Near-Field Cosmology with Dwarf Elliptical Galaxies
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Ultra-compact dwarf galaxies: a new component of galaxy clusters and groups

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Abstract. We recently reported the discovery of a new galaxy type, ultra-compact dwarf (UCD) galaxies, in both the Fornax and Virgo clusters. Here we present new detections of a larger population of UCDs in the Fornax Cluster, as well as the first detections of UCDs in two galaxy groups. We extended our original survey of the Fornax Cluster 1 magnitude fainter, finding a further 46 new compact objects. This means that UCDs outnumber normal galaxies in the central region of the Fornax Cluster. We used this large UCD sample to test the tidal stripping model: simulations indicate that only about half of the UCD population may have formed by disruption of the observed population of nucleated dwarf galaxies. As the UCDs are strongly clustered towards the cluster centre, we conclude that the remaining UCDs must be associated with the much earlier assembly of the central galaxy.

Keywords. globular clusters: general, galaxies: star clusters, galaxies: dwarf, galaxies: formation

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1. Introduction

Our study of compact dwarf galaxies in the Fornax Cluster was originally motivated by the desire to determine if the cluster contained any “M32-like” compact elliptical galaxies as suggested by Ferguson (1989). We used the FLAIR-II multi-object spectrograph on the 48-inch U.K. Schmidt Telescope to measure redshifts of some 500 compact galaxies in the direction of the cluster (Drinkwater *et al.* 2001). None of the M32 candidates turned out to be cluster members so we concluded that whatever process resulted in M32 is not important in the cluster environment. There were other surprises however, notably that 8 of the previously-classified background galaxies were actually cluster members.

The detection of these new cluster members motivated us to start a much more extensive spectroscopic study to improve our knowledge of the dwarf galaxy population of the Fornax Cluster. The *Fornax Cluster Spectroscopic Survey* (FCSS; Drinkwater *et al.* 2000) has used the 2dF 400-fibre spectrograph on the 3.9m Anglo-Australian Telescope to perform the first *all-object* survey of a galaxy cluster. Rather than select resolved objects (i.e. “galaxies”), we have observed all objects (i.e. “stars” and “galaxies”) in our magnitude range ($16.5 < b_J < 19.8$) in three 2dF fields around the cluster centre. The targets were selected from U.K. Schmidt Telescope photographic survey plates: 65% were morphologically classified as stars and 35% as galaxies.

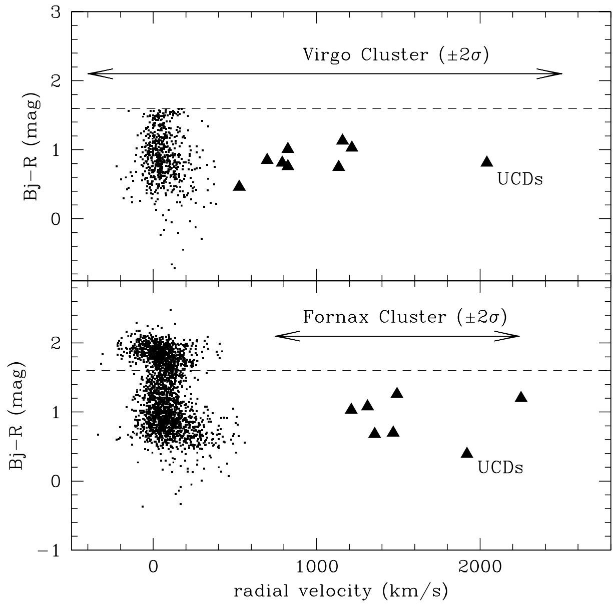

Figure 1. Comparison of the Virgo (upper) and Fornax (lower) Cluster UCDs (triangles) with foreground Galactic stars (points). For the Virgo, only stellar objects with $B_J - R < 1.6$ (dashed line) were observed. For each cluster the 2σ velocity range about the mean redshift is shown.

2. A new type of galaxy; also in the Virgo Cluster

To our surprise, six of the "stars" in the FCSS were found to have redshifts consistent with cluster membership: they were not Galactic stars. Two of these had previously been identified in a smaller survey by Hilker *et al.* (1999). As these objects were unlike any known objects in the cluster we described them as "ultra-compact dwarf" (UCD) galaxies (Phillipps *et al.* 2001).

In subsequent investigations we have shown that the UCDs are unlike any known type of galaxy or star cluster and therefore form a new class of galaxy (Drinkwater *et al.* 2003). They do not appear to be isolated globular clusters because they are much larger (r_e = 10–20 pc) than Galactic globulars (r_e = 3–5 pc), they do not follow the same relation between velocity dispersion and luminosity as globulars, and they have higher mass-to-light ratios (M/L = 2–4) than globulars (M/L = 1–2). They are not extreme cases of known galaxy types as we have shown they are very widely separated from known types in surface brightness as a function of luminosity. Our initial hypothesis is that UCDs are the remnant nuclei of nucleated dwarf elliptical galaxies tidally disrupted by the cluster potential. We refer to this process as galaxy threshing (Bekki *et al.* 2001).

We predicted that UCDs should be found in similar numbers in the Virgo Cluster around the central galaxy M87 as it is similar in size to NGC 1399 in Fornax and is surrounded by a similar surface density of dwarf elliptical galaxies. We used 2dF again to measure stellar objects towards the centre of the Virgo Cluster, but this time, informed by the properties of the Fornax UCDs we did not observe the reddest stellar objects. As a result we were able to test our hypothesis with only a few hours of service observations: in just 3 hours were were able to detect 9 UCDs in the Virgo Cluster. The results for both the Fornax and Virgo clusters are compared in Fig. 1 which also indicates our revised colour selection for Virgo.

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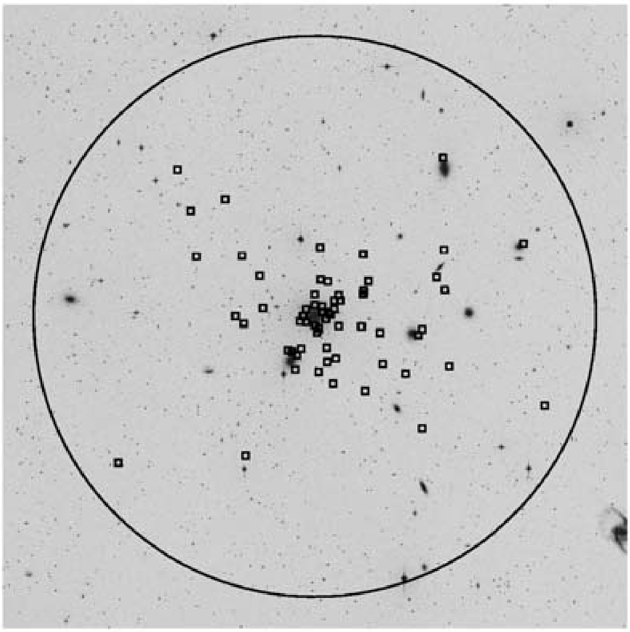

Figure 2. The distribution of the large population of UCDs (squares) in the Fornax Cluster. The circle shows the 2-degree diamater 2dF field searched for UCDs.

3. Large UCD Population

Based on our galaxy threshing hypothesis for UCD formation we predicted that the luminosity function of UCDs should approximately follow that of the nuclei of dE,N galaxies (e.g. Binggeli & Cameron 1991). On that basis we used 2dF to search the central region of Fornax for UCDs to a fainter limit of $b_J < 21.5$ and avoiding the red objects. We expected to triple our sample, but actually found 10 times as many objects making a total of 63. The locations of the objects are shown in Fig. 2. We note that these objects outnumber normal galaxies in the cluster centre.

In Fig. 3 we compare the magnitude and velocity distributions of the new UCDs with normal dE,N galaxies (Ferguson 1989) and globular clusters (Dirsch *et al.* 2004). It is clear that the new objects overlap the distribution of globular clusters, however there are some significant differences in their dynamical properties. First we note that the UCDs ($\sigma_v = 262 \pm 29\mathrm{kms}^{-1}$) are more relaxed than the dE,N galaxies in the same region ($\sigma_v = 417 \pm 63\mathrm{kms}^{-1}$) at the 99% confidence level. Conversely, the mean velocity of the UCDs ($< v >= 1556 \pm 40\mathrm{kms}^{-1}$) is larger than that of the globular clusters ($< v >= 1445 \pm 16\mathrm{kms}^{-1}$) at the 99% confidence level.

4. Origin of UCDs

We have used the larger population of UCDs to make further tests of the galaxy threshing hypothesis by making numerical simulations of the process, taking the parent population of UCDs to be the total of all current UCDs and dE,N galaxies. We then simulate their possible orbits to estimate the fraction of parent orbits at a given radius which will be threshed to form UCDs. In Fig. 4 we compare this to the observed fraction. The simulations predict at most half the current population of UCDs. This is basically because the UCDs are significantly more centrally-concentrated than the dE,N galaxies.

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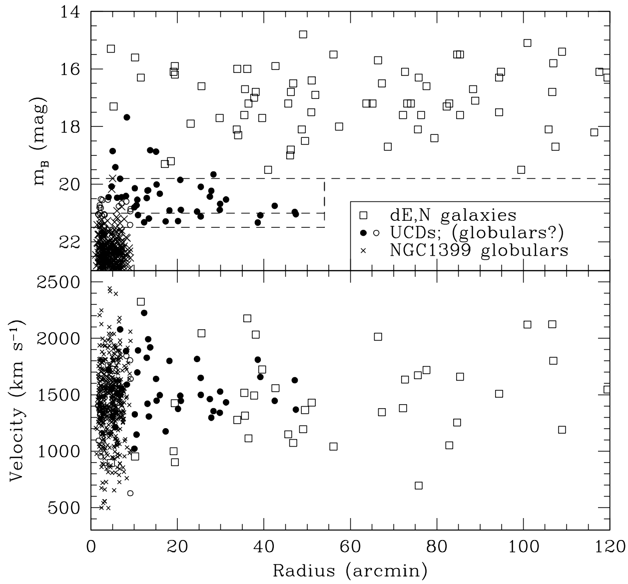

Figure 3. Radial distributions of dwarf elliptical galaxies, UCDs and globular clusters in the Fornax Cluster. Upper panel: apparent magnitude as a function of radius. The dashed lines indicate the parameter range we have searched for UCDs with completeness levels of 96% ($m < 19.8$), 82% ($19.8 < m < 21$) and 36% ($21 < m < 21.5$). Lower panel: velocity distributions.

There is no significant friction involved in the threshing process, so threshed objects will continue on the same orbits as their progenitors. We therefore infer that a significant fraction of the UCDs formed in close orbits around the central cluster galaxy. This implies an earlier formation age in hierarchical structure formation scenarios.

5. Summary

The main result we have presented here is that there is a large population of fainter UCDs in the Fornax Cluster. Whilst there is undoubtedly some overlap between these objects and true globular clusters associated with the central galaxy of the cluster, the UCD population has a significantly higher mean velocity than the globulars. The UCDs are also distributed over a much larger region of intra-cluster space than the globular clusters. The large sample of UCDs has enabled us to make a new test of the "galaxy threshing" hypothesis for their formation. We find that disruption of dE,N galaxies can only account for about half the observed UCD population. This is basically because the UCDs are much more concentrated to the cluster centre than the dE,N galaxies; they also have a much lower velocity dispersion. We have just begun searches for UCDs in a number of galaxy groups to investigate if their formation is dependent on the cluster environment. Our preliminary results suggest they are also present in groups, but in lower numbers: we have found one each so far in the Dorado and NGC 1400 groups.

Acknowledgements

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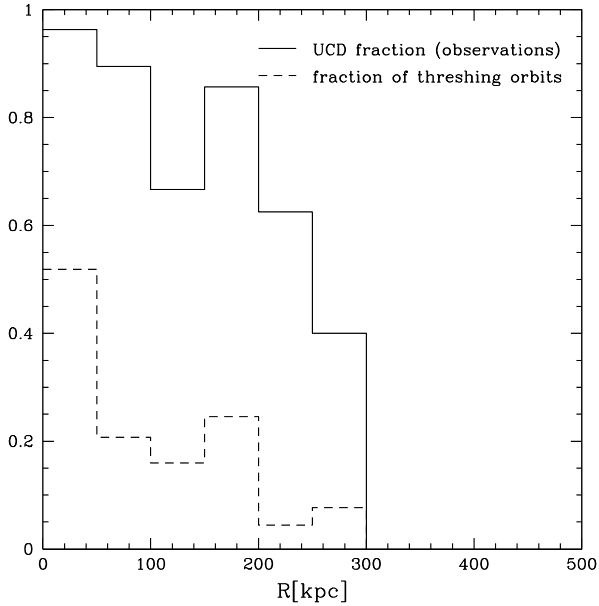

Figure 4. Predicted fraction of UCDs formed from threshed dE,N galaxies as a function of radius based on simulations of the threshing process. This is compared to the actual fraction of UCDs defined as the number of UCDs divided by the total number of UCDs plus dE,Ns. We assume a distance of 20 Mpc to Fornax.

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Discussion

Caldwell:: In the mean, the UCDs are more massive and have higher M/L than GCs, but is there an overlap in the distributions such that some of the fainter UCDs in Fornax might be GCs?

Drinkwater:: Yes, there is clearly an overlap in luminosity. We hope to use internal properties to separate objects in this range: internal velocity dispersion and M/L.

Mieske:: 1) The GC system in Fornax (NGC1399, Dirsch *et al.* 2003) has been shown to extend out to 30' and possibly beyond. Therefore one has to be careful in postulating that the fainter UCDs which extend out to about 40' cannot be GCs. 2) In your comparison

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between the LF of UCDs and the GCLF of NGC1399, you should remark that the GCLF has been scaled down by a factor of ca. 50 to fit into the plot.

Drinwater:: Yes, I agree on both your points and I will investigate the numbers from the Dirsch *et al.* sample. Thank you.

Jordan:: A population of intra cluster globular clusters has been hypothesized for a long time and recently detected. West *et al.* (1995) presented a model that predicts the number of intra cluster globulars based on the mass of the cluster. Have you compared your number counts with the prediction of their models?

Drinkwater:: I haven't, but that is something I'd like to do.

Saviane:: You said that UCDs were predicted by Disney. On what theoretical grounds?

Drinkwater:: Disney's work wasn't theoretical really. He noted that current galaxy surveys were only sensitive to a small range of surface brightness so that low- and high-surface brightness objects would be missed. therefore he inferred large undiscovered populations of such objects, of which UCDs are one example.

Kroupa:: The formation of UCDs may be seen now in the Antenna galaxies as the young "knots", or star-cluster complexes, as described by Whitmore *et al.* (1999) and Kroupa (1998).

Drinkwater:: Yes, this is one formation scenario we should consider, especially as the long axis of the UCD distribution in Fornax points towards the infalling subcluster.

Diemand:: In the "galaxy threshing" model: why did you start with an initial radial distribution similar to *todays* UCDs + dEs? CMD models motivate a much more concentrated (r^{-3}) initial population. In this case the larger efficiency of tidal destruction and stripping at smaller radii could explain the different concentrations of ICL + GCs, UCDs and dEs today.

Drinkwater:: Our initial hypothesis was intentionally naive as we didn't have a good understanding of CDM-type predictions. We are now collaborating with people from the Virgo Consortium to make more realistic models.

Read:: What is the implication of these results for the missing satellite problem? If you go deeper, do you expect to find yet more of these things?

Drinkwater:: We certainly expect to find more as we go both fainter and wider in our searches. My guess is they don't have enough dark mass to contribute much to the missing satellite problem, but others here are more expert in that area.

Karachentsev:: Did you try to search for UCDs in the Leo I Group? This is the nearest E-dominated group, situated in the zone of the SDSS. It can be reached with ACS in the snap-shot survey, too.

Drinkwater:: Thank you; that is an excellent suggestion.