of the dark halo (Gieles, Heggie, & Zhao 2011). In any case, it is clear that the least massive GCs in dwarfs are susceptible to evaporation on timescales of Gyrs, suggesting that clusters like the one in And I are likely to be dissolving.

It is worth considering whether this GC could be an M31 object projected onto And I, as the dwarf sits at a projected radius of 45 kpc from M31. The surface density profile of M31 GCs from Huxor et al. (2011) predicts 0.004 GCs kpc^{-2} at the projected distance of And I. Since the area within the half-light radius itself is $\sim 1.4 \text{ kpc}^2$, the expected number of contaminant GCs from M31 is about 0.006. Even if we conservatively increase this estimate by about 50% to account for incompleteness of the GC search for objects with $M_V > -6$, the predicted number of M31 GCs within the half-light radius of And I is still < 0.01 . Given that the GC is much closer to the galaxy centre than the half-light radius, this calculation shows the GC is very unlikely to be an M31 interloper, though of course it would be desirable to obtain a radial velocity.

3 DISCUSSION

As noted in the Introduction, GCs are rare among Local Group galaxies with low stellar masses, and And I (with $M_V = -11.7$; McConnachie 2012) is among the most extreme examples—only Eridanus II ($M_V = -7.1$) and Andromeda XXV ($M_V = -9.7$) have lower luminosities and still host a GC. Here we place this galaxy and star cluster in the larger context of low-mass galaxies with GCs.

The best-studied GC system of a low-mass galaxy in the Local Group is that of the Fornax dwarf spheroidal ($M_V =$

-13.4 ; McConnachie 2012), which has five clusters with absolute magnitudes ranging from $M_V = -5.1$ to -8.1 (Strader et al. 2003). One of these GCs, with $M_V = -7.3$, is more metal rich than the others and is located near the centre of the galaxy, and hence is sometimes cited as a candidate nuclear star cluster, though its radial velocity appears offset from the field stars in the galaxy centre (Hendricks et al. 2016). The dynamical friction timescale for the Fornax GCs is less than a Hubble time, so the survival of its GC system is a puzzle; one proposed solution is that the dark matter distribution in the Fornax dSph is cored rather than cusped, leading to a longer inspiral time (Goerdt et al. 2006).

Considering other M31 satellite galaxies: besides the faint And I and Andromeda XXV GCs, more luminous clusters were proposed to be affiliated with And XVII ($M_V = -8.7$) by Irwin et al. (2008), but kinematic studies have shown these GCs are unlikely to be bound to the dwarf (Veljanoski et al. 2014).

The Local Group dwarf irregular WLM hosts one massive GC (Stephens, Catelan, & Contreras 2006), while WLM is more luminous than the Fornax dwarf spheroidal, its stellar mass is lower, such that this GC makes up at least 5% of the total mass of the galaxy, and an astonishing $\sim 25\%$ of the stars with $[\text{Fe}/\text{H}] < -2$ (Larsen et al. 2014).

Beyond the Local Group, a number of galaxies in the luminosity range $-10 \lesssim M_V \lesssim -11.5$ likely host at least one GC (e.g., Georgiev et al. 2010; Da Costa et al. 2009). While a firm association between candidate GCs and host galaxies has not been confirmed via spectroscopy for most of these objects, in many cases, the GCs are definitively identified via *HST* imaging, and it is reasonable to assume that most of these proposed associations are correct. Noting a few of the extremes among this group, the galaxy KK27 ($M_V = -10.1$) with two candidate GCs is currently the lowest luminosity galaxy known outside the Local Group with GCs (Georgiev et al. 2010). The IKN galaxy, in the M81 group, is slightly more luminous ($M_V = -11.5$) but has five GCs (the most luminous with $M_V = -8.5$), which together make up at least 10% of the total stellar mass of this galaxy (Tudorica, Georgiev, & Chies-Santos 2015; Larsen et al. 2014).

Overall, we conclude that while uncommon, GC systems in dwarf galaxies fainter than $M_V \sim -12$ are not exceptional. Deeper observations of Local Group dwarfs, and the ongoing discovery of low-mass galaxies beyond the Local Group (e.g., Crnojević et al. 2016b), are likely to reveal less massive galaxies with GCs, and the properties of these GCs may offer compelling constraints on the structure of the dark matter halos in these galaxies (Contenta et al. 2017; Amarisco 2017).

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