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A LARGE POPULATION OF ULTRA-COMPACT DWARFS AND BRIGHT INTRACLUSTER GLOBULARS IN THE FORNAX CLUSTER

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ABSTRACT

All the previously cataloged ultracompact dwarf (UCD) galaxies in the Fornax and Virgo clusters have $17.5 < b_J < 20$. Using the 2dF spectrograph on the Anglo-Australian Telescope, we have carried out a search for fainter UCDs in the Fornax Cluster. In the magnitude interval $19.5 < b_J < 21.5$, we have found 54 additional compact cluster members within a projected radius of $0\overset{\circ}{.}9$ (320 kpc) of the cluster center, all of which meet our selection and observational criteria to be UCDs. These newly identified objects, however, overlap in luminosity and spatial distribution with objects classified as globular clusters (GCs) belonging to the central cluster galaxy NGC 1399; in fact, about half of the objects in our sample are included in recent catalogs of NGC 1399/Fornax GCs. The numbers, luminosity function, and spatial distributions of our compact object sample are consistent with being the bright tail of the Fornax cluster-wide GC population. Yet, our present larger sample of intergalactic compact objects forms a dynamically distinct population from both the NGC1399 GCs and the nucleated dwarf ellipticals in Fornax. This supports the interpretation that the UCDs, which populate the bright tail of the GC luminosity function, are, in some respects, a separate class of objects, at least to the extent that they have experienced a distinct dynamical history and origin, which differs from the bulk of the NGC1399 GCs. Correcting for our spectroscopic incompleteness, we estimate that there are $\sim 105 \pm 13$ of these brighter compact cluster objects down to $b_J < 21.5$ in the central region of the Fornax, and hence these UCDs/globulars outnumber other galaxy types in this space. The differences in their dynamics and distribution compared to dwarf ellipticals (dEs) may be consistent with a threshing or tidal destruction origin, if they have come from a subpopulation of dE galaxies on initial orbits that rendered them susceptible to such processes.

Key words: galaxies: clusters: general – galaxies: dwarf – globular clusters: general

1. INTRODUCTION

Galaxy transformation processes in dense environments leave rich clusters littered with the remains of disrupted galaxies (Bassino et al. 1994; West et al. 1995; Bekki et al. 2001; Moore 2004). Observational evidence verifying these processes has been accumulating, with detections of diffuse light trails, intracluster stars and planetary nebula (PN), and intergalactic globular clusters (GCs; Gregg & West 1998; Adami et al. 2005; Durrell et al. 2002; Ford et al. 2002; Feldmeier et al. 2004; Bergond et al. 2007).

A new class of extremely compact galaxies has recently been discovered in the Fornax and Virgo clusters; although they are much smaller in physical size than conventional dwarf galaxies, they are relatively easy to detect in nearby clusters. Hilker et al. (1999) found two compact objects in a spectroscopic survey of the Fornax Cluster center, and our Fornax Cluster Spectroscopic Survey (FCSS; Drinkwater et al. 2000b; see also Phillipps et al. 2001; Drinkwater et al. 2003; Jones et al. 2006) identified six cluster members (including the two objects from Hilker), which were either unresolved or just marginally resolved in ground-based imaging, thereby escaping detection in previous redshift surveys. These objects are relatively faint, $-13 \leqslant M_B \leqslant -11$, with typical sizes of <100 pc, much smaller than any other type of galaxy (Drinkwater et al. 2003; Haşegan et al. 2005; Evstigneeva et al. 2007); as such, they were named "ultracompact dwarf" (UCD) galaxies. High-resolution *Hubble Space Telescope* (*HST*) imaging and Very Large Telescope (VLT) echelle spectroscopy have established that UCDs are a new type of low-luminosity compact galaxy, distinct from both globular star clusters and all known types of dwarf galaxies (Drinkwater et al. 2003). In the Virgo cluster, Haşegan et al. (2005) and Jones et al. (2006) have identified ∼ 15–20 objects, which are morphologically indistinguishable from the Fornax UCDs, suggesting that such objects are ubiquitous in clusters.

Explanations for the origin and nature of UCDs include unusually luminous GCs (e.g., Hilker et al. 1999; Drinkwater et al. 2000a; Phillipps et al. 2001; Mieske et al. 2002), evolved extremely luminous star clusters formed in galaxy interactions (Fellhauer & Kroupa 2002; Maraston et al. 2004), and low-luminosity analogs of M32 (Drinkwater et al. 2000a). Some theories have argued that highly compact galaxies might have formed in the early Universe (Blanchard et al. 1992; Tegmark et al. 1997), and UCDs may prove to be such objects. A favored hypothesis for the formation of UCDs is that they are the remnant nuclei of dwarf elliptical galaxies that have been tidally disrupted during passages close to the central cluster galaxy; we refer to this process as "galaxy threshing" (Bekki et al.

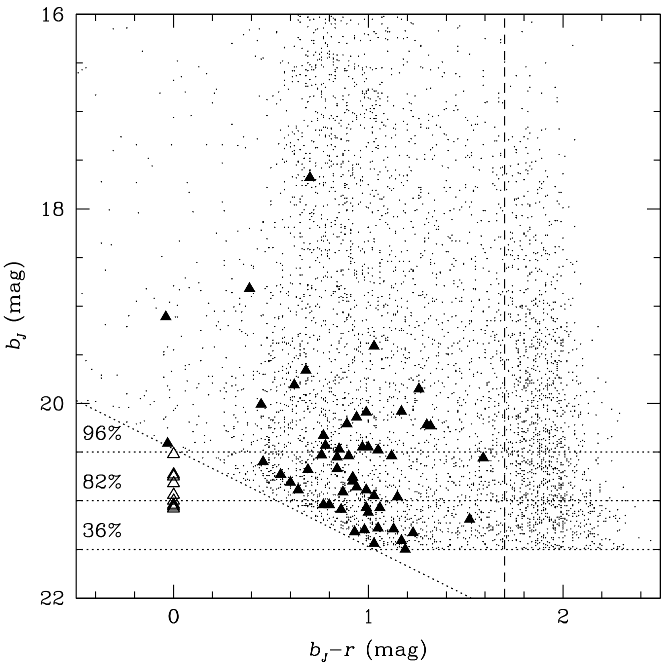

Figure 1. Color–magnitude distribution of confirmed stars (dots) and UCDs (triangles) in our survey field. The b_J magnitudes are plotted against $b_J - r_f$ color. The sample was selected by limiting b_J magnitude, and the completeness limits (fraction of targets with measured redshifts) are shown for the three b_J ranges indicated by horizontal dotted lines. The $r < 20.4$ detection limit of the r plate is shown by the angled dotted line: UCDs satisfying our b_J limits but not detected on the r plate are plotted here as open triangles with arbitrary $b_J - r = 0$ colors. All the UCDs, including these, satisfy our color selection $b_J - r_f < 1.7$ shown by the vertical dashed line.

2001, 2003). Recently, a deeper survey of the central region of the Fornax Cluster found 54 new GC-like objects within 20′ of NGC1399 down to $V = 21.0$ mag (to $M_B \simeq -9.8$ mag) (Mieske et al. 2004). They concluded that the brighter ($V < 20$) objects are consistent with UCDs formed by the threshing process but that most of the fainter objects are genuine GCs. UCDs may also be either remnant nuclei or other giant star clusters from late-type galaxies destroyed by the cluster potential, as has been suggested for the giant globular G1 in Andromeda (Meylan et al. 2001). Whatever their nature, these compact objects are an important constituent of galaxy clusters, and determining their origin and evolution will help in understanding the formation of galaxy clusters.

We present the results of observations that extend the search for fainter UCD-like objects in the Fornax Cluster over a much larger field accessible to Two-Degree Field (2dF). Based on the luminosity function (LF) of nucleated dwarf ellipticals (dE,N) nuclei in the Virgo Cluster known when we began our observations (Binggeli & Cameron 1991), searching 1.5 mag deeper for UCDs in the Fornax Cluster should have approximately tripled the original sample of six UCDs. In Section 3, we present our surprising result that 54 new compact objects were found, many more than expected. Preliminary results of some of these observations were given in Drinkwater et al. (2004); here we present further observations and discuss the properties of the new compact cluster members in detail, and discuss their relation to objects classified as ordinary GCs. We adopt a distance of 19 Mpc ($m - M = 31.4$) to the Fornax Cluster to be consistent with previous work (Dirsch et al. 2004).

Table 1
Observations

Date	Set	Exp. (hr)	Seeing (arcsec)
2003 Oct 21	15	2.0	2.0
2003 Oct 21	16	2.0	1.7
2003 Oct 22	14	1.5	1.7
2003 Oct 22	17	4.5	2.3
2003 Oct 23	18	2.5	1.5
2003 Oct 23	19	4.0	1.5
2004 Nov 12	20	4.0	1.4

2. OBSERVATIONS

The original FCSS observations in the central field of the Fornax Cluster produced six UCDs in the range $16.5 < b_J < 20.0$. Here, we define UCDs simply as objects, which were classified as "stellar" (unresolved) in the photographic Automatic Plate Measuring (APM) catalog but were found to have redshifts consistent with the membership of the Fornax Cluster (600 km $\mathrm{s}^{-1} < cz < 2500$ km s^{-1}); see Drinkwater et al. (2000b). Such objects are too bright to be typical GCs. Allowing for incompleteness, we might expect one more UCD in this magnitude range (Drinkwater et al. 2000a; Jones et al. 2006). If UCDs arise by "galaxy threshing" of dE,N then the UCD luminosity distribution should follow that of the dE,N nuclei (Binggeli & Cameron 1991), and extension of our search for 1.5 mag fainter (to $b_J \approx 21.5$) than the original discovery observations should triple the UCD sample size to ~ 20.

In 2003 October and 2004 November, we made new 2dF observations in Fornax to test this prediction. As in our search of the Virgo cluster, we restricted the observations to a limited color range ($b_J - r < 1.7$) and also to slightly less than the whole 2dF field (radius $< 0\overset{\circ}{.}9$), selecting targets from the APM Catalog of b_J and r photographic survey plates. In the extension to fainter magnitudes for this current work, we were limited by the depth of the r plate data, which reaches only $r < 20.4$ mag. For objects that were not detected on the r plate, we, therefore, did not apply a color selection, but observed all objects with $18 < b_J < 21.5$; for these objects, we have only an upper limit on their $b_J - r$ colors, but all are bluer than $b_J - r = 1.7$ (Figure 1).

The 2dF observations (Table 1) and reductions were carried out in the standard fashion as outlined in Drinkwater et al. (2000b), except that longer exposure times were used to reach the fainter magnitude limits. In four nights, we observed 2500 unresolved "stellar" targets of which 54 proved to be cluster members. Combined with our first sample of six UCDs, this brings the total number of UCDs in Fornax to 60 (Table 2). Their color, magnitude, and spatial distributions are shown in Figures 1 and 2. Contained in our full sample of 60 UCDs are 29 objects previously listed by Mieske et al. (2004) in their study of the central 20′ region. Nine more objects have been identified as intergalactic GCs by the work of Bergond et al. (2007), which covers a 90′ × 40′ strip centered on NGC1399, covering about 40% of our larger survey area. The sample we present here extends almost to the full 1° radius of the 2dF system.

In Table 2, we identify objects already found in other spectroscopic surveys (Mieske et al. 2002; Dirsch et al. 2004; Bergond et al. 2007). There are now at least four distinct naming conventions for UCDs/globulars in Fornax; with the large numbers now being found throughout the cluster (and we also anticipate in Virgo), we suggest that they be designated by their J2000 coordinates (the IAU convention name) to avoid confusion.

Table 2
UCDs in Fornax

N	α	δ	r_f	b_J	$v_{\rm rad}$	$\Delta v_{\rm rad}$	Notes
	(2000)		(mag)	(mag)	(km s^{-1})	(km s^{-1})	
1	03 34 51.51	−35 44 02.8	20.3	21.0	1369	68	
2	03 36 22.28	−35 36 34.3	19.7	20.4	1462	76	
3	03 36 26.72	−35 22 01.6	19.1	20.1	1499	117	
4	03 36 27.74	−35 14 13.9	18.9	20.2	1297	45	
5	03 36 28.70	−34 56 30.7	. . .	21.1	1658	65	
6	03 36 34.36	−35 19 32.5	19.9	21.0	1817	104	GC230.7
7	03 36 47.65	−35 29 36.9	19.9	20.9	1446	89	
8	03 36 47.74	−35 48 34.1	20.3	20.9	1340	91	
9	03 36 51.68	−35 30 38.9	20.2	21.3	1375	46	GC41.40
10	03 37 03.30	−35 38 04.6	18.6	19.9	1491	39	UCD 1, 2-2031
11	03 37 24.91	−35 36 09.7	19.6	20.3	1496	55	
12	03 37 27.61	−35 30 12.6	19.4	20.5	1828	77	GC46.30
13	03 37 38.29	−35 20 20.6	20.4	21.3	2226	87	
14	03 37 41.85	−35 41 22.8	20.2	21.3	1175	61	2-078
15	03 37 43.06	−35 22 11.9	20.2	20.7	1146	86	
16	03 37 43.56	−35 15 09.6	20.4	18.9	1641	99	4-2028
17	03 37 43.60	−35 22 51.8	19.2	20.1	1326	82	GC302.3
18	03 37 45.13	−35 29 01.6	19.9	20.9	1641	63	GC85.30
19	03 38 05.08	−35 24 09.6	18.4	19.4	1212	32	UCD 6, 2-2143
20	03 38 06.33	−35 28 58.8	18.7	. . .	1312	57	UCD 2, 2-2111, 91:93
21	03 38 06.53	−35 23 04.0	19.6	20.5	1510	64	2-2153
22	03 38 09.27	−35 35 07.0	20.2	21.4	1806	58	GC445.7
23	03 38 10.39	−35 24 06.1	18.9	20.1	1549	64	81:47
24	03 38 10.78	−35 25 46.0	19.4	20.5	1764	55	2-2134
25	03 38 12.02	−35 39 57.2	19.7	21.2	1307	63	2-073
26	03 38 14.25	−35 26 43.8	20.3	21.5	1377	96	GC365.2
27	03 38 16.54	−35 26 19.7	19.7	20.6	1125	101	0-2024
28	03 38 17.61	−35 33 02.8	19.8	20.8	1505	92	89:22
29	03 38 18.48	−35 27 39.8	20.3	21.3	1332	63	0-2062, 89:107
30	03 38 21.73	−35 26 16.5	. . .	21.0	1403	76	80:12
31	03 38 21.84	−35 25 13.8	. . .	20.5	1411	170	80:30
32	03 38 23.27	−35 20 00.8	19.8	20.7	1370	64	0-2066
33	03 38 23.78	−35 13 49.5	19.3	20.2	1993	199	3-2027
34	03 38 25.08	−35 29 25.3	20.2	21.1	1158	64	2-2106
35	03 38 25.56	−35 37 42.8	19.6	20.5	1698	52	1-2024
36	03 38 26.76	−35 30 07.7	20.1	21.1	1475	72	0-2069
37	03 38 28.83	−35 28 47.1	. . .	21.1	1460	77	GC212.2
38	03 38 29.04	−35 22 56.5	19.5	20.5	1720	74	0-2031
39	03 38 29.07	−35 25 00.3	. . .	20.7	1491	73	78:117
40	03 38 36.86	−35 28 09.5	20.2	20.8	1365	56	
41	03 38 36.99	−35 25 44.2	. . .	21.0	1322	87	
42	03 38 39.37	−35 27 05.8	20.4	21.4	1644	135	1-058
43	03 38 40.23	−35 27 03.1	. . .	20.8	1230	112	
44	03 38 41.98	−35 33 13.4	19.2	19.8	2080	148	1-021
45	03 38 43.14	−35 28 01.5	20.2	21.0	1574	117	
46	03 38 45.81	−35 34 27.4	20.1	20.6	1845	87	
47	03 38 47.49	−35 37 13.5	20.0	21.1	1893	68	
48	03 38 50.73	−35 33 48.3	20.4	20.4	1887	105	
49	03 38 54.10	−35 33 33.6	17.0	17.7	1591	36	UCD 3, 1-2053
50	03 39 17.72	−35 25 30.2	19.9	20.8	1022	46	1-060, GC241.1
51	03 39 20.56	−35 19 14.6	18.9	20.2	1420	64	3-2004
52	03 39 34.78	−35 53 44.2	20.0	20.7	1528	74	
53	03 39 35.95	−35 28 24.5	18.4	18.8	1920	40	UCD 4, 1-2083
54	03 39 37.21	−35 15 21.7	20.0	20.9	1800	93	3-2019
55	03 39 43.56	−35 26 59.5	19.6	20.0	1448	101	
56	03 39 52.58	−35 04 24.1	19.0	19.7	1355	72	UCD 5
57	03 40 19.94	−35 15 29.8	20.1	21.1	1650	74	
58	03 40 24.98	−35 06 37.6	19.8	20.5	1433	59	
59	03 40 37.11	−34 58 40.0	20.1	21.3	1811	159	
60	03 41 35.88	−35 54 57.8	19.8	21.0	1629	57	

Notes. Photometry is from the APM digitized sky survey database; objects with . . . photometry entries are either not detected or merged with nearby objects. Original six UCDs from Phillipps et al. (2001) and Jones et al. (2006) are identified. Also identified are objects in common with Mieske et al. (2002), Mieske et al. (2004; hyphenated), Dirsch et al. (2004; colons), or Bergond et al. (2007; GC).

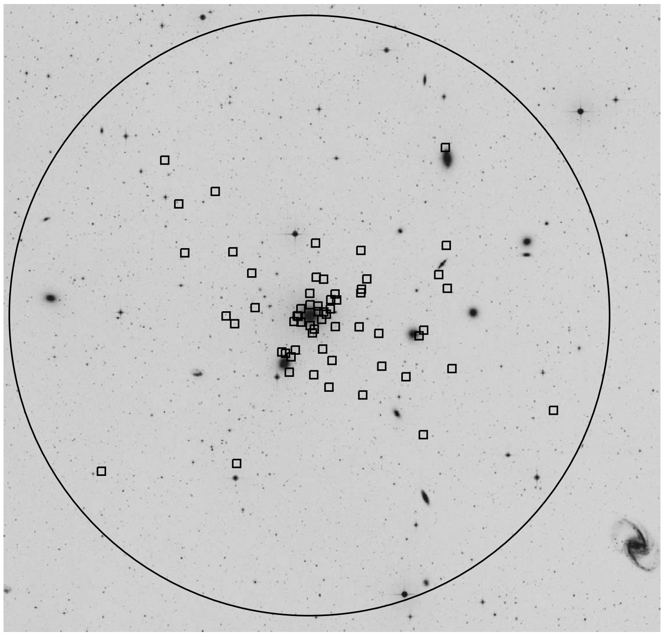

Figure 2. Distribution of all 60 UCDs overlaid on a 2° wide b_J Digitized Sky Survey image of the center of the Fornax Cluster. The circle indicates the $0\overset{\circ}{.}9$ radius within which the UCD search is complete.

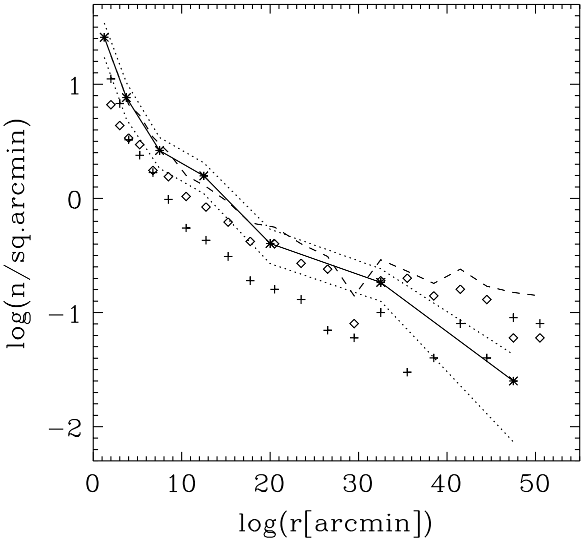

Figure 3. Comparison of the radial density distributions of the total GC population in Fornax (dashed line) and the sample of 60 UCDs from this paper (solid line). The total GC distribution is formed by adding the red (+) and blue (diamonds) areal densities from Bassino et al. (2006). The UCD distribution has been scaled upward by a constant (56) to match the innermost two points of the GCs; dotted lines show the 1σ Poisson uncertainties of the UCD sample.

Our final sample is 96% complete (defined as the fraction of the input targets with well-measured redshifts) in the magnitude range $16 < b_J < 20.5$ (18 cluster members found), 82% complete in the magnitude range $20.5 \leqslant b_J < 21$ (21 found), and 36% complete in the fainter range $21 \leqslant b_J < 21.5$ (21 found). The completeness limits are indicated in Figure 1. Correcting for incompleteness, we, therefore, expect the total number of objects, which meet our search criteria in this region (radius $<0\overset{\circ}{.}9$), $16 < b_J < 21.5$, to be $\sim 105 \pm 13$. For simplicity, we will refer to the compact cluster members identified by our survey as UCDs, but below we discuss the large overlap in properties and actual objects with the samples of Fornax GCs from other surveys.

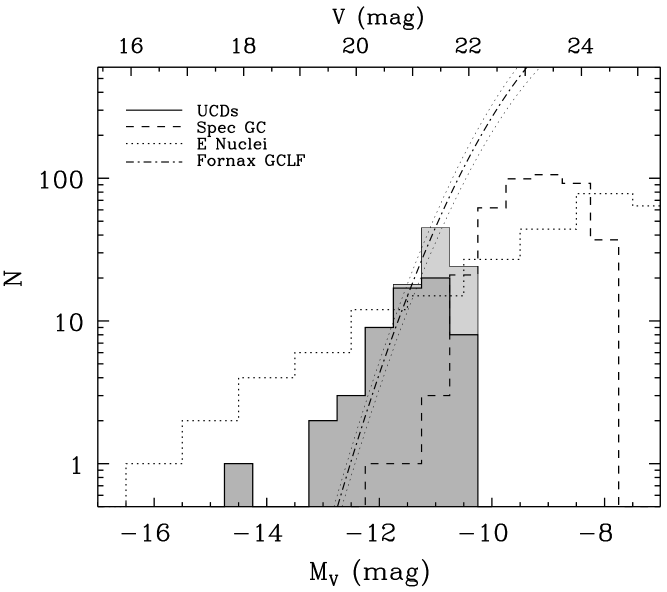

Figure 4. Observed and completeness-corrected LFs of Fornax UCDs (solid histograms) from this work, compared with the Dirsch et al. (2004) spectroscopic sample from the inner 10′(dashed histogram) and with the total Fornax cluster-wide GC population of 11, 100 ± 2400 from Bassino et al. (2006; Gaussian curves). The total globular population, as represented by a Gaussian, accounts for nearly all of the UCDs, suggesting that they are the bright tail of the Fornax GCLF. The LF of early-type galaxy nuclei (dotted histogram) of the total present-day Fornax population, based on the FCC (Ferguson 1989), has been estimated using the relation between the total and nuclear magnitudes from the ACSVCS survey (Côté et al. 2006).

3. PROPERTIES OF THE FAINTER UCD SAMPLE

The most remarkable feature of the new, fainter, compact cluster members is the sheer number of objects, many more than the ∼20 expected by extrapolating from the number of bright UCDs and assuming that they should follow the present day dE,N luminosity and spatial distributions. The large size of the sample now permits a statistical analysis of the distribution of their luminosities, velocities, and positions within the cluster. The clustering of many of the objects in our sample around NGC1399, and a few around NGC1404 and other big galaxies, suggests a connection with the GC population. Yet a significant fraction of the UCD sample, ∼ 50%, is spread throughout intracluster space, loose in the general cluster potential, and not bound to any particular bright galaxy.

Recent work by Bassino et al. (2006) has used deep wide-field imaging to determine the spatial distribution and LF of GC candidates over a wide area of Fornax, essentially coextensive with our spectroscopic survey out to $0\overset{\circ}{.}9$ from NGC1399. In Figure 3, we compare these red (plus signs), blue (diamonds), and summed (dashed line) globular spatial densities as a function of distance from the center of NGC1399 to the radial density profile (solid line) of our UCD objects. We have multiplied the UCD density trend by a constant to scale the innermost two points to lie on top of the total globular distribution to facilitate comparison of the shapes of the two data sets. Within the small number statistics of the UCD sample, there is complete agreement between the shapes of the radial density profiles of the two populations. The UCD density drops off a bit faster in the outermost point, but this is subject to small number statistics of the UCDs and also to somewhat uncertain background corrections for the GC data (Bassino et al. 2006).

In Figure 4, we compare the luminosities of the combined UCD sample (also shown corrected for our incompleteness estimate) with those of the 450 spectroscopically confirmed GCs around NGC 1399 (Dirsch et al. 2004). Where the two samples overlap, the UCDs rise well above the globulars, but the plotted GC sample is limited to a very incomplete subsample within 10′ of the cluster center, while the UCDs extend to 0°.9, essentially the entire Fornax Cluster, and have been corrected for incompleteness. To compare our UCD sample to what would be expected for the total GC population emanating from NGC1399 and extending throughout the Fornax potential well, we integrated the radial density GCs in Fornax as measured by Bassino et al. (2006) to estimate the total number of globulars in our 2dF survey region. It is surprisingly high, $\sim 11,100 \pm 2400$ out to 0°.9, the uncertainties being driven mainly by background corrections in the outer regions. Because their survey covers most of Fornax and includes all globulars, regardless of which galaxy they might belong to, this produces a total GC count for Fornax. In Figure 4, we plot the Gaussian representation of the GC luminosity function (GCLF) uncertainties with a total population of 11,100 (solid curve) and $\sigma = 1.3$ mag, the best estimate width from Bassino et al. (2006). The dotted curves show the ± 2400 populations. If the LF of the GCs of Fornax can be approximated by a Gaussian, even in the extremely bright 5σ tail, then the comparison in Figure 4 shows that the UCD sample we have collected, corrected for incompleteness, is consistent with being drawn from that population. There is perhaps still a very small excess of objects at $M_V \approx -12$ to -13 compared with a Gaussian population, but it is a mere handful, ∼ 5–10, in the brightest three bins.

Côté et al. (2006) have shown that a majority of, perhaps all, early-type galaxies have a nuclear star cluster, averaging 0.32% of the luminosity of the parent galaxy. This suggests that disruption of other galaxy types, not just dE,Ns, could produce UCDs if the nuclei survive largely intact and do not themselves lose much luminosity during the transformation. Using the entire population of early-type galaxies listed in the Fornax Cluster Catalog (FCC; Ferguson 1989), we have estimated the LF of early-type nuclear magnitudes. There are 295 objects in this subsample, mostly dEs, but of course including even the brightest ellipticals. The resulting LF (dotted histogram, Figure 4) is flatter than the GCLF, and extends to much higher luminosities. It is conceivable that a smaller subpopulation of early-type galaxies has been disrupted, their nuclei becoming UCDs, and perhaps even accounting for the slight excess over the GCLF at $M_V < -12$. A majority of late-type galaxies also have nuclei or giant nuclear star clusters (Rossa et al. 2006; Carollo et al. 1998), and their disruption in a dense cluster environment is probably easier than large early types, so all destroyed galaxies potentially contribute to the remnant nuclei population, the brightest of which would be detected as UCDs. Given the comparative LFs in Figure 4, either just a small fraction of the original galaxy population has been disrupted over the lifetime of Fornax or the nuclei as well largely do not survive the destructive tides. Another result of this comparison, if valid, is that the brightest UCDs come from $\sim L^*$ galaxies, and not from dwarfs.

The comparison of luminosity as a function of radial distance between our present UCD sample and the Dirsch et al. (2004) spectroscopic globular sample is shown in the upper panel of Figure 5. The globulars extend only out to 10′, but in this region, there is some overlap in magnitude, $20.5 < b_J < 21.5$. The distribution of the detected UCDs indicates that we would expect more to exist at still larger radii, and the existence of UCDs right at our magnitude limit suggests that yet fainter examples exist. This too is consistent with the bulk of the known UCDs being at the bright end of the GCLF.

The above evidence weighs in favor of UCDs being interpreted simply as bright globulars. In our present sample, however, there is statistical evidence that UCDs—the objects populating the bright tail of the GCLF—differ as a class from lower luminosity compact systems. We compare the velocity distributions of the UCDs with both the NGC 1399 GCs, and the Fornax population of dE,N and a few dwarf S0 galaxies in the middle panel of Figure 5 (Table 3). To explore the trends with the cluster position, we have formed running means of the velocities and dispersions within each of the three samples (Figure 5). The UCD and dE sample means have been computed for sliding subsamples of 15 objects as a function of the cluster radial position; the sliding subsample size for the noisier velocity data but a much larger GC sample is 51 objects. These points are plotted at the median radial locations of each subsample, so the step sizes in the position are not necessarily equal. The shaded regions are the 1σ confidence limits simply determined by $\sqrt(n)$ statistics.

The mean velocity of the UCDs is 1497 km s^{-1} compared with 1439 km s^{-1} for GCs; this difference is marginally significant at the 94% confidence level according to a student's *t*-test. Looking at Figure 5, the mean velocity trends are clearly in good agreement inside of 6′. They begin to differ in the range $6' < R < 10'$, where the GCs have a mean velocity of 1420 km s^{-1} (318 km s^{-1} rms), almost exactly that of NGC1399 (1415 km s^{-1}), while the 10 UCDs in this interval have a much larger mean velocity of 1659 km s^{-1} (191 km s^{-1} rms), indicating that these UCDs are not part of the dynamical system of NGC 1399. A student's *t*-test shows that these velocity means differ with 99.5% significance. The 19 UCDs within 6′ of the center of NGC 1399 have a mean velocity of 1397 km s^{-1} (151 km s^{-1} rms), so these objects are probably truly associated with the NGC 1399 dynamical system, as can be expected from their proximity. The UCDs and dE population velocities (solid and dashed curves) merge seamlessly, confirming that the UCDs as a group belong to the cluster potential and not to NGC 1399 alone.

We compute the running mean velocity dispersions and associated uncertainties of the various samples (bottom panel, Figure 5) using the rigorous prescription of Pryor & Meylan (1993), again with bin sizes of 15 for the UCDs and dEs, and 51 for the GCs. Overplotted on the running means are discrete points showing the number of independent intervals in each sample, given the chosen smoothing lengths. The shaded areas and error bars indicate the 1σ uncertainties. The velocity dispersion running means reveal additional differences (bottom panel, Figure 5). The UCDs as a sample have a lower overall velocity dispersion (228 ± 25 km s^{-1}) than either the dE,N galaxies within 60′ (435 ± 74 km s^{-1}) or the GCs (318 ± 13 km s^{-1}), with significances of 99.99% and 99.8%, respectively, determined from an *F*-test. Inside of 10′, the UCD and GC dispersions differ at the 99.3% level; inside of 6′, this becomes 99.9%. The UCDs form a more relaxed or lower energy population compared to either run-of-the-mill globulars or present-day dE,N galaxies. The fall-off of sample dispersion from 10′ to 30′ in the UCDs is also seen in the spectroscopic results for bright Fornax globulars reported by Bergond et al. (2007). If UCDs started life as dE,N galaxies, having low energy orbits would facilitate threshing to convert them to UCDs: dEs with low energies relative to the cluster will be most affected

Table 3
Fornax Velocity Member dE/S0,N Galaxies

FCC	α	δ	b_j	$v_{\rm rad}$	src	x	y	R	Type
	(2000)		(mag)	(km s^{-1})		(arcmin)			
019	03 22 22.92	−37 23 50.3	15.2	1497	1	−191.87	−116.82	226.71	dS0(8),N
036	03 25 12.25	−32 54 09.7	15.9	2325	1	−167.24	152.86	224.74	dE4 pec,N
043	03 26 02.46	−32 53 41.5	13.5	1223	1	−156.71	153.33	217.58	dS0/2(5),N
055	03 27 18.05	−34 31 33.9	13.9	1252	2	−138.19	55.45	148.18	S0(9),N
068	03 28 51.97	−33 50 45.3	16.5	2030	2	−119.81	96.26	152.8	dE5,N
081	03 30 10.12	−33 41 35.8	17.1	1893	2	−103.77	105.42	147.16	dE1,N
082	03 30 30.52	−34 15 36.0	16.4	1157	3	−98.86	71.42	121.39	dE1,N
085	03 30 46.21	−35 32 57.9	16.3	1673	2	−94.13	−5.95	94.38	dE0,N
100	03 31 47.67	−35 03 05.5	15.5	1660	1	−82.14	23.92	85.36	dE4,N
101	03 31 46.90	−35 40 32.4	17.2	1051	2	−81.66	−13.52	82.88	dE0,N or S
106	03 32 47.77	−34 14 18.9	15.1	2066	2	−70.52	72.70	100.93	d:S0(6),N
111	03 33 03.64	−33 43 27.8	16.8	1283	3	−67.65	103.55	123.31	dE0,N
116	03 33 12.83	−36 01 02.4	16.1	1204	2	−63.93	−34.02	72.62	dE1,N
134	03 34 21.80	−34 35 33.4	17.6	1381	2	−50.88	51.46	72.18	dE5 pec,N or E
135	03 34 30.89	−34 17 51.0	15.5	1232	2	−49.18	69.17	84.67	dS0(5),N
136	03 34 29.54	−35 32 45.9	14.8	1206	2	−48.71	−5.75	49.08	dE2,N
150	03 35 24.06	−36 21 49.2	15.7	1411	2	−37.23	−54.80	66.38	dE4,N
164	03 36 12.94	−36 09 59.0	16.4	1427	2	−27.46	−42.97	51.06	dS0(5),N
174	03 36 45.47	−33 00 48.8	16.7	1801	2	−21.70	146.20	147.76	dE1,N or E(cD)
181	03 36 53.21	−34 56 17.3	17.2	1113	3	−19.63	30.73	36.43	dE2,N
188	03 37 04.66	−35 35 24.0	16.1	1046	2	−17.15	−8.38	19.10	dE0,N
195	03 37 23.41	−34 54 00.1	16.7	1315	3	−13.45	33.02	35.63	dE5,N
202	03 38 06.55	−35 26 22.7	15.3	825	2	−4.57	0.64	4.62	d:E6,N
203	03 38 09.25	−34 31 05.8	15.5	1124	2	−4.07	55.92	56.07	dE6,N
204	03 38 13.76	−33 07 36.0	14.9	1364	2	−3.19	139.42	139.45	dS0(8),N
205	03 38 07.22	−38 05 43.8	16.9	1450	2	−4.29	−158.71	158.77	dE1,N?
207	03 38 19.27	−35 07 43.4	15.9	1403	2	−1.99	19.29	19.40	dE2,N
208	03 38 18.80	−35 31 49.4	17.3	1720	4	−2.08	−4.81	5.24	dE2,N
211	03 38 21.48	−35 15 34.6	16.3	2260	2	−1.54	11.44	11.54	d:E2,N
221	03 39 05.78	−36 05 55.2	17.7	1724	3	7.43	−38.90	39.61	dE4,N
222	03 39 13.42	−35 22 15.7	15.6	792	2	9.05	4.76	10.22	dE0,N
223	03 39 19.60	−35 43 29.0	16.2	781	2	10.27	−16.47	19.42	dE0,N
230	03 40 01.30	−34 45 28.5	17.2	1088	2	18.96	41.54	45.63	dE5,N
241	03 40 23.41	−35 16 32.8	16.6	2045	3	23.35	10.47	25.57	dE0,N
243	03 40 27.02	−36 29 56.1	16.5	1404	1	23.72	−62.92	67.30	dE1,N
245	03 40 33.86	−35 01 21.4	16.0	2187	2	25.56	25.66	36.17	dE0,N
252	03 40 50.38	−35 44 53.5	16.0	1415	1	28.68	−17.87	33.84	dE0,N
253	03 40 55.34	−37 50 16.8	16.3	1677	1	28.89	−143.26	146.24	dE5,N?
254	03 41 00.77	−35 44 31.1	17.6	1517	3	30.80	−17.50	35.47	dE0,N
255	03 41 03.55	−33 46 43.2	13.7	1271	2	32.12	100.30	105.22	S0 (6),N
260	03 41 12.79	−35 09 29.8	17.0	1493	2	33.48	17.52	37.73	dE0,N
261	03 41 21.53	−33 46 09.2	15.8	1492	1	35.85	100.86	106.93	dE3 pec,N / ImIV
264	03 41 31.83	−35 35 20.9	16.8	1888	2	37.17	−8.33	38.12	dS0 (8),N
266	03 41 41.31	−35 10 12.5	15.9	1551	1	39.30	16.81	42.68	dE0,N
274	03 42 17.31	−35 32 25.7	16.5	950	2	46.44	−5.41	46.78	dE0,N
278	03 42 27.27	−33 52 14.2	16.8	2125	1	49.46	94.78	106.69	dE6,N
286	03 43 12.69	−34 38 35.0	18.1	1673	2	58.35	48.43	75.61	dE0,N?
288	03 43 22.77	−33 56 19.5	15.4	1088	2	60.93	90.69	108.95	dS0(9),N
296	03 44 32.94	−35 11 44.8	16.3	856	2	74.35	15.27	75.79	dE1,N
298	03 44 44.41	−35 41 00.5	16.6	1620	2	76.23	−13.99	77.61	dE2,N
303	03 45 14.08	−36 56 12.4	15.5	1980	1	80.94	−89.19	120.97	dE1,N
316	03 47 01.52	−36 26 14.9	16.3	1546	1	103.08	−59.23	119.45	dE3,N
319	03 47 16.32	−32 18 07.6	16.4	1445	1	111.43	188.89	218.29	dE6,N

Notes. x, y, and R are the distances in arcminutes in α, δ, and radially of each object from the center of NGC1399. The FCC number and galaxy types are from Ferguson (1989). Sources for radial velocities are (1) Drinkwater et al. (2001); (2) Karick (2005); (3) Drinkwater et al. (2000b); (4) Mieske et al. (2002).

and more quickly stripped of their halos, while objects with high energies will minimize their time spent near the cluster center, increasing the likelihood that they will remain as dEs over the life of the cluster. The velocity and dispersion measurements are summarized in Table 4.

To test that the kinematic differences are not the spurious result of systematics of the 2dF fiber spectroscopy, we compared our velocities with those derived from slit data for 25 GCs in common with Dirsch et al. (2004) and eight objects in common with Bergond et al. (2007; Figure 6). The scatter is consistent

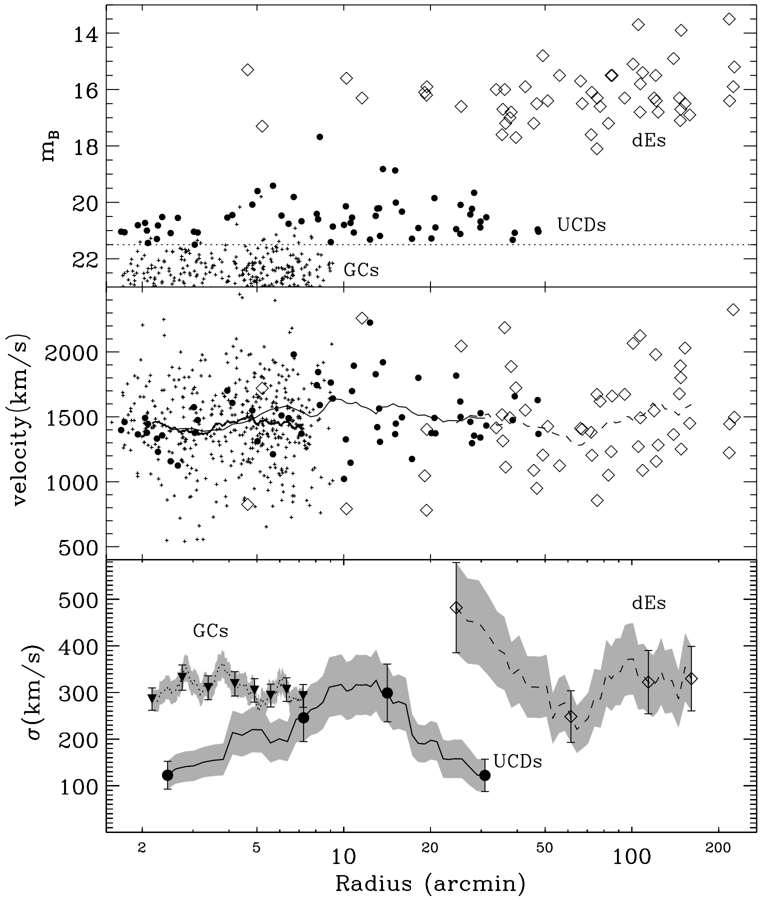

Figure 5. Comparison of the UCD, GC, and dE populations as a function of the cluster position. The upper panel shows that the three samples are relatively separate in magnitude, though there is a little overlap between the GCs and UCDs. In the bottom two panels, running means of the velocity and dispersion for the UCDs (solid) compared with those for GCs (dotted; Dirsch et al. 2004) and dE,N galaxies (dashed; see Table 3) reveals differences in dynamical properties. In the bottom panel, the discrete points show the independent binning of the data: 15 objects in each point for the UCDs and dEs, and 50 for the globulars. The shaded areas and error bars indicate the 1σ uncertainties. Although the UCDs and dE,N samples form a continuous distribution in velocity space, there appears to be a real difference in the mean velocities of the UCDs and GCs in the $6'$–$10'$ radius interval. The velocity dispersions of the three classes markedly differ as a function of the cluster radius.

Table 4
Velocity Distributions

Sample	N	$\overline{v}$ (km s^{-1})	σ_v (km s^{-1})	t-test $\overline{v}$	F-test σ_v
GCs ($< 10'$)	440	1439 ± 16	318 ± 13	...	99.26,99.76
GCs ($< 6'$)	332	1445 ± 18	319 ± 15	...	99.93
GCs ($6'$–$10'$)	108	1420 ± 32	318 ± 26	99.45	87.3
UCDs (all)	60	1497 ± 31	229 ± 25		
UCDs ($< 10'$)	28	1481 ± 41	205 ± 36		
UCDs ($< 6'$)	19	1397 ± 40	153 ± 35		
UCDs ($6'$–$10'$)	9	1659 ± 68	192 ± 70		
dE,Ns (all)	53	1472 ± 55	387 ± 43	...	99.99
dE,Ns ($< 60'$)	22	1403 ± 95	435 ± 74	...	99.99

Notes. The final two columns show the results of a student's t-tests or F-tests as to how much the GC or dE,N samples differ from the corresponding UCD sample mean velocity $\overline{v}$ or velocity dispersion σ_v. Ellipses indicate that the significance is $< 90\%$. For comparison, the velocity of NGC 1399 is 1415 ± 58 km s^{-1} and the mean cluster galaxy velocity is 1493 ± 36 km s^{-1} with $\sigma_v = 374 \pm 26$ km s^{-1}. There is a known difference between the giant ($\sigma_v = 308 \pm 30$ km s^{-1}) and dwarf ($\sigma_v = 429 \pm 41$ km s^{-1}) galaxy velocity dispersions (Drinkwater et al. 2001).

with the typical errors of $\sim$ 100 km s^{-1} for Dirsch et al. (2004), though there are five outliers. The comparison with Bergond et al. (2007) is much better, owing partly to their tiny errors of $\sim$ 10 km s^{-1}. The 2dF spectra of the five outliers are reasonably good, and we have confidence in the derived velocities. There is no systematic trend with the cluster position of 2dF and literature velocity differences for the UCDs, except possibly over a restricted interval of $< 8'$. Using the fitted line shown, a velocity correction can be derived to apply to the 2dF results; this, however, produces an even lower dispersion

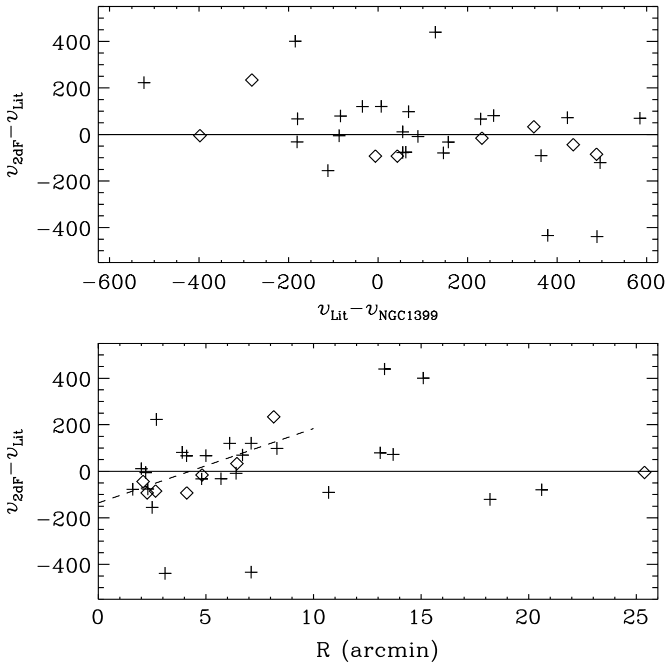

Figure 6. Comparison of the 2dF UCD velocities with the literature values for 25 objects in common with Dirsch et al. (2004) and eight objects with Bergond et al. (2007) within 25′ of the cluster center. There is no systematic trend with either velocity or with cluster position, except possibly for the 22 objects clustered inside 8′ around the fitted line shown. If this trend is removed from the 2dF UCD velocities, the UCD sample dispersion drops to even lower values in this radial interval.

for the UCDs in this interval (198 km s^{-1} compared with 231 km s^{-1}). We conclude that the differences in the velocity means and, especially, velocity dispersions for the three samples are real, and perhaps slightly underestimated by the 2dF data. The only selection criterion that separates the GCs and UCDs, however, is apparent magnitude, so the dynamical difference strongly suggests that our sample somehow constitutes a distinct population of objects, whether or not they are indeed UCDs or the bright end of the GCLF.

The objects in our cluster-wide sample are preferentially distributed along a northeast-southwest locus. If UCDs do come from threshing or stripping of larger galaxies, then their distribution in Fornax may reflect the initial orbits or direction of merging of the parent objects. Coincidentally, this elongated distribution is aligned toward the infalling subcluster to the southwest identified in Drinkwater et al. (2001), and this same distribution has been noted by Bergond et al. (2007).

4. DISCUSSION

Our observations have extended the FCSS results to search for fainter UCDs in the central 1°.8 diameter region of the Fornax Cluster, revealing an unexpectedly large number of compact objects spread throughout the intracluster space, 60 in total. The size of our sample allows us to make statistical comparisons of this population with GCs associated with the central galaxy, and the general population of nucleated dwarf elliptical galaxies.

Our results beg the question of what kind of objects UCDs really are: a separate class of dwarf galaxy or merely extremely bright GCs. The LF of our sample of 60 compact cluster members is consistent with them being at the bright tail of the ordinary GCLF (assuming that the extreme of this function remains Gaussian in the many sigma bright tail), with perhaps ∼ 5–10 extra objects in the brightest range, $M_V < -12$ (Figure 4). Their spatial distribution too is nearly identical with that of the general Fornax GC population (Figure 3). If the UCDs are the luminous tip of the cluster-wide iceberg of globulars, then, assuming that the intergalactic GCLF is similar in shape to that for individual galaxies (Bassino et al. 2006), a deeper spectroscopic survey of the intergalactic regions of Fornax should reveal thousands of GCs floating in the space between galaxies. With the European Southern Observatory (ESO) VLT and VIMOS in a low dispersion mode, it is straightforward to reach $V = 23$, bringing in range ∼ 35% of the intergalactic GC population (Figure 4).

Even though the spatial distribution and photometric properties of the 60 compact cluster members indicate a close relationship with the general globular population in Fornax, they form a dynamically distinct population from both the NGC 1399 GCs and the Fornax dE,N galaxies, having higher mean velocity and a lower velocity dispersion (Figure 5; Table 4). These results apply especially to spatially restricted subsamples and to the total populations of each type, yet the only difference in selecting the GC and UCD samples for observation is apparent magnitude. Indeed, many objects are in both our sample and those of Dirsch et al. (2004) and Bergond et al. (2007). Whatever the nature of the objects identified here as UCDs, the dynamical differences are consistent with them being a different class of objects from run-of-the-mill GCs in the halo of NGC1399, at least with respect to mechanisms of formation or secular evolution over a Hubble time. The dynamical differences would seem to be compatible with the threshing hypothesis for the origin of UCDs (Bekki et al. 2001, 2003).

Deciding the nature of UCDs distills down to the question of what distinguishes a galaxy from a star cluster. Star clusters are usually thought of as simple stellar populations: effectively single age, single metallicity, and with dynamical masses identical to stellar masses. Thus, for a time, it appeared that the decision as to whether a given object is a UCD or a GC could be made on the basis of a determination of the mass-to-light (M/L) ratio; objects with mass greater than could be accounted for by stellar population models were deemed UCDs (Drinkwater et al. 2003; Haşegan et al. 2005). This result is heavily model dependent, however, as more complex population synthesis is often able to produce higher M/L ratios (Evstigneeva et al. 2007; Hilker et al. 2007) by adopting (in the absence of any observational constraints) bottom-heavy initial mass functions (IMFs), one is again led to the possibility that UCDs are merely overgrown globulars and not a different beast entirely. Still, there are a few Virgo objects in the Haşegan et al. (2005) sample with M/L ratios in the range 6–10, which, if real, are high enough to require dark matter for all reasonable population models. Additionally, there are objects in Fornax, which appear to have intermediate age populations (Gregg et al. 2009; Mieske et al. 2006; Hilker et al. 2007) making them distinct from Milky Way globulars and more akin to dE,N nuclei or low-luminosity ellipticals, dark matter considerations kept aside. Perhaps the objects with high M/L and/or intermediate age populations are the remnant nuclei of disrupted high-luminosity galaxies, while most compact cluster members are simply globulars.

Progress in understanding the nature of UCDs can be made on several fronts. One way is to obtain better echelle resolution spectroscopy for dispersion measurements of a larger sample of UCDs spanning a larger luminosity range. Coupled with the available *HST* imaging, a larger set of mass and M/L determinations will address the dark matter issue. Detailed spectral synthesis of flux-calibrated, intermediate-resolution spectra covering a large wavelength range can in principle constrain the IMF of UCDs. Such modeling would also constrain the age range of the stellar population. Fornax is a relatively small cluster of galaxies, so, even with a population of 11,000 globulars, the bright luminosity tail, where the UCDs reside, contains just a few dozen objects and it is not a statistical certainty if the small excess seen in Figure 4 is meaningful; a census of intergalactic UCDs/GCs in a larger cluster would help in this respect. Larger spectroscopic samples of intergalactic GCs would also test the assumption that the GCLF is, in fact, a Gaussian, which is open to question.

Understanding UCDs, and intergalactic GCs for that matter, also hinges on understanding their relationship to other dwarf galaxies in clusters, especially dE galaxies. The spatial distribution of UCDs is significantly different from that of existing nucleated dwarf galaxies in the same part of the cluster: the UCDs are much more centrally concentrated, as would be expected from the significantly smaller velocity dispersion. These results lead us to revise our original hypothesis for the formation of UCDs that they represent a small subset of the *current distribution* of cluster dE,N galaxies, which have been tidally disrupted by the cluster potential ("galaxy threshing") to leave just the nuclei remaining. In the galaxy threshing process, the remaining nuclei keep the same orbits as the parent galaxies and thus would have the same radial distributions and velocity dispersion; there is no significant loss of energy that would allow them to fall into closer orbits around the central galaxy. Only a subset of dwarf galaxies, however, are on initial orbits that will lead to threshing, so a difference in velocity dispersion between the objects threshed and those not (yet) threshed is expected. In a future paper, we will model this in detail to ascertain whether the observed distribution and velocities of UCDs in Fornax are consistent with threshing of an initial population of dE,N galaxies. The results presented here suggest that if UCDs are created by threshing dE,Ns, then a substantial fraction of UCDs must be from a parent population that formed on closer, low-energy orbits around the cluster center, objects predestined to become UCDs. Their present elongated distribution (Figure 2) also apparently reflects the initial dynamics of the input objects, possibly from galaxies in subclusters merging with the main cluster body.

In future work, we plan further high-resolution spectroscopic observations to distinguish UCDs and GCs using their internal dynamics. It is vital to determine if the intracluster space between the giant galaxies is occupied by a population of faint compact objects—true intracluster GCs perhaps (West et al. 1995)—so deeper low resolution spectroscopy is also called for. We also plan to use cosmological simulations of cluster formation to determine if there might have been populations of dwarf galaxies formed on low-energy orbits more readily susceptible to galaxy threshing, facilitating the formation of UCDs.

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