Mon. Not. R. Astron. Soc. **000**, 1–?? (2004) Printed 18 August 2007 (MN LATEX style file v2.2)

A new population of extended, luminous star clusters in the halo of M31

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18 August 2007

ABSTRACT
We present three new clusters discovered in the halo of M31 which, although having globular-like colours and luminosities, have unusually large half-light radii, $\sim$ 30 pc. They lie at projected galactocentric distances of $\approx$ 15 to $\approx$ 35 kpc. These objects begin to fill the gap in parameter space between globular clusters and dwarf spheroidals, and are unlike any clusters found in the Milky Way, or elsewhere to date. Colour-magnitude diagrams, integrated photometric properties and derived King profile fit parameters are given, and we discuss possible origins of these clusters and their relationships to other populations.

Key words: galaxies: star clusters – galaxies: M31.

1 INTRODUCTION

Over the past several years we have undertaken a major survey of M31, which has revealed a wealth of unexpected substructure (Ferguson et al. 2002), the most prominent being a giant stream of stars near the minor axis (Ibata et al. 2001). As part of this study of M31, we have searched for globular clusters (GCs) in a large part of the halo. GC systems have been shown to be valuable tools for the study of the evolution of their host galaxies, acting as chemical and dynamical probes (West et al. 2004). Specifically, most GCs are believed to be old objects, and thus provide clues to the earliest epochs of galaxy formation history.

The three clusters presented here were discovered during this search for classical GCs, whose results are more fully documented in another paper (Huxor et al. in prep). While undertaking aperture photometry of one of the GCs found, a diffuse cluster was serendipitously discovered nearby in the same field (cluster 1, hereafter C1, in figure 1). The object was not classed as a single object by the INT-WFS (Isaac Newton Telescope Wide Field Survey) pipeline (Irwin & Lewis 2001), and hence, had been missed by the semi-automated techniques that we employed in the main GC survey. It is very distinctive in being significantly more extended than typical GCs: aperture photometry giving a half-light radius (R_h) of 35 pc, assuming a distance to M31 of $\sim$780 kpc (McConnachie et al. 2005). We were therefore motivated to undertake a visual survey of all the INT-WFS images for the M31 region, which resulted in the discovery of two further objects with similar properties. In this paper we present the three clusters, which are unlike any found around the Milky Way, M31 or indeed elsewhere to date, in that although many MW GCs have half-light radii approaching 30 pc, they are faint. These new clusters, however, are of average GC lumonosity.

2 THE NEW CLUSTERS

The fields visually investigated include the whole INT-WFS M31 survey, an area far into the halo, and an additional region south along the Andromeda Stream, and towards M33, making a total area of more than 40 square degrees (see figure 2). The survey consists of V and Gunn i band images with exposures of between 800-1000 seconds, reaching (average 5 σ) limiting magnitudes of i = 23.5 and V =24.5, and taken in average seeing of 1.2 arcsec. These images were processed by the INT WFS pipeline provided by the Cambridge Astronomical Survey Unit, which includes tools for astrometry, photometry and object description and classification (Irwin & Lewis 2001).

The location of the clusters (star icons), in relation to M31 is shown in figure 2, while postage stamp images (1 arcmin × 1 arcmin) of the clusters are shown in figure 1. The

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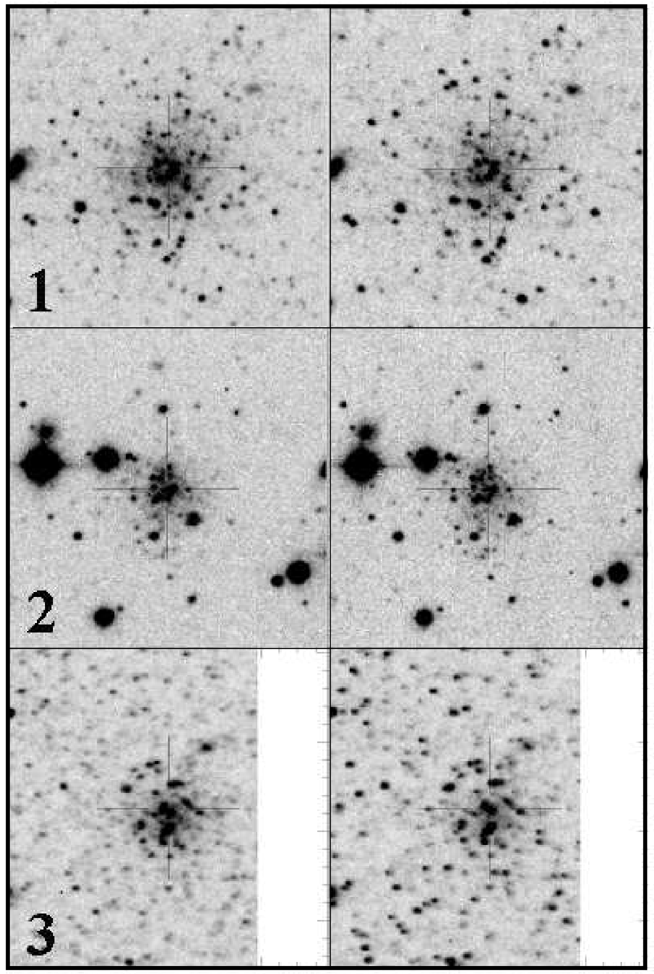

Figure 1. V and i band images of the new luminous 'extended' clusters, from the INT Wide Field Survey images. Each image is 1 arcmin × 1 arcmin, with North up and East to the left. Cluster 3 is a partial image as it lies on the edge of an INT-WFS field.

clusters appear, in projection, to cover a range of environments, from the far halo (C2), to near the disk (C3; though we note that if C3 is a disk object, it lies at a very large radius of 27 kpc).

The positions of the three extended globular clusters were cross-checked against existing catalogues starting with the GC lists of Barmby (http://cfa-www.harvard.edu/∼pbarmby/m31gc.html; Barmby et al. 2000) and the newly published Revised Bologna Catalog (http://www.bo.astro.it/M31/; Galleti et al. 2004). In addition, other databases such as Vizier (Ochsenbein, Bauer, & Marcout 2000) and NED (http://nedwww.ipac.caltech.edu/index.html) were consulted for any prior identifications. C1, the richest cluster, has previously been catalogued from a large scale survey as a background low surface brightness galaxy, object N04-1 of O'Neil, Bothun, & Cornell (1997). However, the INT-WFS survey image clearly shows it to be a resolved star cluster.

CMDs of the clusters (see figures 4, 5 and 6) were made from the INT-WFS images by performing DAOPHOT (IRAF implementation) profile-fitting photometry on the regions of the images containing the clusters. This level of crowding is an ideal application of profile-fitting photometry, and the large number of bright stars on the images allows a good PSF model to be constructed in each case. The resulting CMDs are fully consistent with metal-poor, old stellar populations at the distance of M31. There is no evidence for a population of young main sequence stars at these locations. The integrated $(V-I)_0$ colours are also consistent with low metallicity (Worthey 1994) if indeed they are an old population.

Table 1 lists the clusters' basic integrated properties: magnitudes were derived at 12 arcsec, and (V-I) at the smaller radius of 8 arcsec (but no smaller due to the clumpiness of the clusters). Prior to undertaking the aperture photometry analysis of the clusters, bright stars (i.e. with i' < 20) were automatically clipped out of the images and replaced with a local background estimate using the existing WFS object catalogues to drive the clipping algorithm.

The INT-WFS data were taken with Harris V (V') and

Table 1. Properties of the Extended Clusters. R_h is the half-light radius calculated assuming a distance to M31 of 780 kpc, which is also used the determination of absolute magnitude. It is not easy to determine accurate uncertainties on the values of R_h, given the sparseness of the clusters, and the necessity to account for foreground and background contamination, however we estimate the accuracy to be better than ≈20%. Extinction corrected magnitudes use the Schlegel, Finkbeiner, & Davis (1998) maps.

ID	RA (J2000) h m s	Dec (J2000) ° ′ ″	V	V_0	$(V-I)_0$	R_h (pc)	M_V
M31WFS-C1	00 38 19.5	+41 47 15	17.6	17.4	0.88	34	-7.1
M31WFS-C2	00 42 55.0	+43 57 28	17.1	16.8	0.93	26	-7.7
M31WFS-C3	00 38 04.6	+40 44 39	17.6	17.3	1.02	26	-7.1

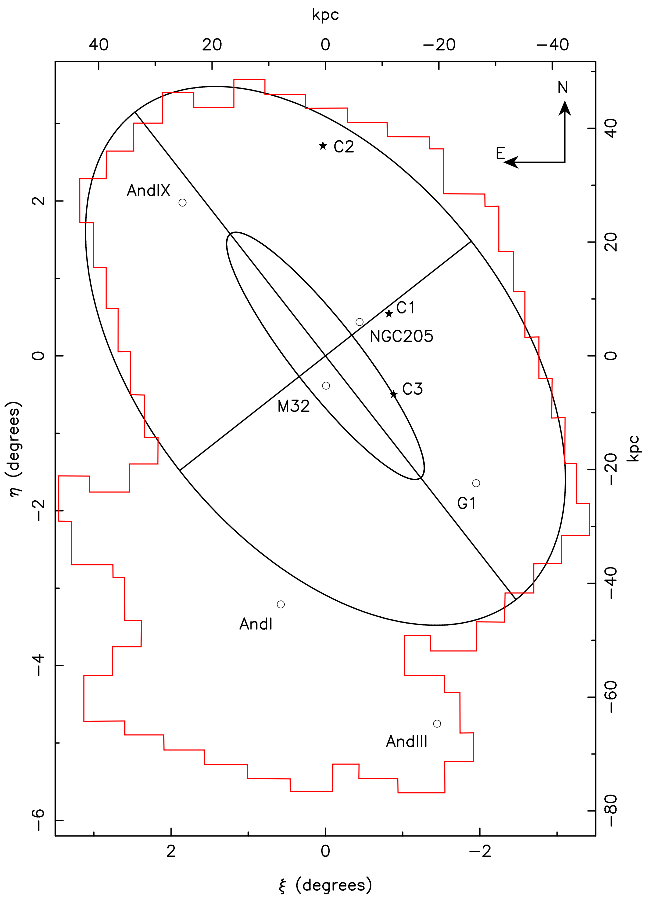

Figure 2. The location of the new extended globular clusters (stars) in relation to major landmarks of the M31 system (open circles), and the survey area (dotted outline, red in electronic version). The ellipses represent a 2 degree radius disk aligned and tilted to the inclination of M31 and an oblate halo of axial ratio 0.6 aligned along the major axis. The kpc scales correspond to a distance to M31 of 780 kpc.

Sloan-Gunn i′ filters. The colour transformations applied to determine Landolt (1992) Johnson V and Cousins I magnitudes were I = i′ - 0.101(V-I) and V = V′ - 0.005(V-I).

Empirical King Profiles:

$$\Sigma(r) = \Sigma_0 \left[\frac{1}{\left(1+(r/r_c)^2\right)^{1/2}} - \frac{1}{\left(1+(r_t/r_c)^2\right)^{1/2}} \right]^2$$

were fit to the aperture photometry, from which R_h was

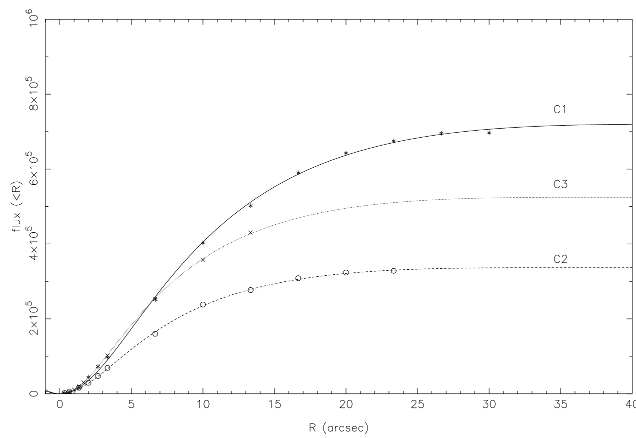

Figure 3. King profiles for the clusters where the flux is measured simply in ADU counts

determined (figure 3). There are some uncertainties associated with the values: In the case of C2, likely foreground contamination from stars was removed first. The cluster C3 lies at the edge of the INT field but the fractional area missing is small allowing us to obtain photometry only to a radius of 13 arcsec.

3 DISCUSSION

These objects are unusual because, whilst all three clusters have magnitudes and colours typical of the M31 GC population, their half-light radii (R_h) are considerably greater. The data available for the MW (van den Bergh 1996 and references therein) shows that there are several GCs (which are also generally at large Galactocentric radius) with half-light radii in excess of 15 pc, but these MW clusters are considerably fainter, and rather more compact, than the newly found clusters in M31. The very distant, and extended, Galactic globular NGC 2419 stands as a notable exception, being considerably more luminous. Conversely the newly discovered extreme MW cluster (Willman et al. 2004) has similar half-light radius but is some 4 magnitudes fainter.

The distinction between different types of stellar cluster is becoming increasingly complex, with even the boundary between open and globular clusters sometimes being blurred. Borderline objects have been identified, such as BH 176 (Ortolani, Bica, & Barbuy 1995) which could be a true globular cluster or a very old open cluster. The situation

Table 2. Derived King profile fit parameters for the clusters, giving core radii r_c, tidal radii r_t, the concentration parameter (c) = $\log(r_t/r_c)$, Σ_0 - the model scale surface brightness (obtained by converting counts in 12 arsec radius to solar luminosities, assuming a distance of 780 kpc), ρ_0 the central luminosity density, and equivalent total integrated V magnitude M_V from the profile fit.

ID	r_c pc	r_t pc	c	Σ_0 $L_\odot pc^{-2}$	ρ_0 $L_\odot pc^{-3}$	M_V
M31WFS-EC1	23	166	0.86	29	0.53	-7.3
M31WFS-EC2	17	132	0.89	70	1.73	-7.8
M31WFS-EC3	16	140	0.94	42	1.12	-7.2

is complicated further by ω Cen, which although long classified as a GC, has many unusual features, such as a wide metallicity spread of its component stars(Suntzeff & Kraft 1996), a characteristic shared by the bright M31 globular cluster G1 (Meylan et al. 2001).

More recently, new classes of object have been identified which begin to fill in the gap in the parameter space between classical GCs and dwarf galaxies. For example, Mieske, Hilker, & Infante (2002) measured the properties of ultra-compact objects (UCOs) [or ultra-compact dwarfs - UCDs] in the Fornax cluster, which are as bright as dwarf ellipticals but very much more compact. Martini & Ho (2004) describe a population of very massive globular clusters in NGC 5128, whose properties overlap with those of nucleated dwarfs and UCDs. At the fainter end of the luminosity scale Brodie & Larsen (2002) described a new class of star cluster found in HST studies of two lenticular galaxies, NGC 1023 and NGC 3384, lying at distances of $\sim$ 10 Mpc. These clusters occupy a region of parameter space having an absolute V magnitude fainter than ≈ -7, a half-light radius greater than 7–15 pc, and have been christened "faint fuzzies" (FFs).

The relationship between all these object types, and MW and M31 dSph galaxies is illustrated in Figure 7. The new extended clusters are shown (solid circles), along with MW GCs from van den Bergh (1996), dSphs associated with the MW (Irwin & Hatzidimitriou 1995), the dSphs associated with M31 (Caldwell et al. 1992 and Caldwell 1999), and G1 (Larsen 2001). The region that would be occupied by the FFs is to to the right of, and above, the dotted lines on the plot (although they are distinguished from the more diffuse MW GCs in terms of their numbers, higher metallicities and disky kinematics).

In terms of morphology and luminosity the new extended clusters are rather more extended and more luminous the FFs (although the magnitudes of the latter may well be underestimates by several tenths of a magnitude due to the aperture corrections chosen for photometry). Furthermore, Brodie and Larsen's FFs are moderately metal rich [Fe/H]$\sim$ -0.6, and consequently have red integrated colours, $(V-I)_0$ of ≈ 1.3.

Looking more broadly at figure 7 we see a variety of objects in the region between classical GCs and dSphs. A number of origins have been proposed to explain the intermediate forms. Zhao (1998) has proposed that NGC 2419, the unusual MW GC, with a half-light radius of ≈ 19 pc may have been accreted from a putative "Ancient Sagittarius Galaxy", along with some of the fainter GCs: Terzan 7, Arp 2, Terzan 8 (which are part of the main body of Sgr) and Pal15. One might therefore speculate that these new M31 objects formed in a dwarf galaxy, which may have since merged with M31. For similar reasons, Brodie & Larsen (2002) have also suggested that their FFs may have formed in dwarfs before joining the host galaxies, although they also consider an alternative theory in which FFs form preferentially in lenticular galaxies with well-developed disks. However, we should point out that by no means are all dwarf galaxy GCs unusually extended.

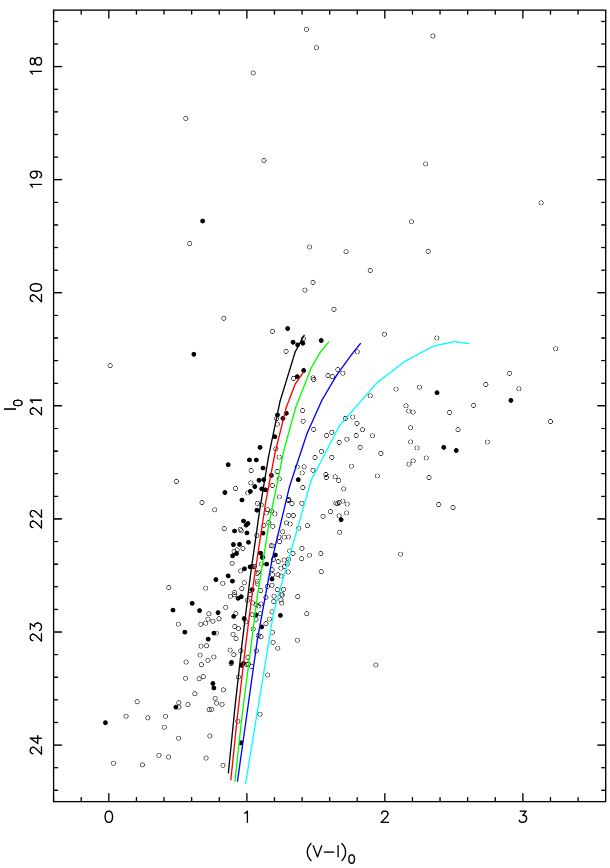

Figure 4. A colour-magnitude diagram for C1 (filled points are within 20 arcsec of the cluster centre) and surrounding field (open points are within a 130 arcsec square region around the cluster). Photometry was obtained using DAOPHOT (IRAF implementation) profile fitting, and has been corrected for foreground extinction via Schlegel et al. (1998). Overplotted are isochrones for galactic globular clusters from Da Costa & Armandroff (1990) shifted to an M31 distance modulus of $\mu_0 = 24.47$ and representing a range of metallicities, from left to right: [Fe/H]=-2.17 (M15); -1.91 (NGC 6397); -1.58 (M2); -1.29 (NGC 1851) and -0.71 (47 Tuc). The RGB locus of the C1 is clearly delineated, and consistent with an old, metal-poor population at the distance of M31.

Other possible scenarios to form extended clusters involve either stripping of dwarfs to form smaller systems, or the merger of star clusters to form larger systems. For example, both G1 and ω Cen GCs are unique, with suggestions that they are the cores of stripped dwarfs (Bekki & Freeman 2003; Bekki & Chiba 2004; Ideta & Makino 2004; Tsuchiya, Korchagin, & Dinescu 2004). Martini & Ho (2004) speculate that due to the presence of extra-tidal light, that some of their massive

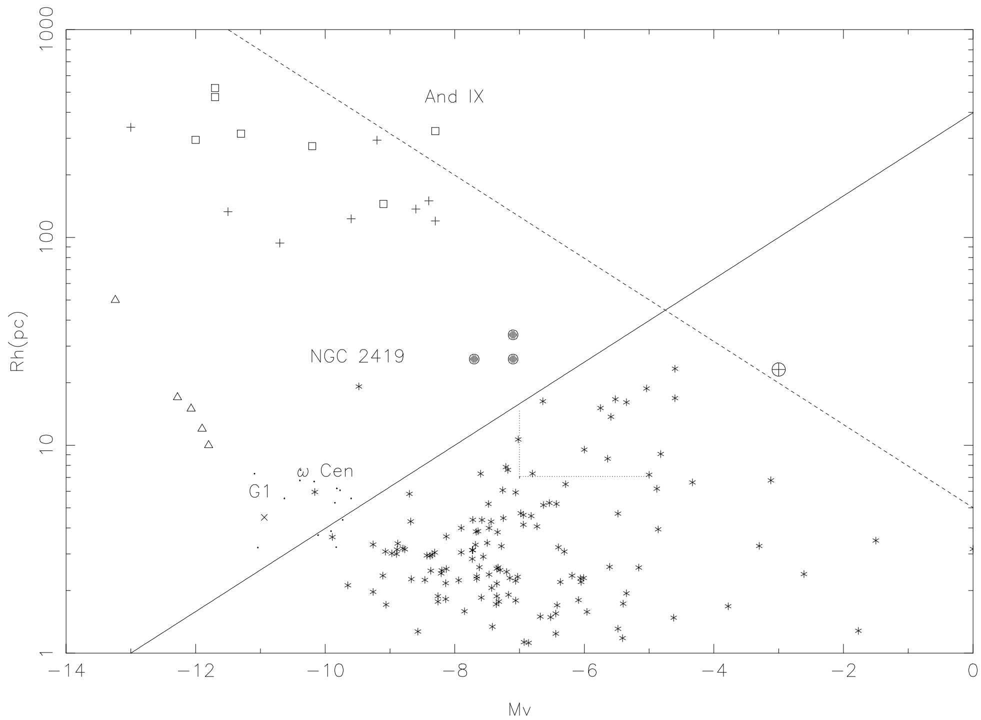

Figure 7. Plot of log R_h against M_V for the new extended clusters (filled circles), MW GCs (asterisks, van den Bergh 1996), MW associated dSphs (plus signs, Irwin & Hatzidimitriou 1995), M31 associated dSphs (open squares, Caldwell et al. 1992; Caldwell 1999), the M31 GC G1 (cross signs, Larsen 2001), UCOs (triangles, Mieske, Hilker, & Infante 2002), the massive GCs in NGC5128 (points, Martini & Ho 2004) and the newly discovered MW companion (cross in circle, Willman et al. 2004). The M31 dSph, AndIX, is also included, using an exponential fit to the radial profile determined by us from the INT-WFS catalogues and using the luminosity from Zucker et al. (2004). In addition the line of the equation $\log R_h = 0.2M_V + 2.6$ is plotted (solid line, from van den Bergh & Mackey 2004), and that for a value of constant average surface brightness within R_h (dashed line) illustrating one selection effect. The dotted L-shape indicates the region where FFs are found. The Galactic GCs ω Cen and NGC 2419 are also labelled.

GCs in NGC 5128 may be the nuclei of stripped dwarfs. Numerical simulations by Bassino, Muzzio, & Rabolli (1994) suggest that the nuclei of dwarf nucleated galaxies survive encounters with a giant galaxy, and they propose that such a scenario may explain the large number of GCs in many galaxies. Depending on the characteristics of the progenitor dwarf, and of the encounter orbit, a range of remnant clusters can be produced. In their models, the surviving clusters are more massive and have larger tidal radii than globular clusters (or our new extended clusters). However, they suggest that more concentrated nuclei and closer encounters with the centre of the giant galaxy might produce more compact clusters, such as GCs. Indeed, it has been proposed that M54 is the nucleus of the Sagittarius dwarf (Bassino & Muzzio 1995, but see Monaco et al. 2005 for a contrary view).

Such a scenario has important implications. For example, it has been suggested that if, as postulated, all galaxies have central black holes, such stripped objects should have black holes at their cores, and (Gebhardt, Rich, & Ho 2002) report to have found evidence, albeit controversial, for such a black hole in G1. It is also believed that GCs, unlike dSphs, do not possess a dark matter halo, leaving open the question of the dark matter content for any intermediate forms, such as those listed above. However, Bekki & Chiba (2004) found that any progenitor dwarf would have to have had its DM halo stripped to form a G1-like cluster.

It has been argued that G1 and ω Cen can be better explained as the product of merger events. For example, Baumgardt et al. (2003) propose a model for G1 involving merger of two smaller GCs (and argue that there is no need to invoke a central BH). Fellhauer (2004) has suggested that ω Cen could be the product of a merger of “super star clusters”, themselves created in a starburst event triggered by the accretion of a dwarf satellite, which derives its diverse stellar population by capturing old field stars from the dwarf. Furthermore, since the progenitor dwarf itself may have been the product of merging, it would retain traces of these past merging events. Mieske, Hilker, & Infante (2004) find that their results are consistent with both stripping and the merged stellar super-clusters scenarios for UCOs.

Does any of this help in understanding our new objects? The two mechanisms discussed above by which extended clusters may be produced from other objects (by nurture, as it were), involve either merging of massive star clusters or stripping of dSphs. Fellhauer & Kroupa (2002), using N-body simulations, find that they can form FF-like objects from the merger of the “super star clusters” noted above, such as might have their origins in galaxy-galaxy interaction. Formation in such a single interaction event might

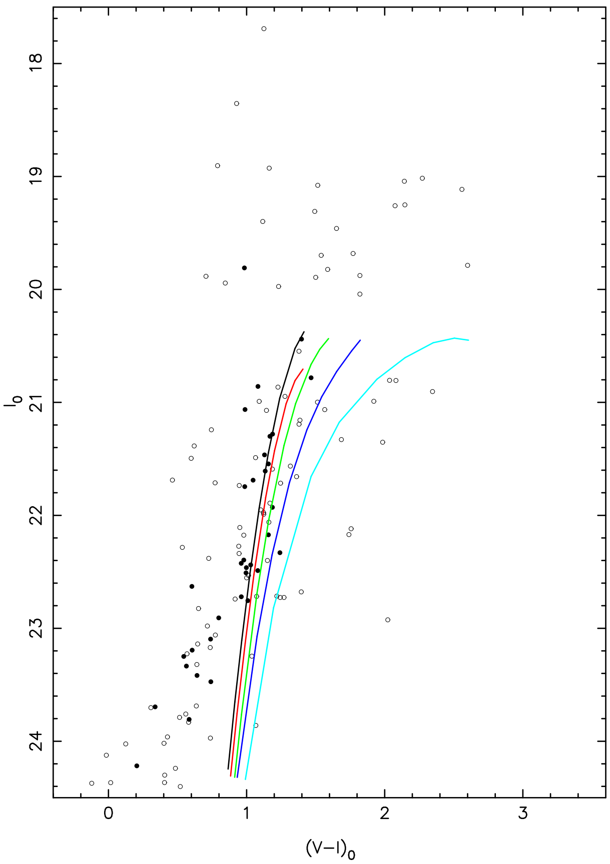

Figure 5. CMD for C2, similar to figure 4, but in this case the radius used to define the cluster region was 14 arcsec. Although fewer points, a reasonably clear (metal-poor) sequence is seen.

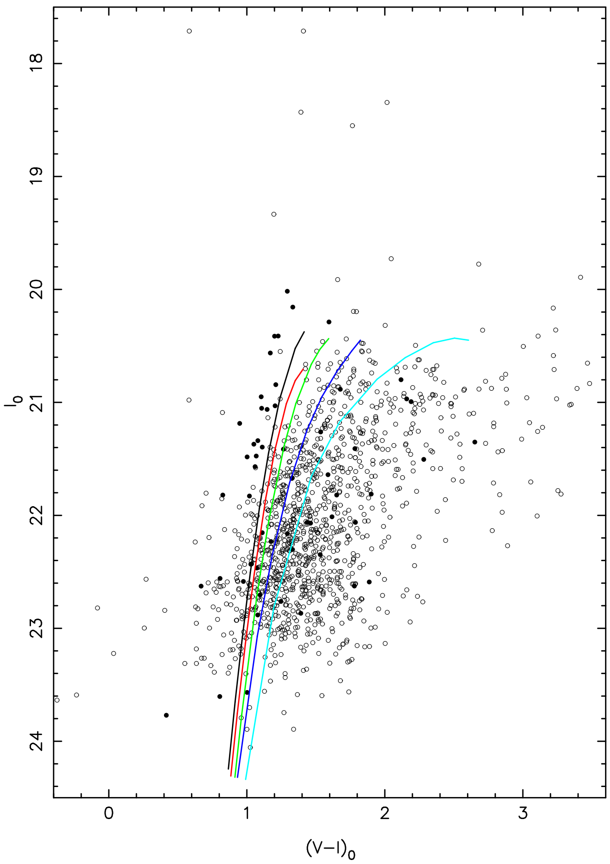

Figure 6. CMD for C3, similar to figure 4, again defining the cluster (filled points) to be within 14 arcsec radius. In this case the quality of the image was poorer, and the crowding due to M31 disk/spheroid stars much worse. Nonetheless, the very blue (metal-poor) RGB locus of the cluster is clearly seen.

explain why a population of extended clusters is found in M31 but not in the MW. In the Fellhauer and Kroupa picture the FF clusters are subsequently tidally truncated to obtain the observed cluster sizes, which may not be relevant given the large galactocentric radii of the M31 clusters. On the other hand, van den Bergh & Mackey (2004) have noted that only two Galactic GCs lie above the equation log $R_h = 0.2M_V + 2.6$ on the plot in figure 7, ω Cen and NGC 2419. They prefer the stripped dwarf model for these two objects and suggest that clusters above the line can be best explained by such stripping, such as that modelled in Bassino, Muzzio, & Rabolli (1994).

The question naturally arises as to what distance from M31 could clusters such as ours survive against tidal disruption, which obviously relates to the issue of how long-lived such clusters can be. If we take a typical GC mass-to-light ratio of 2, the absolute magnitude values in table 1 give masses for the clusters of $\approx 1.5 \times 10^5 M_\odot$. Employing a logarithmic halo model and assuming a circular velocity of 250 km s^{-1}, we find a galactocentric distance of ≈ 25 kpc is required to produce the tidal radii observed. This is consistent with the radii at which we observe our clusters, and also the fact that none have been found at smaller distances.

The above assumes a M/L typical for GCs, but it is also possible, particularly if the new clusters are stripped dwarfs, that they could have some dark matter component. In this regard it is interesting that Willman et al. (2004) suggest that their object may be an extreme dwarf galaxy due to its position on the M_V/R_h plot (their figure 10), an argument which might also be applied to our new clusters.

The fact that the similarly extended but much fainter Willman object has been discovered in the MW, but no objects similar to our M31 clusters strongly indicates that no such population exists in our Galaxy. This suggests that there might be important differences between the formation and evolution of M31, in comparison with the MW, to allow for this new cluster population for form and survive. This could be established by searching for similar clusters in more distant galaxies covering a range in Hubble type and environment, but here it becomes increasingly difficult to distinguish such clusters from background galaxies.

4 CONCLUSION

We have presented three newly discovered globular-like (in terms of luminosity and colour) clusters in the halo of M31 with unusually large half-light radii, of around 30 pc (compared to typical GC values between 1 and 7 pc). These objects start to fill the gap in parameter space between (negligible dark matter) classical GCs and (dark matter dominated) dwarf spheroidals. This is a region which in recent times has also been encroached by a variety of new objects, such as the UCOs in Fornax and massive GCs in NGC 5128. Our clusters are lower luminosity systems than these, and are rather brighter and more extended than the so-called faint fuzzy clusters (FFs), found by (Brodie & Larsen 2002) in two lenticular galaxies, and also bluer indicating a lower metallicity.

The extended M31 clusters have no known analogues in the Milky Way, where such clusters would certainly have been discovered if they existed, unless hidden by the plane of the Galaxy. This suggests that they could hold important clues to the differing formation histories of these galaxies. If these clusters were not born with their present morphology then one may speculate that they are the stripped cores of cannibalised dwarf spheroidal galaxies, or the products of cluster mergers perhaps themselves created in a previous interaction of a gas-rich companion with M31.

Unlike the UCOs and faint fuzzies, these objects are comparatively nearby in M31, and hence (like G1) open to detailed, resolved, investigation by both HST and ground-based instruments. Further, ongoing, observations will reveal more about the nature of these intriguing objects: metallicity, HB morphology, systemic and internal kinematics.

ACKNOWLEDGMENTS

AH is funded by a Particle Physics and Astronomy Research Council (PPARC) studentship. The research of AMNF has been supported by a Marie Curie Fellowship of the European Community under contract number HPMF-CT-2002-01758.

This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

The Isaac Newton Telescope is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias

We would also like to thank the referee, Sydney van den Bergh, whose comments greatly improved the quality of this paper.

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