Weighing Ultracompact Dwarf Galaxies in the Fornax Cluster

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High-resolution spectra from the Ultraviolet and Visual Echelle Spectrograph (UVES) were used to derive internal velocity dispersions of Ultracompact Dwarf galaxies (UCDs) in the Fornax cluster of galaxies. The velocity dispersions, together with highly spatially resolved luminosity profiles from Hubble Space Telescope imaging (ACS camera), allowed us to derive the dynamical masses of the UCDs. We show that the mass-to-light ratios of UCDs in Fornax are consistent with those expected for pure stellar populations. No dark matter contribution is needed. Thus, these UCDs seem to be the result of star-cluster formation processes within galaxies, rather than being compact dwarf galaxies formed in dark-matter halos.

Dwarf galaxies have only been extensively studied in the last three decades. Dwarf spheroidals are considered to be the faintest galaxies, having baryonic masses comparable to those of bright globular clusters ($\sim 10^6 \, M_\odot$), but are 50–200 times more extended. It has been believed that dwarf galaxies are diffuse structures, with the exception of the compact elliptical M32, a companion of the Andromeda galaxy, which is ~ 8–10 times smaller than dwarf ellipticals of comparable luminosities, but about 150 times more luminous than the brightest globular clusters of the Local Group. The gap in luminosity between globular clusters and compact dwarf galaxies has started to be filled in observationally over the last decade, thanks to several large spectroscopic surveys in nearby galaxy clusters.

Compact objects with masses greater than those of normal globular clusters were only discovered about 10 years ago. In 1999, two bright compact objects were confirmed as members of the Fornax cluster in a spectroscopic survey that was designed as a follow-up of a photometric investigation of dwarf ellipticals in the Fornax cluster (Hilker et al. 1999). One year later, in 2000, a systematic spectroscopic survey within a two-degree field centred on Fornax revealed five compact members in the magnitude range $-13.5 < M_V < -12.0$ (Drinkwater et al. 2000) which were one year later dubbed 'Ultracompact Dwarf Galaxies' (UCDs) by Phillipps et al. (2001). In Figure 1 we show the location of the seven brightest UCDs in the Fornax cluster.

We now know several physical properties of UCDs thanks to significant growth in this research field. After the first discovery of UCDs in the Fornax cluster (summarised in a Nature article by Drinkwater et al. in 2003), many surveys were developed to search for UCDs in different environments and at fainter magnitudes. Bright UCDs were also found in the Virgo cluster, and fainter ones in both clusters. With absolute magnitudes in the range $M_V = -13.5$ to -11.0 they are up to 3 mag brighter than ω Centauri, the most massive globular cluster (GC) of the Milky Way, but about 3 mag fainter than M32. Their sizes are related to their luminosities. Unlike globular clusters which are characterised by a more or less constant size (~ 3 pc half-light radius), the sizes of UCDs increase with luminosity reaching half-light radii of ~ 100 pc. Some of the brighter UCDs exhibit a small low-surface-brightness envelope with extensions up to several hundred parsecs. Most of the brightest UCDs have slightly subsolar metallicities ([Fe/H] ~ -0.5 dex), similar to the 'red', metal-rich bulge GCs of giant galaxies.

In summary, one might say that the name 'ultracompact dwarf galaxies' (UCDs) applies to old stellar systems in the transition region between globular clusters and compact dwarf galaxies.

Formation scenarios for UCDs

An important question that is keeping UCD researchers busy is whether UCDs should be regarded as galaxies or whether they are more closely linked to globular clusters. Various formation scenarios have been suggested that reflect the different viewpoints. The four most promising are:

1. UCDs are the remnant nuclei of galaxies that have been significantly stripped in the cluster environment ('threshing' scenario, e.g. Bekki et al. 2003). Good candidates for isolated nuclei in the local environment are the Galactic globular clusters ω Centauri and the giant star cluster G1 in Andromeda.
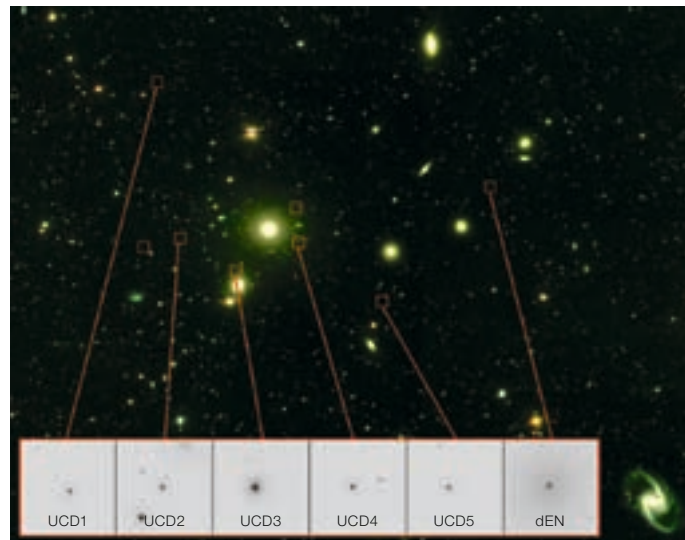

Figure 1: Panoramic view of the Fornax cluster with its population of UCDs. The background image was taken with the Michigan Curtis Schmidt Telescope at the Cerro Tololo Observatory. Insets are HST/STIS images of five UCDs in Fornax and a nucleated dwarf elliptical galaxy in Fornax (far right).

If this formation channel is viable one would not expect a dark matter component in UCDs since 'threshing' simulations show that the dark matter halo of dwarf galaxies is completely stripped within a few Gyrs. In Figure 2 we show a UCD and a nucleated dwarf elliptical in comparison. Both are located in the very heart of the Fornax cluster.

2. UCDs were formed from the agglomeration of many young, massive star clusters that were created during merger events (e.g. Fellhauer and Kroupa 2002). Such super-star cluster complexes are observed in interacting galaxies like the Antennae. In this formation process no dark matter would be involved.

3. UCDs are the brightest globular clusters and were formed in the same GC formation event as their less massive counterparts (e.g. Mieske et al. 2004). The most massive GCs then supposedly formed from the most massive molecular clouds (MCs) of their host galaxy. The luminosity-size relation of the most massive clusters suggests that there is a break of the formation/collapse physics at a critical MC mass. Also in this case no dark matter in UCDs is expected.

4. UCDs are genuine compact dwarf galaxies, formed in small dark-matter halos at the low mass end of cosmological substructure. This scenario has the advantage that no external processes, like mergers or tidal disruption, are needed. A considerable dark-matter component is expected if this formation channel applies.

How can a massive *star cluster* be discerned from a low-mass compact *galaxy*? The answer may be hidden in the seen and unseen mass of UCDs. Dwarf galaxies are expected to be dark matter dominated, globular clusters are not. Thus, the best way to distinguish between these two possibilities is to measure the masses of UCDs. In order to do so we need to measure the motion of stars within UCDs with high-resolution spectroscopy. The faster their motion, the larger the UCD mass. The Ultraviolet and
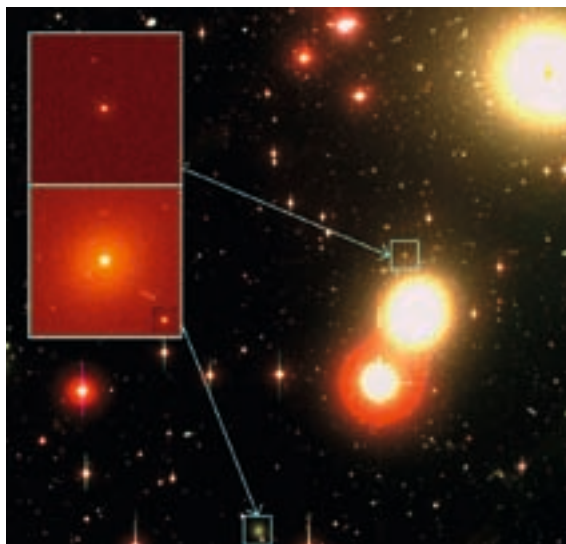
Figure 2: A composite image of the central region of the Fornax cluster based on data acquired at the 2.5-m DuPont telescope at the Las Campanas Observatory. Images in the filters *B*, *V*, *I* and were combined to make the colour composite. The insets show HST/STIS images of a UCD (upper) and a nucleated dwarf elliptical galaxy (lower).

Visual Echelle Spectrograph (UVES) at the VLT is an ideal instrument to solve the UCD riddle.

UVES spectroscopy

High-resolution spectra were obtained for four Fornax UCDs, one nucleus of a dwarf elliptical and several reference stars (mostly red giant stars) in service mode at the VLT in 2000/2001. The integration times were between one and six hours, depending on the brightness of the UCD. For the reduction of the spectra, the UVES pipeline, provided by ESO,

was used with some slight modifications. The spectral resolution of the final, reduced spectra was ~ 8 km s^{-1}. The signal-to-noise ranged between 10 and 20 at 5 900 Å. In Figure 3 we show spectra of the four UCDs and four reference stars in the wavelength region of the Sodium (Na) doublet absorption lines. Such absorption lines are important features to measure the internal velocity dispersion of the UCDs. One can clearly see that UCD absorption lines are broadened with respect to the ones of the reference stars. This broadening is caused by the internal velocity dispersion of stars populating the UCDs.
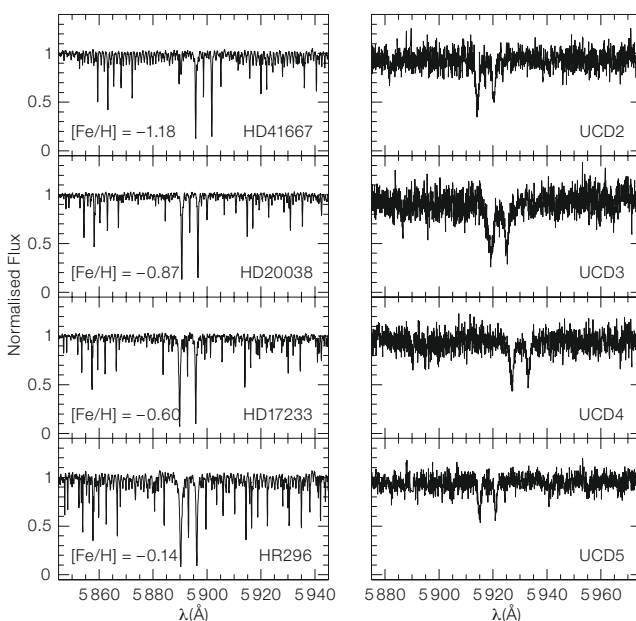
Figure 3: UVES spectra of four standard stars (left) and four UCDs (right) around the wavelength region of the Na doublet.

Internal velocity dispersions

The kinematic analysis of the spectra was performed using a direct-fitting method (van der Marel and Franx 1993). First, the spectra were placed on a logarithmic wavelength scale and normalised. Then, the reference star spectra were convolved with Gaussian velocity dispersion profiles in the range 2 to 60 km s^{-1}. All UCD spectra were fitted with all sets of smoothed 'template' spectra. In this process the template spectra are shifted in wavelength and scaled to match the redshifts and absorption strengths of the UCD spectra. The best-fitting Gaussian velocity dispersion profile is determined by χ^2 minimisation in pixel space. Figure 4 illustrates the fitting method for the brightest UCD in the Na doublet region. The reference spectrum (middle panel) is shifted, broadened and scaled to match the target spectrum (lower panel).

The velocity dispersions of the Fornax UCDs, derived from this method, range between 22 and 30 km s^{-1}, with errors of 1–3 km s^{-1}. These velocity dispersions are larger than those of 'normal' globular clusters (~ 5–15 km s^{-1}).

Mass modelling

As outlined above, the masses and mass-to-light ratios of the UCDs are important physical parameters for understanding their origin. In particular, the mass-to-light ratio (M/L) can be used as an indicator for the presence of dark matter and/or the violation of dynamical equilibrium. If UCDs were the counterparts of globular clusters – thus a single stellar population without significant amounts of dark matter – one would expect M/L values as predicted by standard single stellar population models (e.g. Maraston 2005). If UCDs are of cosmological origin – formed in small, compact dark-matter halos – they might be dominated by dark matter and show a high M/L value. Mass-to-light ratios that are larger than expected from single stellar populations can, however, also be caused by objects that are out of dynamical equilibrium, e.g. tidally disturbed stellar systems.
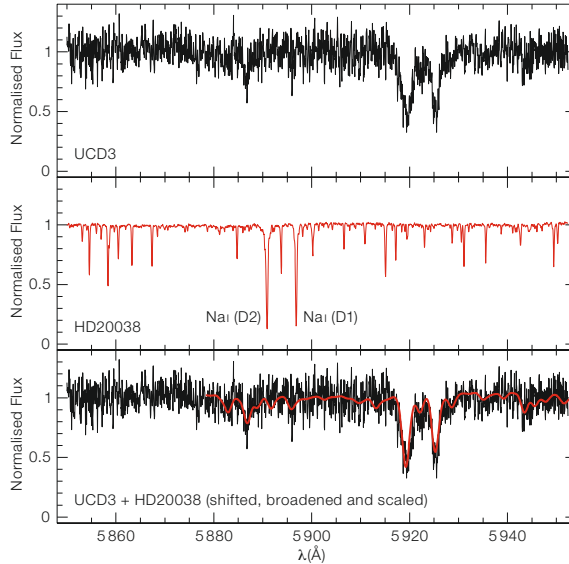
Figure 4: Illustration of velocity dispersion measurement for UCD3.

To derive the masses of the UCDs a new modelling program has been developed that allows to choose between different representations of the surface brightness profile of UCDs (i.e. Nuker, Sersic or King laws) and corrects the observed velocity dispersions for observational parameters (i.e. seeing, slit size). The light-profile parameters of the UCDs were obtained from Hubble Space Telescope imaging (Evstigneeva et al. 2007). In general, King models are good representations of globular cluster light profiles. UCDs, however, are better fitted by Nuker or generalised King laws, especially in the outer parts. Figure 5 illustrates the model output of our program. The three-dimensional density distribution, the cumulative mass distribution and the projected velocity dispersion profile that simultaneously fit the observed velocity dispersion and the light profile of UCD2 are shown.
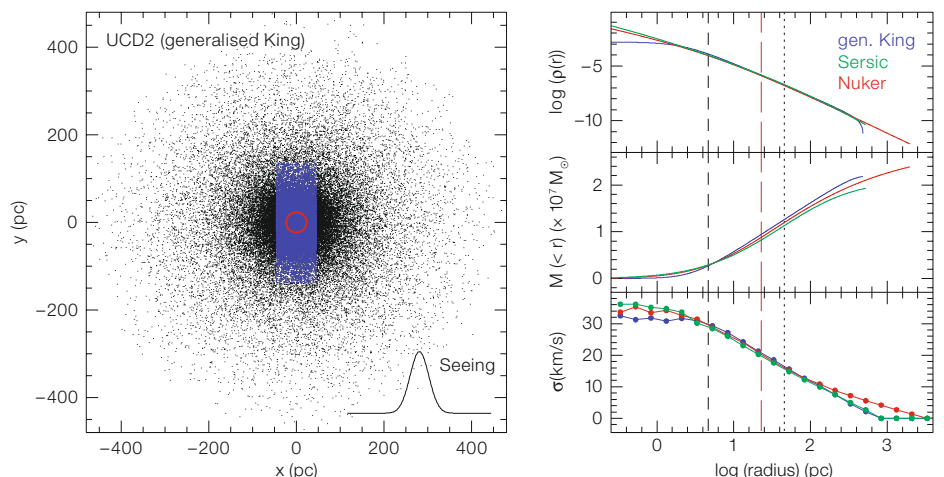
Figure 5: Model output for UCD2. Grey dots represent 100 000 test particles. Blue dots are those 'stars' whose centres fall into the analysed slit area. The red circle (and red dashed line on the right) indicates the projected half-light radius of UCD2. The right panels show, from top to bottom, the three-dimensional density distribution, the cumulative mass distribution and the projected velocity dispersion profile for three different light-profile representations of UCD2. The vertical short dashed line indicates the radius of 1 ACS pixel and the dotted line half the slit width.

The masses of the UCDs derived in this way range between 1.8 and 9.5×10^7 $M_\odot$. For comparison, the mass of the most massive Galactic globular cluster, ω Centauri is $\sim 0.5 \times 10^7$ $M_\odot$. The baryonic mass of Local Group dwarf spheroidals is comparable to that of UCDs.

Dynamical *versus* stellar masses

Knowing the age and the metal content of a stellar population, one can, in principle, predict its total mass. This is the task of stellar population models. A non-trivial ingredient of these models is the initial mass function (IMF) of the stars in the stellar population. The shape of the IMF, i.e. whether there are more or less low-mass stars as compared to high-mass stars, influences the total M/L ratio of a stellar population.

We have compared the derived dynamical masses of UCDs in Fornax to those expected from stellar population models. The dynamical M/L_V of the UCDs range between 3 and 5 $M_\odot/L_{\odot,V}$. In Figure 6 we show these M/L_V values as a function of metallicity [Z/H] and as a function of (V–I) colour (taken from Mieske at al. 2006). Results for the dwarf elliptical nucleus (FCC303) and a fifth UCD in Fornax (Drinkwater et al. 2003) are also shown in this figure. The difference between assuming a Kroupa or Salpeter IMF is that a Salpeter IMF implies that two of five Fornax UCDs would be dominated by intermediate-age populations of $\sim$ 5 Gyr. Using a Kroupa IMF all UCDs are compatible with old, galactic globular cluster-like ages. Figure 6 suggests that the M/L_V values of the UCDs can, in principle, be explained by pure stellar populations. Dark matter is not mandatory for any of the objects. This conclusion, however, applies to the central region, where we have the data covered by our spectroscopic observations (within 1–3 half-mass radii). It cannot be ruled out that UCDs are dominated by dark matter at large radii where high signal-to-noise spectra cannot easily be obtained due to the very low surface brightness. Also, high-quality (high signal-to-noise) spectroscopic data are needed to better constrain the Fornax UCD metallicities and to deter-
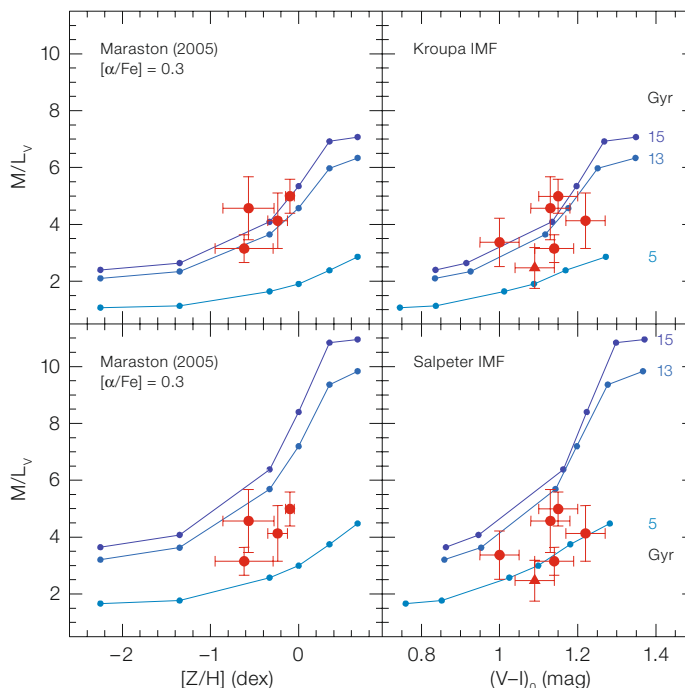

Figure 6: Dynamical M/L_V ratios of Fornax UCDs (red circles) and the nucleus of FCC303 (red triangle) are compared to expected M/L_V values from stellar population models of various ages (blue lines). On the left, M/L_V is plotted versus metallicity [Z/H], on the right versus the colour $(V-I)_0$. The adopted IMFs are indicated in the right panels.

mine their ages and abundances for a reliable comparison with stellar population models.

We conclude that ultracompact dwarf galaxies are most probably the result of star cluster formation processes within galaxies – i.e. large globular clusters, assembled star cluster complexes, nuclear star clusters – rather than being genuine cosmological substructures themselves – i.e. compact galaxies formed in small, compact dark-matter halos. No dark-matter component is needed for UCDs within 1–3 half-mass radii.

Future prospects

While we have good ideas about the possible origin of UCDs, there are many questions left to answer concerning their nature. Some important ones include: Do UCDs have multiple stellar populations?

What is the chemical abundance pattern of UCDs? What is their luminosity weighted age? Why do some UCDs have quite high M/L ratios? Is this due to tidal disturbances? Or do they contain dark matter? Do UCDs harbour black holes?

Some of these questions will be answered in the next years with the help of ongoing and future observing programmes (in particular with the VLT).

References

Bekki K. et al. 2003, MNRAS 344, 399
Drinkwater M. J. et al. 2003, Nature 423, 519
Evstigneeva E. A. et al. 2007, AJ 133, 1722
Fellhauer M. and Kroupa P. 2006, MNRAS 367, 1577
Hilker M. et al. 2007, A&A 463, 119
Hilker M. et al. 1999, A&AS 134, 75
Maraston C. 2005, MNRAS 362, 799
Mieske S., Hilker M. and Infante L. 2004, A&A 418, 445
Mieske S. et al. 2006, AJ 131, 2442
Phillipps S. et al. 2001, ApJ 560, 201
van der Marel R. P. and Franx M. 1993, ApJ 407, 525