# A class of compact dwarf galaxies from disruptive processes in galaxy clusters

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**Dwarf galaxies have attracted increased attention in recent years, because of their susceptibility to galaxy transformation processes within rich galaxy clusters[1–3]. Direct evidence for these processes, however, has been difficult to obtain, with a small number of diffuse light trails[4] and intra-cluster stars[5,6] being the only signs of galaxy disruption. Furthermore, our current knowledge of dwarf galaxy populations may be very incomplete, because traditional galaxy surveys are insensitive to extremely diffuse or compact galaxies[7]. Aware of these concerns, we recently undertook an all-object survey of the Fornax galaxy cluster[8]. This revealed a new population of compact members[9,10], overlooked in previous conventional surveys. Here we demonstrate that these 'ultra-compact' dwarf galaxies are structurally and dynamically distinct from both globular star clusters and known types of dwarf galaxy, and thus represent a new class of dwarf galaxy. Our data are consistent with the interpretation that these are the remnant nuclei of disrupted dwarf galaxies, making them an easily observed tracer of galaxy disruption.**

We used the Two Degree Field (2dF) multi-object spectrograph on the 3.9 m Anglo-Australian Telescope to make a large all-object spectroscopic survey of the Fornax galaxy cluster[8]. The 400-fibre multiplex advantage of the 2dF spectrograph allowed us to include unresolved objects (normally ignored as 'stars'). Among these 'stars' we discovered[9,10] a population of objects in the cluster with luminosities of $M_V \approx -11$ mag, intermediate between typical globular star clusters ($M_V \approx -8$ mag) and normal dwarf galaxies ($M_V \approx -11$ to $-16$ mag). These 'ultra-compact' dwarf (UCD) galaxies are unlike other dwarf galaxies of similar luminosity by virtue of their high central concentration and thus star-like morphology in typical one-arcsecond-resolution ground-based imaging. At the distance of the Fornax cluster[11] (20 Mpc; Hubble constant $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) this implies sizes of, at most, 100 pc.

We proposed[9] that the UCDs were either unusually large and isolated star clusters or a new type of compact galaxy, perhaps formed by the disruption of nucleated dwarf galaxies. The UCDs are more luminous than Galactic globular star clusters, but they could be the extreme bright tail of the populous globular cluster system around the central galaxy of the Fornax cluster NGC1399 (ref. 12). The UCD luminosities, however, also suggestively overlap the luminosity distribution of the nuclei of dwarf elliptical galaxies (which peaks at $M_V \approx -10$ mag; ref. 13). A third possibility is that UCDs are simply ordinary nucleated dwarf ellipticals, but at one extreme of a continuous sequence of envelope luminosities, having envelopes too faint to be easily detected. The lack of extended halos around the UCDs in photographic images[10] argued against this third hypothesis.

Here we present new observations of the UCDs, aimed at determining their nature. Our deep imaging of the Fornax cluster confirms that UCDs are morphologically distinct from ordinary dwarf ellipticals, and our high-resolution imaging and spectroscopy show that they are not globular star clusters; we therefore conclude that they represent a new class of dwarf galaxy. Our interpretation is that the UCDs are the stripped nuclei of dwarf elliptical galaxies and therefore represent a method of tracing galaxy disruption processes in clusters.

That normal dwarf galaxies and UCDs are quite distinct, morphologically, is shown in Fig. 1, where we present an envelope surface brightness versus core luminosity plot. Nucleated dwarf elliptical (dE,N) galaxies show a correlation between the effective surface brightness of their envelopes and their core luminosities. In contrast, UCDs lie in a completely different region of this diagram: because they have no detectable outer envelope, only upper limits can be put on their surface brightness, all of which lie 3.5 magnitudes (a factor of 25) fainter than the dE,N galaxies with the same nuclear luminosity. Any intermediate objects would easily have been detected in our survey, so UCDs are clearly not part of the normal distribution of dwarf elliptical galaxies. The UCDs are also more concentrated to the centre of the cluster than the dwarf galaxies[9]; the radial distribution of the seven known UCDs differs from that of the 37 dE,N galaxies in our survey at the 99.7% confidence level. We therefore conclude that UCDs are not extreme examples of normal dwarf galaxies with very faint envelopes.

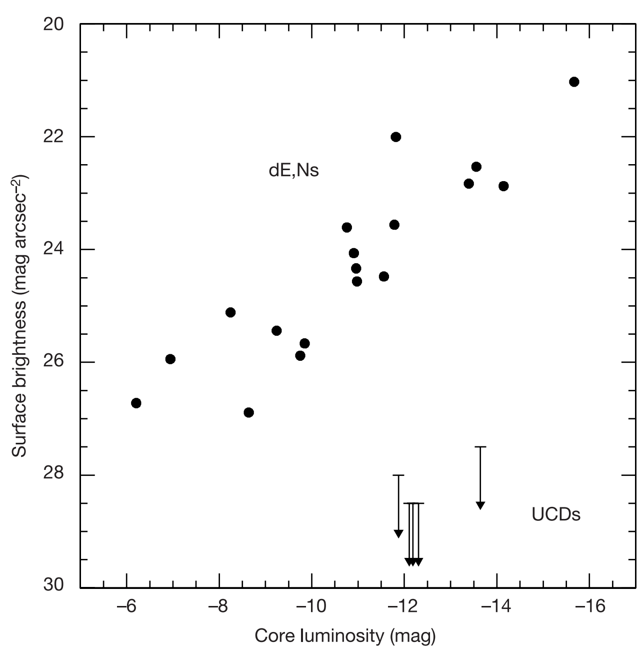


**Figure 1** Comparison of the morphology of UCD galaxies with normal dE,N galaxies in the Fornax cluster. The envelope effective surface brightness in the V-band of the objects is plotted as a function of the V-band luminosity of their cores. The luminosity is in units of V-band absolute magnitude $M_V = \mathrm{const.} - 2.5\log_{10}(L)$, with luminosity $L$ increasing from left to right. The surface brightness of the UCDs are upper limits, because no envelopes were detected on scales greater than the image resolution (2 arcseconds full-width half-maximum). The data are from deep images of 2.4 square degrees in the centre of the Fornax cluster taken with the 100-inch du Pont telescope of the Las Campanas Observatory[24]. This region contains the original five UCDs as well as 18 dE,N galaxies[25].

We obtained high-resolution imaging with the Hubble Space Telescope (HST) of the first five UCDs discovered. We also observed a normal dE,N galaxy for comparison. Further comparisons are provided by similar published observations of six dwarf elliptical galaxies in the Virgo cluster[14]. Our images are shown in Fig. 2. The UCDs are very compact, typically only a few times larger than the 0.05-arcsecond image resolution. The UCD profiles were well fitted by both King models (normal for globular star clusters) and de Vaucouleurs $R^{1/4}$ law profiles (normal for giant elliptical galaxies) but are not consistent with the exponential profiles typical of normal dwarf galaxies (excluded at the 99.9% confidence level). The effective radii (defined to contain half the light) of the UCDs range from 10 to 22 pc. In the case of UCD3, the most luminous UCD, the model profile required an additional, but still very small (60-pc scale length), exponential halo component for a good fit. As expected, the comparison nucleated dwarf, FCC303, also required a two-component model of a core plus a larger (300-pc scale length) exponential halo. The UCD cores are all significantly larger than Galactic globular star clusters (typical effective radii of 3–5 pc) and are also larger than the 8-pc core of FCC303. Conversely, the UCDs are all smaller than known dwarf galaxies. Even the halo we do detect around UCD3 is tiny for a dwarf elliptical; the most compact normal dwarf galaxies in the Virgo cluster have scale lengths of 160 pc (ref. 15).

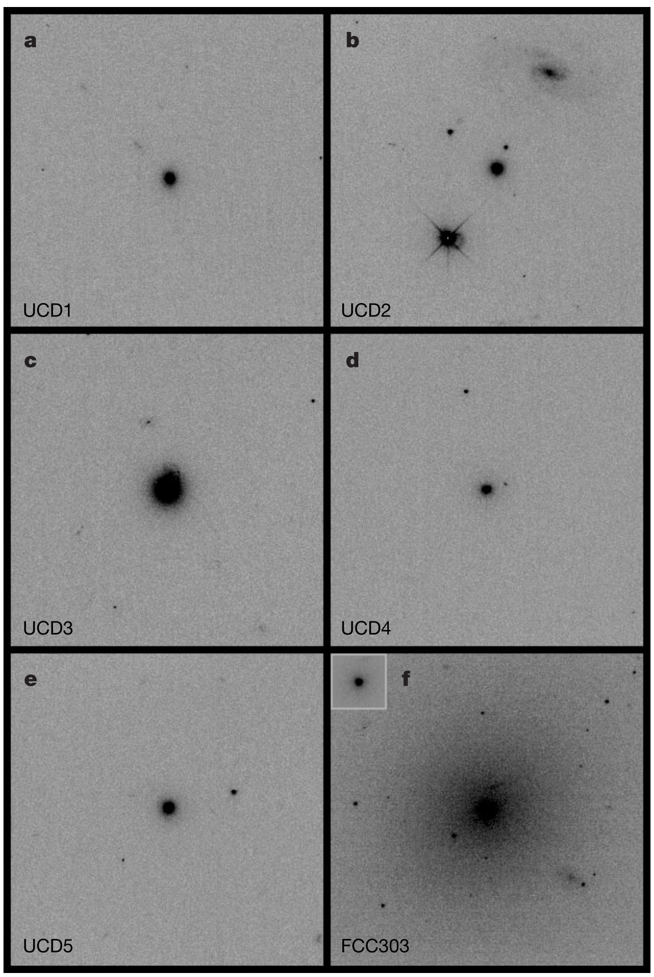


**Figure 2** Comparison of Hubble Space Telescope images of the UCD galaxies with a normal nucleated dwarf galaxy (FCC303; ref. 25). Panel **f** is at the same contrast as **a**–**e**; the inset in **f** is at a lower contrast to show the nucleus. The extended halo of FCC303 more than fills the 30-arcsec field (2.9 kpc or $9.0 \times 10^{19}$ m at the Fornax cluster). These images, shown in negative format, were obtained in the unfiltered mode of the Space Telescope Imaging Spectrograph (STIS). The one-orbit (40-min) exposures were made in the 'clearpass' optical CCD imaging mode of STIS for maximum sensitivity. We measured the UCD sizes with the "Ishape" program[26], which iteratively convolves a chosen model profile with the STIS point-spread function to match the galaxy profile by minimizing a $\chi^2$ difference statistic. We used a fitting radius of 0.8 arcsec (16 pixels) corresponding to the same physical radius of 75 pc as used in the Virgo study[14] and obtained effective radii for the UCDs of 10–22 pc.

To study the internal dynamics and estimate the masses of the UCDs and FCC303, we measured their internal velocity dispersions with the Very Large Telescope (VLT) and the W.M. Keck Telescope. The velocity dispersions range from 24 to 37 km s$^{-1}$, considerably higher than those of Galactic globular star clusters, but overlapping the values published for the most luminous globular star clusters in the spiral galaxy M31 (ref. 16). Assuming the UCDs are dynamically relaxed systems, we can use their sizes and velocity dispersions to estimate their masses. Using a King model mass estimator[17] for our profile fits we obtain masses of $1–5 \times 10^7 M_\odot$ (solar masses) for the UCDs and $1.4 \times 10^7 M_\odot$ for the dE,N galaxy nucleus, compared to around $4 \times 10^6 M_\odot$ for the most massive globular star clusters[16]. We obtained similar masses using Plummer models[18], although these profiles did not fit out data as well. Using the HST data to measure the total V-band luminosities of the UCDs, we derived their mass-to-light ratios. The mass-to-light ($M/L$) ratios range from 2 to 4 in solar units, compared to around unity for typical globular star clusters. The largest globular star clusters in M31 have $M/L = 1–2$. In summary, the UCDs have luminosities, sizes and velocity dispersions similar to the cores of nucleated dwarf galaxies (in both the Fornax and Virgo[14] clusters), but are larger and have higher mass-to-light ratios than even the largest globular star clusters.

The distinction between UCDs and other types of stellar system is made even clearer if we consider the dynamical correlations between the physical observables of luminosity and velocity dispersion shown in Fig. 3. The figure compares UCDs with globular clusters, dE,N galaxies and giant elliptical galaxies. We also include the large Milky Way globular cluster, ω Centauri, which is thought to have originated outside the Milky Way[19]. The UCDs lie well off the globular cluster $L \propto \sigma^{1.7}$ relation[16], filling a previously unoccupied part of the diagram, but on an extrapolation of the elliptical galaxy $L \propto \sigma^4$ Faber–Jackson law[20].

The properties of the cores of the comparison dE,N galaxies are also shown: these are distributed between the globular clusters and the UCDs. The locations of the UCDs and the dwarf galaxy nuclei strongly support the 'galaxy threshing' hypothesis: UCDs are nucleated dwarf galaxies whose outer envelopes have been tidally stripped by interactions with the central cluster galaxy[3]. Removing the halo of a normal dE,N galaxy reduces the total luminosity by a factor of about 100 (5 mag), but barely changes the central velocity dispersion and nuclear luminosity (the dynamical relaxation time of the remaining core can be as long as $10^{11}$ years). The predicted effect of threshing is shown as a dotted line in Fig. 3 connecting the positions of FCC303 and that of its nucleus alone.

The case for tidal stripping is further supported by our detection of a small halo around the largest UCD. This object may be partially stripped, caught at an intermediate stage between UCDs and dE,N galaxies. As threshing will have been at least as important at earlier times in the life of the cluster, this implies a much larger population of UCDs than the seven currently known, although if they have the same luminosity function as dwarf galaxy nuclei[13], most will be fainter than the limit of our survey.

Our new observations confirm that UCDs are qualitatively

  

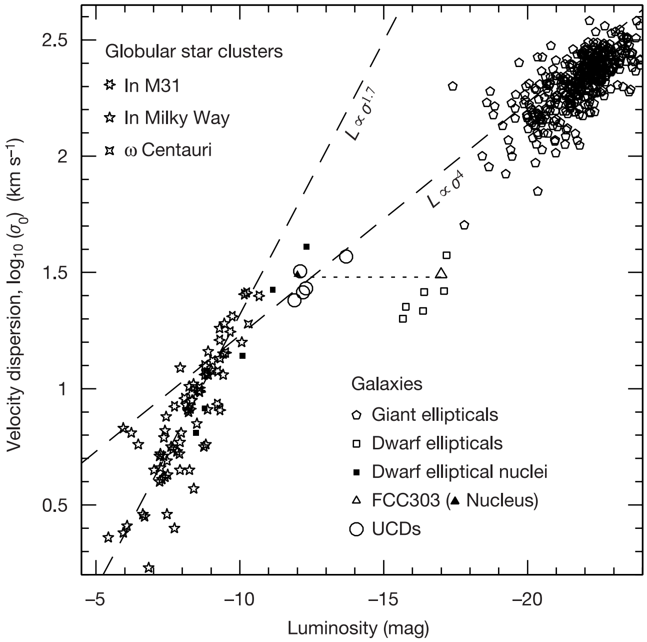


**Figure 3** Comparison of the internal dynamics of the UCDs with normal galaxies and globular star clusters. The internal velocity dispersions ($\sigma_0$) of the different objects are plotted as a function of luminosity as in Fig. 1. The dashed lines show the Faber–Jackson relation[20] for elliptical galaxies and the steeper relation[16] followed by Galactic and M31 globular clusters. The dotted lines show the path predicted by our 'threshing' scenario for nucleated dwarfs being stripped to form UCDs. The small solid symbols show the locations of dwarf galaxy nuclei after model subtraction of their parent galaxies. All the data are taken from the literature (globular clusters[16], ω Centauri[27], ellipticals[28], nucleated dwarf ellipticals[14]) except for our measurements of the UCDs and FCC303. Note that the UCDs fill a previously empty region of the diagram between the globular clusters and galaxies. The velocity dispersions were obtained from high-resolution spectra using the VLT and the W.M. Keck Telescope echelle spectrographs. We measured velocity dispersions using standard cross-correlations of the object spectra with stellar template spectra to determine both a redshift and a correlation width. The correlation width was used to estimate the velocity dispersion by comparison with results from artificially broadening the template stars by convolution with gaussian filters of known widths.

different to both nucleated dwarf galaxies and the most luminous globular star clusters. Even if UCDs were formed from dE,N galaxies, as proposed by the threshing hypothesis, they constitute a new and distinct type of galaxy, just as spirals stripped of their star-forming abilities constitute the galaxy type S0 (ref. 21), and merging disk galaxies are believed to form ellipticals. The discovery of these objects confirms the prediction[7] that very compact galaxies exist that were previously misclassified as foreground stars.

Although we have shown that UCDs are dynamically distinct from globular star clusters, the two can only be distinguished at the distance of the Fornax cluster by high-resolution imaging and spectroscopy. Any UCDs captured by the central elliptical may therefore be mistaken for ordinary globular star clusters in existing studies. The two populations could be separated, in principle, by observations similar to those we described here, but the requisite spectroscopy for fainter objects would be challenging with existing 8–10-m telescopes. Any dismantled dwarf elliptical galaxies captured by the central galaxy will also contribute ordinary globular star clusters to the mix. Together, these processes may explain the unusually high frequency of globular star clusters in the central elliptical galaxies of galaxy clusters[22] because these dwarf galaxies also contain higher than average globular cluster populations[23]. Searches for UCDs in other rich environments, such as the populous Virgo cluster as well as dense groups, will clarify the nature and origin of UCDs while also potentially exploring the role of tidal disruption processes in galaxy and cluster evolution. □

Received 5 February; accepted 15 April 2003; doi:10.1038/nature01666.


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**Acknowledgements** This paper is based on observations made with the HST, the European Southern Observatory VLT, the W.M. Keck Telescope, and the Las Campanas Observatory 100-inch du Pont Telescope. This work is supported by the Australian Research Council and the Australian Nuclear Science and Technology Organisation. M.D.G. acknowledges support from the National Science Foundation and from the Space Telescope Science Institute and NASA which is operated by AURA, Inc. Part of this work was performed under the auspices of the US Department of Energy by University of California Lawrence Livermore National Laboratory.

**Competing interests statement** The authors declare that they have no competing financial interests.

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