Stellar Population Constraints on the Dark Matter Content and Origin of Ultra-Compact Dwarf Galaxies

Igor V. Chilingarian\textsuperscript{1,2}†, Véronique Cayatte\textsuperscript{3} and Gilles Bergond\textsuperscript{4}

\textsuperscript{1}Observatoire de Paris-Meudon, LERMA, UMR 8112, 61 Av. de l’Observatoire, 75014 Paris, France
\textsuperscript{2}Sternberg Astronomical Institute, Moscow State University, 13 Universitetskii prospect, 119992, Moscow, Russia
\textsuperscript{3}Observatoire de Paris-Meudon, LUTH, UMR 8105, 5 pl. Jules Janssen, 92195 Meudon, France
\textsuperscript{4}Instituto de Astrofísica de Andalucía (IAA/CSIC), Camino de Huetor 10, 18008 Granada, España

Accepted 2008 August 4. Received 2008 June 23; in original form 2008 May 16

ABSTRACT
We analyse intermediate-resolution VLT FLAMES/Giraffe spectra of six ultra-compact dwarf (UCD) galaxies in the Fornax cluster. We obtained velocity dispersions and stellar population properties by full spectral fitting against \textit{pegase.hr} models. Objects span a large range of metallicities (–0.95 to –0.23 dex), 4 of them are older than 8 Gyr. Comparison of the stellar and dynamical masses suggests that UCDs have little dark matter at best. For one object, UCD3, the Salpeter initial mass function (IMF) results in the stellar mass significantly exceeding the dynamical one, whereas for the Kroupa IMF the values coincide. Although, this object may have peculiar dynamics or/and stellar populations, the Kroupa IMF seems more realistic. We find that UCDs lie well above the metallicity–luminosity relation of early-type galaxies. The same behaviour is demonstrated by some of the massive Milky Way globular clusters, known to contain composite stellar populations. Our results support two following UCD formation scenarios: (1) tidal stripping of nucleated dwarf elliptical galaxies; (2) formation of tidal superclusters in galaxy mergers. We also discuss some of the alternative channels of the UCD formation binding them to globular clusters.

Key words: galaxies: dwarf – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: stellar content – galaxies: kinematics and dynamics

1 INTRODUCTION
A new class of compact dwarf galaxies, called UCDs, was discovered a decade ago in the Fornax cluster \cite{hil99,drinking2000,phil2001}. These objects, being brighter and much larger than globular clusters (GCs), but still far below luminosities and sizes of both dwarf elliptical (dE) and compact elliptical (cE) galaxies, fill an empty region on the Fundamental Plane \cite{diorgovski1987}. Their origin still remains a matter of debate; several alternatives are considered: (1) UCDs are the result of the evolution of primordial density fluctuations \cite{phil2001}; (2) they have been formed through mergers of GCs or simply represent the extreme high-luminosity end of the GC luminosity function \cite{mieske2002}; (3) UCDs are nuclei of tidally stripped (“threshed”) nucleated dE (dE,N) galaxies \cite{balk2003} or dE,Ns with very low surface brightness; (4) UCDs are created as tidal superclusters during major mergers of galaxies \cite{fell2003,kisslerpatig2000}.

Mass-to-light ratios of UCDs vary quite significantly \cite{drinking2000,haseg2001,hil2004}, suggesting the presence of dark matter in some of them. \cite{haseg2001} propose to use M/L ratio (i.e. presence of dark matter) as a criterion to distinguish between “UCD galaxies” and massive GCs. Developing this idea, we conclude that the presence of dark matter in a compact stellar system rejects two formation scenarios – in this case UCDs cannot be GCs neither they can be created as tidal superclusters during galaxy mergers. On the other hand, if the stellar population is not old and metal-poor, the primordial density fluctuation scenario will become implausible, leaving the only channel of UCD formation to be the tidal stripping of dE,Ns.

Stellar population analysis may also help to choose the formation scenario. Presently published data \cite{mieske2004,exten2007} based on the analysis of absorption line strengths (Lick indices, \cite{worth1994}) suggest that UCDs are old and rather metal-poor.
Table 1. Final sample of UCDs and dEs. (2) and (3) give identification according to Bergond et al. (2007) and Evstigneeva et al. (2007), (4)-(7) provide the number of individual exposures and the total exposure times (seconds) in the two observational programmes (B and D indices are for Bergond et al. and Drinkwater et al.), (8) lists approximate signal-to-noise ratio per pixel at $\lambda = 5300$ Å for the combined spectra.

| n | IDB   | IDE   | nB  | tB, s | nD  | tD, s | S/N |
|---|-------|-------|-----|-------|-----|-------|-----|
| 1 | ucd257.5 | UCD1  | 3   | 10200 | 3   | 7200  | 19  |
| 2 | ucdA   | UCD2  | 3   | 10200 | -   | -     | 9   |
| 3 | UCD3   | -     | -   | 6600  | 15  |
| 4 | ucdB   | UCD4  | 2   | 7200  | 3   | 6600  | 13  |
| 5 | UCD5   | -     | -   | 6000  | 9   |
| 6 | ucd329.7 | -     | 11200 | -     | -   | 15  |
| 7 | FCC182 | 3     | 10200 | -   | -   | 40  |
| 8 | FCC266 | 3     | 9704  | -   | -   | 17  |

In this paper, we present stellar population parameters for 6 Fornax cluster UCDs, compare them with dE,N nuclei, and derive stellar masses to check for the presence of dark matter assuming different stellar IMFs.

2 DATA: SOURCES, REDUCTION, ANALYSIS

We have used the data obtained in the courses of two independent studies of compact stellar systems in the Fornax cluster by G. Bergond et al. (program 074.A-0756) and M. Drinkwater et al. (program 074.A-0508). Both datasets are publicly available through the ESO Data Archive. The data have been obtained with the ESO Very Large Telescope using the FLAMES/Giraffe spectrograph in the multi-object “MEDUSA” mode (130 fibres in a 25 arcmin circular field of view), in the LR04 setup giving a resolving power $R \approx 6300$ in the wavelength range 5010–5831 Å (dispersion 0.2 Å pix$^{-1}$, $\sigma_{\text{inst}} \approx 18$ km s$^{-1}$), and reduced in exactly the same way as the data for the Abell 496 cluster as described in Chilingarian et al. (2008). The 1.2 arcsec-wide FLAMES/Giraffe fibres corresponding to a spatial size of about 110 pc at the Fornax distance (19 Mpc), are significantly larger than the typical effective radii of UCDs in the Fornax cluster. Therefore, our stellar population and velocity dispersion measurements referenced below should be considered as global values (however, see discussion about aperture corrections in Mieske et al. 2008).

Observations of the central part of the Fornax cluster produced about 900 individual spectra (see details on observations in Bergond et al. 2007 and Firth et al. 2007). We inspected them visually to identify those having reasonable signal-to-noise ratios and also to take out background galaxies; spectra of the objects common to the two studies have been co-added.

We ended up with a list including about 40 spectra of foreground Milky Way stars and members of the Fornax cluster of different nature: GCs, UCDs, dE and non-dwarf galaxies. In this paper we analyse six UCDs and two dE,N nuclei (FCC 182 and FCC 266), while the brightest GCs and other Fornax cluster members will be presented in detail in the forthcoming paper. Our sample is presented in Table 1.

We have fit the high-resolution PEGASE.HR (Le Borgne et al. 2004) simple stellar population (SSP) models against the observational data using the NBURSTS full spectral fitting technique (Chilingarian et al. 2007b). The fitting algorithm works as follows: (1) a grid of SSP spectra with a fixed set of ages (nearly logarithmically spaced from 20 Myr to 18 Gyr) and metallicities (from $-2.0$ to $+0.5$ dex) is convolved with the instrumental response of FLAMES/Giraffe as explained in Section 4.1 of Chilingarian et al. (2007b), (2) a non-linear least square fitting against an observed spectrum is done for a template picked up from the pre-convolved SSP grid using 2D-spline interpolation on log $t$ and $Z$, broadened according to the line-of-sight velocity distribution (LOSVD) parametrised by $v$ and $\sigma$ and multiplied pixel-by-pixel by the $n^{\text{th}}$ order Legendre polynomial, resulting in $n + 5$ parameters determined by the non-linear fitting. For the spectra presented in this paper we used the pure Gaussian representation of the LOSVD and did not fit the $h_3$ and $h_4$ coefficients of the Gauss-Hermite LOSVD parametrisation (van der Marel & Franx 1993) often used to perform the dynamical modelling of galaxies due to low signal-to-noise ratio and insufficient sampling of the LOSVD.

The procedure and input parameters of the fitting (15th order multiplicative continuum, etc.) were exactly the same as ones applied to the sample of Abell 496 low-luminosity early-type galaxies (Chilingarian et al. 2008), thus we refer to that paper for all details concerning the spectral fitting. The only difference introduced here is that we use SSP models computed for two different stellar IMFs: Salpeter (1955) and Kroupa et al. (1993). We use the two grids of template spectra (Salpeter and Kroupa SSPs hereafter) in a completely independent way and provide comparison of the results obtained.

The key to the precise determination of low velocity dispersions from absorption-line spectra is the knowledge of the instrumental resolution as a function of wavelength and fibre number. We found that fibre-to-fibre variations in the “MEDUSA” mode of FLAMES/Giraffe are negligible, while wavelength dependence has to be taken into account.

We performed Monte-Carlo simulations aimed at studying the precision of kinematical and stellar population parameters determined by our spectral fitting technique for objects having very low intrinsic velocity dispersions, close to or smaller than the instrumental resolution of the spectrograph. We used two PEGASE.HR SSP models for the age of 10 Gyr and [Fe/H] = $-1.0$ and $-0.3$ dex, and broadened them using the wavelength-dependent information about the spectral line spread of FLAMES/Giraffe in the LR04 setup. Then we generated sets of mock data (20 realisations for every parameter set) for signal-to-noise ratios of 5, 10, 20, and 30 and internal velocity dispersions of 6, 8, 10, 15, and 20 km s$^{-1}$, resulting in 800 mock spectra, which then were fit using the NBURSTS code. The results are presented in Fig. 1.

Our simulations clearly demonstrate that: (1) FLAMES/Giraffe-LR04 is sufficient to measure internal velocity dispersion down to 8–10 km s$^{-1}$ at a signal-to-noise ratio of 20 with a precision of 10–15 per cent even for metal-poor ([Fe/H] = $-1.0$) objects; (2) for metal-rich ([Fe/H] = $-0.3$) objects we reach twice higher precision of internal velocity dispersion measurements compared...
metallicity and radial velocity determinations returned by metal-poor ones. We notice that uncertainties of age, radial velocities, velocity dispersions, SSP-equivalent ages and metallicities, and least square fitting are consistent with the results of the least square fitting are consistent with the results of the Monte-Carlo simulations.

3 RESULTS

In Table 2 we present the values of the (heliocentric) radial velocities, velocity dispersions, SSP-equivalent ages and metallicities, and B-band stellar mass-to-light ratios for six UCD galaxies and two dE,N nuclei computed for the two IMFs mentioned above. We compare our results with the literature for some of the objects. Absolute magnitudes for UCD 1 to 5 are taken from Evstigneeva et al. (2006) and converted into the B band, for ucd329.7 values are from Bergond et al. (in prep.), and for FCC 182 and FCC 266 from Karick et al. (2003). Velocity dispersion values (σV) for UCD 1 to 5 are “adopted global velocity dispersions” from Table 6 of Hilker et al. (2007); metallicities [Fe/H]lit for UCD 2, 3, and 4 are from Mieske et al. (2006).

In Fig. 3 the discussed spectra are displayed together with their best-fitting PEGASE.HR SSPs. Inner panels show confidence levels of the age and metallicity determinations for the Kroupa et al. (1993) IMF.

The velocity dispersions for 5 of the 6 UCDs are between 23 and 30 km s⁻¹, which is higher than typical values for GCs (e.g. Evstigneeva et al. 2007).

One notices an excellent agreement of our velocity dispersion measurements for the five UCDs (UCD1–5) and global velocity dispersions from Hilker et al. (2007) obtained using completely different instrumentation (VLT UVES, Keck ESI for UCD1) and data analysis technique.

Stellar populations of UCD1, UCD3, UCD4 and ucd329.7 are older than 8 Gyr and exhibit metallicities between −0.67 and −0.23 dex. UCD2 has intermediate age and quite metal-rich stellar population, although with large uncertainties. Our estimates of metallicities for UCD3, and UCD4 are somewhat (0.2–0.25) higher than values reported by Mieske et al. (2006), but the discrepancy is even larger (≈0.65 dex) for UCD2.

The UCD5 spectrum does not contain strong absorption lines in the FLAMES/Giraffe LR04 spectral range, the Mg b triplet is strongly contaminated by a cosmic ray hit. This causes very vague stellar population parameter determination: 3 σ confidence contour remains open in the age direction, i.e. age is undetermined. The global χ² minimum corresponds to a young population (t = 1.2 Gyr, [Fe/H] = −0.49 dex). There is a 1.7σ confidence secondary minimum (t = 3.9 Gyr, [Fe/H] = −0.95 dex). In order to chose between the two possible solutions for UCD5 we have reduced and fit its FLAMES/Giraffe spectra obtained in the blue LR02 setup with the wavelength coverage between 3970 Å and 4545 Å. Quite low efficiency of the spectrograph in this setup is well compensated by the blue colour of the object and the presence of very strong age- and metallicity-sensitive absorption lines (Ca I “H”, G-band, Hγ). The fitting of the LR02 data results in the stellar population parameters compatible with the secondary minimum of the LR04 setup, therefore we adopt the secondary LR04 solution, corresponding to the metal-poor intermediate age population through the rest of the paper.

Fitting with the Kroupa SSPs results in slightly older ages for intermediate and old stellar populations, whereas the metallicities and velocity dispersions remain intact. Mass-to-light ratios are 40–50 per cent lower compared to the Salpeter IMF. This effect is easy to understand keeping in mind that stellar populations with the Salpeter IMF contain larger amount of faint red dwarf stars, weakly contributing to the total light, but increasing the total mass. Therefore, Kroupa IMF-based SSPs having older ages are required to fit “red” spectra.

4 DISCUSSION

4.1 Comparison of Stellar and Dynamical Masses

Given the stellar population parameters and luminosities, we derive stellar masses of UCDs in our sample. The stellar mass estimates, computed from the mass-to-light ratios provided by PEGASE.2 (Fioc & Rocca-Volmerange 1997) for Salpeter and Kroupa et al. IMFs are given in Table 3. In the fourth column we provide the corrected dynamical masses, derived by re-normalising the values of Hilker et al. (2007) by our velocity dispersion measurements (Md,corr = Md(σ/σcorr)²). The fifth and sixth column contain the dark matter fractions estimated from Salpeter and Kroupa SSPs and corrected dynamical masses.

For UCD1, 2, 4, and 5 the Salpeter SSP stellar masses are consistent with the dynamical ones within uncertainties, although in average the stellar masses tend to be lower. The Kroupa et al. IMF decreases them more resulting in a 40–50 per cent lower compared to the Salpeter IMF. This effect is easy to understand keeping in mind that stellar populations with the Salpeter IMF contain larger amount of faint red dwarf stars, weakly contributing to the total light, but increasing the total mass. Therefore, Kroupa IMF-based SSPs having older ages are required to fit “red” spectra.

There is a possibility that the dynamical model of UCD3 used by Hilker et al. (2007) was not correct (for example, (1) the outer component of the UCD3 is not spherically symmetric or (2) there is significant rotation not taken into account, or (3) velocity dispersions are anisotropic).
Table 2. Internal kinematics, stellar populations and stellar $B$-band mass-to-light ratios of 6 UCDs and 2 dEs ($n = 7, 8$) in the Fornax cluster. Columns (5)–(7) and (8)–(10) are for SSP models computed with Salpeter and Kroupa et al. (2003) IMF, respectively.

| n | $M_B$ mag | $\nu_{hel}$ km s$^{-1}$ | $\sigma$ km s$^{-1}$ | $t_{Salp}$ Gyr | $\frac{[Fe/H]}{S}$ | $(M/L)_B$ Salpeter Gyr | $\frac{[Fe/H]}{K}$ | $(M/L)_B$ Kroupa Gyr | $\sigma_{lit}$ km s$^{-1}$ | $\frac{[Fe/H]}{lit}$ dex |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | -11.39 | 1557±1 | 29±1 | 9.1±2.4 | -0.46±0.04 | 5.2±1.3 | 13.1±3.1 | -0.51±0.07 | 3.8±0.9 | 27±2 |
| 2 | -11.47 | 1230±1 | 23±2 | 5.0±1.7 | -0.24±0.07 | 3.8±1.3 | 5.0±1.9 | -0.23±0.08 | 2.3±0.8 | 22±2 |
| 3 | -12.77 | 1500±1 | 26±1 | 13.0±2.5 | -0.23±0.05 | 8.6±1.5 | 17.6±2.7 | -0.22±0.05 | 6.3±1.1 | 23±3 |
| 4 | -11.65 | 1889±1 | 26±1 | 8.1±2.4 | -0.67±0.06 | 4.0±1.1 | 9.9±3.7 | -0.68±0.07 | 2.6±0.9 | 25±3 |
| 5 | -11.19 | 1280±2 | 16±3 | 3.9±0.9 | -0.95±0.04 | 1.8±0.4 | 3.9±0.9 | -0.93±0.04 | 1.1±0.3 | 19±3 |
| 6 | -10.78 | 1379±1 | 28±1 | 11.2±2.4 | -0.30±0.04 | 7.1±1.4 | 14.0±4.0 | -0.33±0.08 | 4.8±1.3 |  |
| 7 | -16.50 | 1700±1 | 38±1 | 6.8±0.5 | -0.10±0.02 | 5.6±0.5 | 8.0±0.7 | -0.13±0.01 | 3.6±0.2 |  |
| 8 | -15.40 | 1551±1 | 19±1 | 1.8±0.3 | -0.24±0.02 | 1.4±0.3 | 2.4±0.4 | -0.30±0.02 | 1.2±0.2 | 22±7 | -0.47 |

1 Central $\sigma$ given by S. De Rijcke (priv. comm.) is lower than the global value ($44$ km s$^{-1}$) from De Rijcke et al. (2005).

2 Metallicity estimation from the full spectral fitting of the VLT FORS1 spectrum (Michielsen et al. 2007).

Figure 2. FLAMES/Giraffe spectra, their best-fitting templates (Kroupa IMF), fitting residuals and confidence levels of the age and metallicity determinations (inner panels) for 6 UCDs and 2 dE,Ns. All graphs are smoothed with the 7 pixel wide box-car for presentation purposes.

which may lead to an underestimated dynamical mass. At the same time, we cannot exclude that SSP models do not represent well the spectrum (e.g. the object contains a metal-rich sub-population, which is not properly modeled). In this case the stellar mass may be overestimated.

Given the large uncertainties of stellar population parameters and, consequently, stellar mass-to-light ratios, we cannot give a decisive answer on a question “Is there dark matter in UCDs?” However, the main conclusion we draw is that UCDs are not dark matter dominated objects and at
Table 3. Comparison of stellar masses of 6 UCDs for Salpeter (2) and Kroupa (3) IMFs; and the dynamical masses for 5 objects (5) from Hilker et al. (2007) corrected using our velocity dispersion estimations, (6)–(7) the dark matter content (per cent) for the Salpeter and Kroupa et al. IMF.

| n  | \( M_{\star, \text{Salp}} \) \( 10^7 M_\odot \) | \( M_{\star, \text{Kroupa}} \) \( 10^7 M_\odot \) | \( M_{\text{d, corr}} \) \( 10^7 M_\odot \) | DM, \% | DMK, \% |
|----|---------------------------------|---------------------------------|---------------------------------|------|------|
| 1  | 2.9±0.7                         | 2.1±0.5                         | 3.7±0.5                         | 20   | 45   |
| 2  | 2.3±0.8                         | 1.4±0.5                         | 2.4±0.3                         | 0    | 40   |
| 3  | 17.5±3.0                        | 12.8±2.2                        | 12.0±2.4                        | -45  | 0    |
| 4  | 2.9±0.8                         | 1.9±0.6                         | 4.0±1.0                         | 30   | 50   |
| 5  | 0.9±0.2                         | 0.5±0.1                         | 1.4±0.5                         | 35   | 65   |
| 6  | 2.3±0.4                         | 1.6±0.4                         |                                  |      |      |

present level of detection, the dark matter content can be explained by uncertainties of the measurements and looseness of the models used to derive dynamical and stellar masses.

4.2 Metallicity-\(M_B\) and metallicity-\(\sigma\) relations

In Fig. 3 we plot metallicities versus velocity dispersions and luminosities of the 6 Fornax cluster UCDs and 2 dE,N nuclei from our sample. They are compared to: (a) Milky Way GCs from McLaughlin & van der Marel (2005), outlined crosses show GCs with direct evidences of multiple stellar populations revealed by the analysis of colour-magnitude diagrams (Piotto 2008); (b) Local Group dEs and dwarf spheroidals (dSph) from Mateo (1998); (c) Abell 496 low-luminosity early-type galaxies from Chilingarian & Mamoun 2008; (d) a sample of intermediate-luminosity and bright early-type galaxies from Sanchez-Blazquez et al. 2005; (e) two compact stellar systems in the Virgo cluster with the spectra available in SDSS DR6 (Adelman-McCarthy et al. 2008): transitional UCD/cE “M59cO” (Chilingarian & Mamoun 2008) and VUCD 7, where the data have been processed exactly in the same way as for M59cO. The aperture size for the Abell 496 dE/dS0 is around 0.8 kpc, so the dE nuclei do not dominate the light, therefore metallicities and velocity dispersions should be closer to the global than to the central values, given flat velocity dispersion profiles usually observed in dEs (Simien & Prugniel 2002; Geha et al. 2003; van Zee et al. 2004).

In the metallicity-luminosity relation (Fig. 3, bottom panel) there is a continuous sequence \(Z \propto L_B^{0.45}\), spanning over 6 orders of magnitude in luminosity, formed by early-type galaxies: from the faintest dSph on the left to the brightest cluster ellipticals on the right. UCD galaxies lie significantly above (0.7–1.0 dex) this sequence, compared to the brightest Local Volume dSph’s, having similar luminosities (see Mateo 1998 and references therein). In this sense, UCDs are similar to cE galaxies (e.g. Chilingarian et al. 2007a) having high metallicities for their luminosities, which probably represent end-products of the galaxy tidal threshing (Bekki et al. 2001).

At the same time, on the metallicity-velocity dispersion plot (Fig. 3, top panel) the loci of UCDs practically coincide with those of dEs. We consider this as an argument for the scenario of tidal threshing of dEs as a way to create UCDs. In this case, a velocity dispersion of a compact nucleus will not change very strongly, while the total luminosity of a progenitor will drop by several magnitudes.

For comparison with massive GCs (McLaughlin & van der Marel 2003) we chose a subsample of Galactic GCs with available measurements of velocity dispersions. Many GCs follow the behaviour of early-type galaxies. The three strongest outliers, namely NGC 104, NGC 6388, and NGC 6441, similarly to UCDs, reside significantly above the sequence of early-type galaxies on the metallicity – luminosity plot (Fig 3). It is remarkable that the latter two exhibit direct evidences of multiple stellar populations (Piotto 2008). Among the three other GCs (NGC 1851, NGC 2808, \(\omega\) Cen) demonstrating composite stellar populations only \(\omega\) Cen follows exactly the trend defined by early-type galaxies. We notice, that the third strongest outlier, 47 Tuc (NGC 104), being at least as massive as NGC 6388 does not have an evident double main sequence (Piotto 2008).
Figure 4. Comparison of ages and metallicities of UCDs with a sample of Virgo cluster dE,N galaxies from SDSS.

In the frame of the tidal stripping scenario, we can also propose an explanation for the large spread of UCD metallicities (−0.25 to −0.93) on the [Fe/H] vs. σ plot. It may be a superposition of the two factors: (1) the relatively high spread of metallicities of dE progenitors of UCDs due to their own environmentally-driven evolution (see discussion in Chilingarian et al. 2008); (2) different conditions during the tidal stripping, which may lead to some changes of the velocity dispersion values compared to the progenitors.

4.3 Comparison of dE,N nuclei and UCDs

In Fig. 4 we compare ages and metallicities of the 6 Fornax cluster UCDs with nuclei of dE,Ns in the Fornax (2 objects, this study) and Virgo (26 objects) clusters, transitional dE/UCD object M59cO (Chilingarian & Mamon 2008) and VUCD7, another UCD in the Virgo cluster. Stellar population parameters for 22 Virgo cluster galaxies (shown in red), as well as for VUCD7 and M59cO are obtained by analysing SDSS DR6 spectra. For the four remaining Virgo dE,Ns shown in blue we used the results based on the 3D spectroscopic observations presented in Chilingarian et al. (2007b,c): diamonds with error-bars correspond to the ages and metallicities of the nuclei and the blue vectors point to the parameters of the “main bodies” of the galaxies.

Apart from the 2 intermediate age objects (UCD4 and UCD5), all UCDs are old, at the same time spanning a large range of metallicities. Most of the dE,Ns exhibit considerably younger stellar populations than UCDs. However, there is a number of old dE,N nuclei (including FCC 182) with ages comparable to those of UCDs. A scenario, assuming that dE,N nuclei are results of repeated or extended star formation episodes in the dE centres, leading to metal enrichment, can explain the observed quite high metallicities of dE,N nuclei.

4.4 Origin of UCD galaxies

The stellar population parameters obtained by our SSP fitting, namely metallicities higher than −1.0 dex, allow us to exclude the scenario of evolving primordial density fluctuations [Phillips et al. 2001], because one would expect much lower metallicities for objects at this mass range.

Low dark matter content leaves space for all remaining channels of the UCD formation. Bekki et al. (2003) showed that in case of dE stripping (“threshing”) the progenitor’s nucleus must not be dark matter dominated; the two other alternatives, GC merging and formation of UCDs as tidal superclusters, assume zero dark matter content.

However, the scenario of merging GCs (Mieske et al. 2002) fails to explain why we do not observe metal-poor UCDs. It is known that GCs exhibit a dichotomy in the metallicity distribution (e.g. review by Brodie & Strader 2006), but observed UCDs correspond only to metal-rich GCs. Why don’t metal-poor GCs merge? Moreover, in case of a merger of metal-poor and metal-rich GCs of the same mass, the resulting luminosity-weighted metallicity in our wavelength range will be lower than the mean value, because metal-poor stellar populations have lower M/L ratios than metal-rich ones. Composite stellar populations observed in massive Galactic GCs (Piotto 2008) comprise two to four SSPs, sometimes significantly different in metallicities, which is evident from deep colour-magnitude diagrams. These objects look good candidates for the GC merger scenario. In addition, we do see metal-poor “composite” GCs (NGC 1851, NGC 2808, ω Cen). Indeed, they are an order of magnitude (except ω Cen, where at least four SSPs are evident) fainter than the UCDs we are discussing here.

On the statistical basis, UCDs are too frequent to be representatives of the high-luminosity end of the GC luminosity function (GCLF). After the initial discussion in Mieske et al. (2002) a significant number of UCDs was discovered. The extrapolation of the GCLF (see e.g. Miller & Lotz 2007) towards bright objects results in the statistical over-population of \( M_V < -11 \) objects. Although, the exact value depends on the adopted GCLF parameters and representation (i.e. Gaussian or \( t_0 \)), we consider this fact important, making this channel of UCD formation scarcely probable.

The old ages of most UCDs, compared to dE,N nuclei, suggest that if we consider the dE,N tidal stripping scenario, it must have happened a long time ago. However, there is a difficulty in explaining the formation of the most metal-rich UCDs, because 8−10 Gyr ago dE,N nuclei must have been less metal rich than presently observed. A possible explanation is a tidal stripping of the most massive dE representatives (dE/E transitional objects) such as IC 3653 or FCC 182.

Another possibility is to create them as stellar superclusters (Fallhauer & Kouzma 2005) during interactions of massive galaxies, in this case metal-rich population formed from the metal-rich gas of the progenitors will be observed in the UCDs. Both scenarios are compatible with low dark matter content. A possible diagnosis is to measure \( \alpha/Fe \) abundance ratios: populations formed in a short and intense star formation episode will be \( \alpha \)-overabundant (e.g. Matteucci 1994). With the present low S/N UCD data we are not able to carry out this test.

Finally, we are left with the two alternatives of UCD formation: UCDs with low metallicities ([Fe/H] < −0.5 dex) are in favour of dE,N tidal stripping, while tidally created superclusters better explain metal-rich UCDs. At present we...
cannot exclude the diversity of the UCD origin suggested by Mieske et al. (2006).

ACKNOWLEDGMENTS

We thank participants of the “Nuclear Star Clusters Across the Hubble Sequence” workshop for fruitful discussions of the preliminary results, S. Mieske for useful advices and discussions of UCD origin, our anonymous referee for valuable comments, P. Di Matteo for providing a link to the presentation of G. Piotto. Special thanks to Gary Mamon for the critical reading of the manuscript. GB is supported at the IAA/CSIC by an I3P contract (I3P-PC2005-F) funded by the European Social Fund, with additional support by DGI grant AYA 2005-07516-C02-01 and the Junta de Andalucía.

REFERENCES

Adelman-McCarthy J. K. et al., 2008, ApJS, 175, 297
Brodie J., Strader J., 2006, ARA&A, 44, 193
Bekki K., Couch W., Drinkwater M., 2001, ApJ, 552, L105
Bekki K., Couch W. J., Drinkwater M. J., Shioya Y., 2003, MNRAS, 344, 399
Bergond G. et al., 2007, A&A, 464, L21
Chilingarian I., Cayatte V., Chemin L., Durret F., Laganá T. F., Adami C., Slezak E., 2007a, A&A, 466, L21
Chilingarian I., Cayatte V., Durret F., Adami C., Balkowski C., Chemin L., Laganá T. F., Prugniel P., 2008, A&A, 486, 85
Chilingarian I., Prugniel P., Sil’chenko O., Koleva M., 2007a, in Vazdekis A., R. Peletier R., eds, proc. of IAU Symposium 241, Cambridge University Press, Cambridge, UK, p.175
Chilingarian I. V., Mamom G. A., 2008, MNRAS, 385, L83
Chilingarian I. V., Prugniel P., Sil’chenko O. K., Afanasiev V. L., 2007b, MNRAS, 376, 1033
Chilingarian I. V., Sil’chenko O. K., Afanasiev V. L., Prugniel P., 2007c, Astronomy Letters, 33, 292
De Rijcke S., Michielsen D., Dejonghe H., Zeilinger W. W., Hau G. K. T., 2005, A&A, 438, 491
Djorgovski S., Davis M., 1987, ApJ, 313, 59
Drinkwater M., Gregg M., Hilker M., Bekki K., Couch W., Ferguson H., Jones J., Phillipps S., 2003, Nature, 423, 519
Drinkwater M. J. et al., 2000, A&A, 355, 900
Evstigneeva E. A., Gregg M. D., Drinkwater M. J., Hilker M., 2007, AJ, 133, 1722
Fellhauer M., Kroupa P., 2005, MNRAS, 359, 223
Fioc M., Rocca-Volmerange B., 1997, A&A, 326, 950
Firth P., Drinkwater M., Evstigneeva E., Gregg M., Karick A., Jones J., Phillipps S., 2007, MNRAS, 382, 1342
Geha M., Guhathakurta P., van der Marel R. P., 2003, AJ, 126, 1794
Ha¸segan M. et al., 2005, ApJ, 627, 203
Hilker M., Baumgardt H., Infante L., Drinkwater M., Evstigneeva E., Gregg M., 2007, A&A, 463, 119
Hilker M., Infante L., Vieira G., Kissler-Patig M., Richtler T., 1999, A&S, 134, 75
Karick A., Drinkwater M., Gregg M., 2003, MNRAS, 344, 188
Kissler-Patig M., Jordán A., Bastian N., 2006, A&A, 448, 1031
Kroupa P., Tout C., Gilmore G., 1993, MNRAS, 262, 545
Mateo M. L., 1998, ARA&A, 36, 435
Matteucci F., 1994, A&A, 288, 57
McLaughlin D. E., van der Marel R. P., 2005, ApJS, 161, 304
Michielsen D. et al., 2007, ApJ, 670, L101
Mieske S., Hilker M., Infante L., 2002, A&A, 383, 823
Mieske S., Hilker M., Infante L., Jordán A., 2006, AJ, 131, 2442
Mieske S. et al., 2008, accepted to A&A, arXiv:0806.0374
Miller B., Lotz J., 2007, ApJ, 670, 1074
Pasquini L. et al., 2002, The Messenger, 110, 1
Piotto G., 1998, Mem. S.A.It. in press, arXiv:0801.3175
Phillipps S., Drinkwater M. J., Gregg M. D., Jones J. B., 2001, ApJ, 560, 201
Salpeter E. E., 1955, ApJ, 121, 161
Sánchez-Blázquez P., Gorgas J., Cardiel N., González J. J., 2006a, A&A, 457, 787
Sánchez-Blázquez P., Gorgas J., Cardiel N., 2006b, A&A, 457, 823
Simien F., Prugniel P., 2002, A&A, 384, 371
van der Marel R., Franx M., 1993, ApJ, 407, 525
van Zee L., Skillman E., Haynes M., 2004, AJ, 128, 121
Worthey G., Faber S. M., Gonzalez J. J., Burstein D., 1994, ApJS, 94, 687