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A COMPARISON OF SURFACE BRIGHTNESS PROFILES FOR ULTRACOMPACT DWARFS AND DWARF ELLIPTICAL NUCLEI: IMPLICATIONS FOR THE "THRESHING" SCENARIO

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ABSTRACT

Using imaging from the *Hubble Space Telescope*, we derive surface brightness profiles for ultracompact dwarfs in the Fornax Cluster and for the nuclei of dwarf elliptical galaxies in the Virgo Cluster. Ultracompact dwarfs are more extended and have higher surface brightnesses than typical dwarf nuclei, while the luminosities, colors, and sizes of the nuclei are closer to those of Galactic globular clusters. This calls into question the production of ultracompact dwarfs via "threshing," whereby the lower surface brightness envelope of a dwarf elliptical galaxy is removed by tidal processes, leaving behind a bare nucleus. Threshing may still be a viable model if the relatively bright Fornax ultracompact dwarfs considered here are descended from dwarf elliptical galaxies whose nuclei are at the upper end of their luminosity and size distributions.

Subject headings: galaxies: dwarf — galaxies: star clusters — galaxies: structure

1. INTRODUCTION

It was noted almost 40 years ago that galaxies appear to define a relatively narrow region of the luminosity–surface brightness plane (Arp 1965). Later on, Disney (1976) postulated that this, rather than being the result of a real physical correlation, was due to a selection effect, in which large diffuse objects would be lost because of the brightness of the night sky, while small compact galaxies would be mistaken for stars and not included in redshift surveys. The existence of this correlation, or otherwise, has important implications for galaxy formation models (Dalcanton et al. 1997; Mo et al. 1998).

A small number of large, luminous low surface brightness galaxies have been discovered (Bothun et al. 1987; Impey et al. 1988), but it is commonly held that such systems are actually rare (Cross et al. 2001). There are also examples of very compact dwarf galaxies (e.g., POX 186; Kunth et al. 1988), but since these objects are easily confused with stars in typical imaging conditions, large "blind" redshift surveys are needed to ascertain their presence, and as stars outnumber galaxies at the typical apparent magnitudes accessible to survey spectrographs, this is uneconomical in terms of the telescope time needed.

Drinkwater et al. (1999), however, showed that in the cluster environment the density of galaxies may be high enough, over a small field of view, that a redshift survey of all objects in the cluster area may be feasible, with acceptable rates of stellar contamination, in order to search for compact objects (Drinkwater et al. 2000; Phillipps et al. 2001). This effort was rewarded by the discovery of the first five representatives of a "new" population of galaxies, the ultracompact dwarfs (UCDs), in the Fornax Cluster. These have stellar appearance in the DuPont plates used by Ferguson (1989) in the Fornax Cluster Catalog (FCC) but nevertheless lie at the cluster redshift (see also Hilker et al. 1999). Deeper imaging and spectroscopic studies have now revealed populations of fainter UCDs in the Fornax (Mieske et al. 2004a; M. J. Drinkwater et al. 2005, in preparation) and Virgo (Drinkwater et al. 2004; Jones et al. 2005) Clusters, as well as some likely UCDs in A1689 (Mieske et al. 2004b).

The nature of UCDs is still uncertain, but one intriguing possibility, suggested by their apparent rarity in the field (J. Liske et al. 2005, in preparation), is that they are the product of the cluster environment. Clusters are known to harbor unusual galaxy populations, rarely encountered elsewhere. One conspicuous example is provided by the class of "nucleated" dwarfs (dE,N) originally discovered in the Virgo Cluster (Binggeli et al. 1985), which represent a large fraction of dwarfs in clusters but have far fewer counterparts in nearby groups (in the Local Group only NGC 205 and the Sagittarius dwarf can be regarded as nucleated). Bekki et al. (2001, 2003) proposed that stripping of the low surface brightness envelopes around nucleated dwarfs may produce a compact remnant, whose properties would be comparable to UCDs ("galaxy threshing").

A test of this hypothesis can be made by comparing the structural properties of UCDs and dE,N nuclei. We present here the results of such a study carried out using images from the *Hubble Space Telescope* (*HST*). We adopt Virgo and Fornax distance moduli of 30.92 and 31.39 mag, respectively, from

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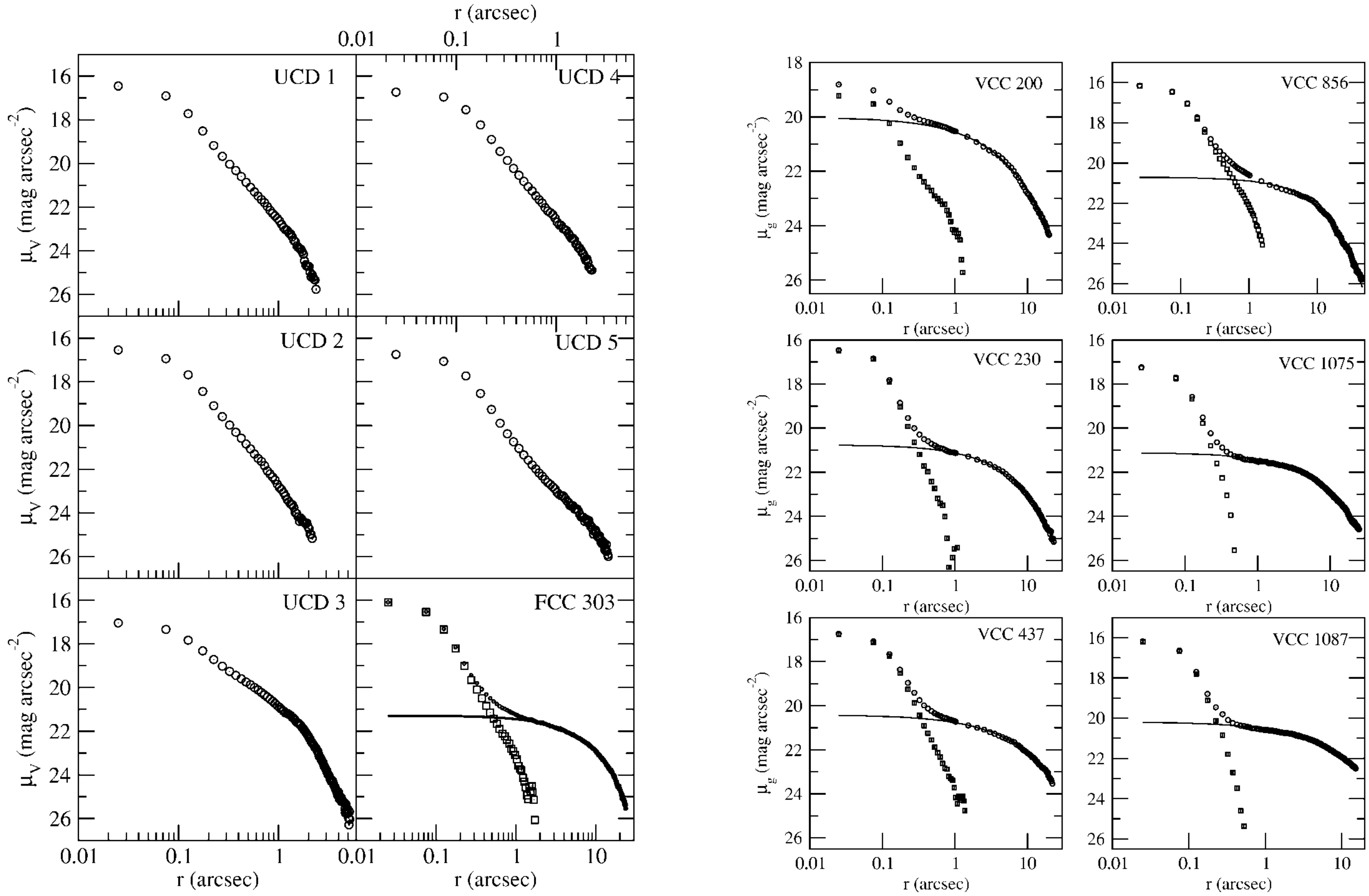

FIG. 1.—Surface brightness profiles (*circles*) from STIS observations of the five original Fornax UCDs and FCC 303 and a selection of dE,N from ACS imaging. The resolution of these profiles is 0″.05. We show the Sérsic model fitted to the envelopes of the dE,N (*solid line*) and the nuclear profile after subtraction of the model envelope (*open squares*). For clarity we show only one point in five of the dE,N envelopes, outside of the inner 1″.

Cepheid distances (Freedman et al. 2001) and extinctions derived from the maps of Schlegel et al. (1998).

2. OBSERVATIONS AND DATA ANALYSIS

The five original Fornax UCDs (Drinkwater et al. 2000; Phillipps et al. 2001) and one Fornax nucleated dwarf (FCC 303) were observed with the Space Telescope Imaging Spectrograph (STIS; Woodgate et al. 1998) through the "open" (50 CCD) filter in Cycle 8 (GO-8685). Exposure times were 1680 s, broken down into at least five dither positions for cosmic-ray removal and to better sample the point-spread function (PSF). We also use images of Virgo nucleated dwarfs taken as part of the ACS Virgo Cluster Survey (ACSVCS; Côté et al. 2004) and observed with the *HST* Advanced Camera for Surveys (ACS) through the *g* and *z* filters, with total exposure times of 750 and 1120 s, respectively. These images were retrieved as fully processed, drizzled, and sky-subtracted files from the *HST* archive[2] and analyzed as described below.

For STIS images of the UCDs, we ran the IRAF task "ellipse" (Jedrzejewski 1987) to derive the surface brightness profile, which we calibrated onto the AB system, with a correction to place the open filter data on the *V* filter scale, assuming a solar spectral energy distribution as specified in the STIS online manual. The 50 CCD bandpass is very broad, and this makes the transformation dependent on the underlying spectral energy distribution. Most realistic spectra, however, do not have a significantly different correction from our assumed solar value.

The profiles are presented in Figure 1. Most UCDs have exponential profiles with very similar scale lengths and central surface brightnesses; only UCD3 is markedly different from all other objects, in that it is much more extended and has a flatter central core than the other UCDs: this object is fitted reasonably well by a Sérsic (1968) profile, with (possibly) a small central excess.

We carried out the same procedure for the STIS image of FCC 303 and for the ACS images of the dE,N. We modeled the envelope of these galaxies using a Sérsic (1968) profile, regarded as the best model for such objects (Davies et al. 1988; Young & Currie 1994). We removed the model halo profile from the data, leaving only the photometric residual of the nucleus. Figure 1 also shows the results of this procedure for FCC 303 (observed with STIS) and a selection of the Virgo dE,N observed with ACS. We use these data to compare the properties of nuclei and UCDs.

As part of this process we also determine the luminosities and colors of the nuclei, using a 1″ aperture from which we remove the flux from the underlying galaxy by integrating the Sérsic profiles derived above. We use the ISHAPE software (Larsen 1999), assuming a circular Plummer profile (Geha et al. 2002) and using a PSF generated by TinyTim (Krist and Hook 1997), to determine half-light radii for the nuclei. We also derive the color for the host galaxy in the inner 1″. These

[2] See http://archive.stsci.edu.

TABLE 1
PROPERTIES OF NUCLEI

VCC	M_g (nucleus)	$g - z$ (nucleus)	r_h (pc)	$g - z$ (galaxy)
200	−9.09 ± 0.04	1.23 ± 0.06	20.8	1.89 ± 0.01
230	−10.76 ± 0.03	1.65 ± 0.05	3.6	1.83 ± 0.01
437	−11.09 ± 0.02	1.62 ± 0.04	8.5	1.89 ± 0.01
856	−11.87 ± 0.02	1.86 ± 0.03	8.5	1.60 ± 0.01
1075	−9.62 ± 0.04	1.54 ± 0.07	4.0	1.80 ± 0.01
1087	−10.60 ± 0.03	1.90 ± 0.04	2.3	1.94 ± 0.01
1185	−10.19 ± 0.04	1.50 ± 0.06	4.4	1.91 ± 0.01
1261	−11.40 ± 0.03	1.80 ± 0.04	4.6	1.80 ± 0.01
1355	−9.84 ± 0.04	1.71 ± 0.06	2.1	1.79 ± 0.01
1407	−10.60 ± 0.03	1.59 ± 0.04	12.2	1.85 ± 0.01
1431	−11.24 ± 0.02	1.55 ± 0.03	19.8	2.05 ± 0.01
1489	−8.32 ± 0.08	1.43 ± 0.09	4.4	1.65 ± 0.01
1539	−9.61 ± 0.04	1.58 ± 0.05	11.4	1.71 ± 0.01
1826	−11.04 ± 0.02	1.34 ± 0.03	5.4	1.94 ± 0.01
1886	−8.61 ± 0.08	1.58 ± 0.10	3.3	1.58 ± 0.01
1910	−11.07 ± 0.02	1.47 ± 0.02	4.6	2.01 ± 0.01
2019	−11.06 ± 0.03	1.74 ± 0.05	2.3	1.81 ± 0.01
2050	−8.80 ± 0.06	1.17 ± 0.09	8.1	1.81 ± 0.01

data are tabulated in Table 1. We put these data on the more commonly used Vega system, rather than the AB system used in the figures (conversion of STIS open filter data to the Vega system is not straightforward and requires assumptions as to the underlying spectral energy distribution; hence, we prefer to use AB values for these comparisons). Errors for galaxy properties are derived from the Sérsic profiles, and errors for nuclear quantities are determined by assuming that the counts obey Poisson statistics and adding errors in quadrature. Errors for the size of the nucleus are difficult to determine, but Larsen (1999) suggests that the half-light radii should be accurate to about 10% for data of good quality.

3. A COMPARISON OF NUCLEAR AND UCD STRUCTURE

Table 1 lists the properties of nuclei: absolute g magnitude (on the Vega system), $g - z$ color, half-light radius (from the Plummer profile), and the $g - z$ color of the center of the host galaxy. In Table 2, we tabulate the V magnitude of the UCDs, calculated over a large aperture whose size is determined with reference to the profiles shown in Figure 1, and their half-light radius for a Plummer profile (except for UCD Fornax 3, which resembles a Sérsic profile more closely). The properties of the nuclei (other than their magnitude and structure) are of secondary importance for our discussion, but these dE,N nuclei resemble bright globular clusters (Harris 1996), while the nuclei are somewhat bluer than the underlying galaxy, as found by Lotz et al. (2004) for a sample observed with the Wide Field Planetary Camera 2 (WFPC2).

Figure 2 plots the surface brightness profiles of a selection of the nuclei (the largest and smallest objects as well as those presented in Fig. 1) and the mean profile of the Fornax UCDs (excluding 3). These profiles were scaled to parsecs, based on published Cepheid distances to the Fornax and Virgo Clusters. The profiles are not deconvolved, but the PSF is relevant only for the inner 0″.2, while we compare structures on scales of 1″–2″. None of the nuclei, with the possible exception of VCC 856 (IC 3328) and FCC 303 (and VCC 1431, which is not shown), is similar to the mean UCD profile. Even for the nuclei of VCC 856 and VCC 1431 and for FCC 303's nuclei, however, there is a discrepancy at large radii, where UCDs are more extended. In general, nuclei appear to have smaller sizes, lower surface brightnesses, and to the extent that this can be determined given the effects of the PSF, steeper profiles than UCDs: UCDs have half-light radii of about 20 pc (cf. Drinkwater et al. 2003), while nuclei have typical sizes of less than 10 pc. While the UCDs are generally more luminous than nuclei, even nuclei of similar luminosity to the UCDs tend to be physically smaller. UCD3 shows a more extended light distribution but broadly resembles the other UCDs at smaller radii, suggesting that it may represent a transitional object between normal dwarf elliptical galaxies and UCDs.

TABLE 2
PROPERTIES OF ULTRACOMPACT DWARFS

UCD	M_V	r_h (pc)
Fornax 1	−11.70 ± 0.01	17.9
Fornax 2	−11.79 ± 0.01	20.3
Fornax 3	−13.24 ± 0.01	...
Fornax 4	−11.90 ± 0.01	20.6
Fornax 5	−11.61 ± 0.01	13.4

Bekki et al. (2001, 2003) model the formation of UCDs by removal of the envelope from dwarf elliptical galaxies through tidal interactions with the gravitational potential of the central galaxy. These simulations show that the remnant nuclei properties are not significantly changed by the threshing process (e.g., Fig. 4 in Bekki et al. 2001). If such is the case, the Fornax UCDs studied here cannot be formed by the extraction of nuclei from typical dE galaxies analyzed here.

The only exception to this appears to be VCC 856. This dwarf galaxy is known to possess a system of weak spiral arms and, possibly, a central bar (Jerjen et al. 2000): VCC 856 may

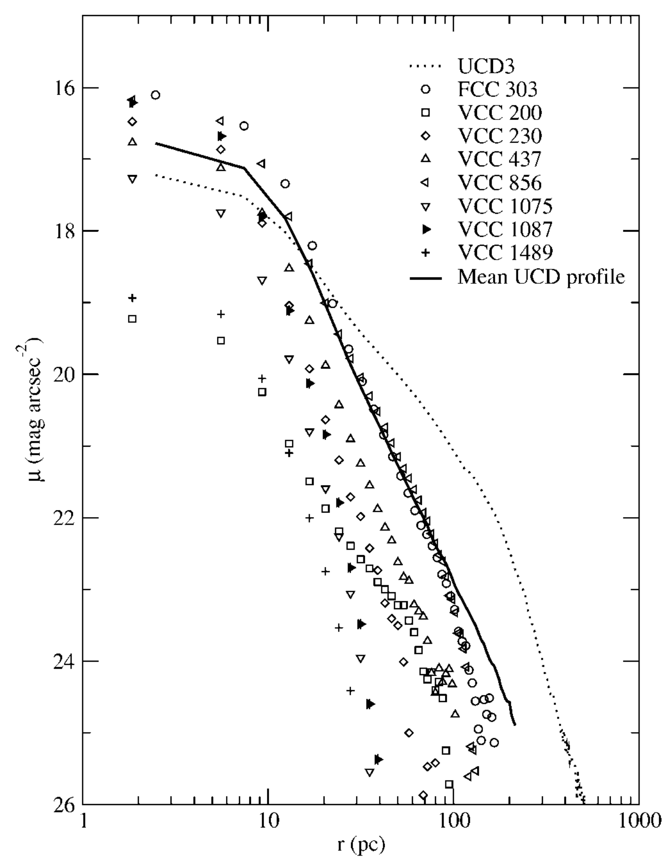

FIG. 2.—Comparison of surface brightness profiles for UCDs and the nuclei of dwarf elliptical galaxies.

be a dwarf example of the class of anemic spiral galaxies (van den Bergh 1976) encountered in clusters. The possibility that UCDs represent remnant nuclei of dwarf spiral galaxies rather than dwarf elliptical galaxies has been mentioned by Phillipps et al. (2001), and the similarity between the nucleus of VCC 856 and UCDs offers some support to this hypothesis (e.g., Moore et al. 1996). VCC 1431 and FCC 303, however, do not possess the obvious spiral structure observed in VCC 856.

One caveat is that the nuclei observed in the ACSVCS may be biased somehow to smaller objects, although Côté et al. (2004) state that the survey is designed to observe 100 galaxies fairly drawn from the Virgo Cluster Catalog of Sandage et al. (1985). The colors and luminosities of the nuclei presented in Table 1 are consistent with the larger sample of Lotz et al. (2004). We have also determined sizes for these latter nuclei and find that the size distribution for nuclei observed with WFPC2 is consistent with the one presented in Table 1. This argues that the ACSVCS samples the population of dE nuclei without obvious bias.

It is possible that the brighter Fornax UCDs are not proper representatives of the general UCD population; their similar structures and surface brightnesses suggest that we may be observing an extreme sample (the "tip of the iceberg" effect), while the fainter UCDs now discovered in the Fornax and Virgo Clusters may be closer counterparts to the nuclei of typical surviving dE.

The five UCDs in this study are the brightest known in Fornax, and the real possibility exists that they have been selectively descended from dE with particularly bright nuclei. A more extensive sample of UCDs and dEs imaged with *HST* can explore their connection more fully. To this end, we now have an ongoing High-Resolution Camera snapshot survey of UCDs in both Fornax and Virgo; this should produce a sample of 25 objects reaching 1–2 mag fainter than the small STIS sample. The simulations carried out to date may not have sufficient resolution to model the transition of a dE in a cluster environment accurately, and perhaps there are additional physical processes that come into play to cause the excess light at large radii in the UCDs. Progress will be made via the interplay of the deeper and multicolor data sets now in progress with *HST* in both the Fornax and Virgo Clusters. These more extensive samples can drive improved modeling, perhaps providing definitive tests for understanding the origin of UCDs.

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