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NUCLEI OF EARLY-TYPE DWARF GALAXIES: ARE THEY PROGENITORS OF UCDS?[1]

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ABSTRACT

To address the question of whether the so-called ultra compact dwarf galaxies (UCDs) are the remnant nuclei of destroyed early-type dwarf galaxies (dEs), we analyze the stellar population parameters of the nuclei of 34 Virgo dEs, as well as ten Virgo UCDs, including one that we discovered and which we report on here. Based on absorption line strength (Lick index) measurements, we find that nuclei of Virgo dEs have younger stellar population ages than UCDs, with averages of 5 Gyr and >10 Gyr, respectively. In addition to this, the metallicity also differs: dE nuclei are on average more metal-rich than UCDs. On the other hand, comparing the stellar population parameters at the same local galaxy density, with UCDs being located in the high density cluster regions, we do not find any difference in the stellar populations of dE nuclei and UCDs. In those regions, the dE nuclei are as old and as metal poor as UCDs. This evidence suggests that the Virgo UCDs may have formed through the stripping of dE nuclei.

Subject headings: galaxies: dwarf, galaxies: evolution galaxies: formation - galaxies: stellar population - galaxy cluster: Virgo cluster

1. INTRODUCTION

Since the discovery of ultra-compact dwarf galaxies (UCDs; Hilker et al. 1999; Phillipps et al. 2001), it is still a complicated puzzle in extragalactic astronomy how such compact and luminous objects may have formed. They are brighter and larger than globular clusters (GCs) (Mieske et al. 2002) and much smaller than early-type dwarf galaxies (dEs) in both size and luminosity. A number of studies targeting various UCD samples in different galaxy clusters also revealed the diverse nature of UCDs: Fornax UCDs are slightly redder on average than Virgo UCDs (Evstigneeva et al. 2008; Mieske et al. 2008, 2006). On the other hand, it is still a matter of debate whether or not the UCDs contain dark matter (Drinkwater et al. 2003; Haşegan et al. 2005; Hilker et al. 2007). This makes them very special objects to study in extragalactic astronomy, suggesting that the presence of dark matter or not can be directly related to whether UCDs have a galactic origin or not.

Overall it has been already noted that Virgo UCDs contain fairly old (age: > 8-10 Gyr) and metal poor (<-0.5 dex) stellar populations (Evstigneeva et al. 2007, hereafter E07). Therefore, it is also proposed that they could be very luminous intra-cluster GCs (Mieske et al. 2002). Another popular formation scenario is the threshing of nucleated dEs Bassino et al. 1994. In this picture, UCDs are the remnants of galaxies that have been significantly stripped in the cluster environment. Numerical simulations (Bekki et al. 2003; Goerdt et al. 2008) have generally confirmed that the remnant nuclei resemble UCDs in their structural parameters.

Stellar population studies of dEs provide evidence that the nuclei have intermediate ages and moderately metal-enriched stellar populations (Koleva et al. 2009; Chilingarian 2009). In addition to this, since UCDs show slightly super solar [α/Fe] abundances, Evstigneeva et al. (2007) argued that the stellar population properties rather support the view that UCDs are luminous globular clusters than being nuclei of dEs.

In this letter, we present a stellar population analysis based on absorption-line strengths (Lick indices, Burstein et al. 1984; Worthey et al. 1994; Trager et al. 1998) of a fairly large sample of 34 nucleated dEs and 10 UCDs in the Virgo cluster. So far, studies comparing stellar population parameters derived from spectra used rather low numbers of objects. Moreover, the extraction of nuclear spectra has been made without subtracting the underlying galactic light, which can still contribute significantly at the photometric center of the dEs. We therefore apply a simple method to subtract most of this light (see Section 2), thus expecting that our measurements are representative for the stellar population properties of the nuclei themselves. Finally, we present the distributions of the stellar population parameters of dE nuclei and UCDs with respect to local galaxy density and to their luminosity, and we try to constrain possible formation scenarios of Virgo UCDs.

2. THE SAMPLE, OBSERVATIONS AND DATA REDUCTION

2.1. *Sample selection and a new Virgo UCD*

Our dE sample comprises 34 nucleated dEs in the Virgo cluster (Virgo cluster catalog, VCC, Binggeli et al. 1985; Binggeli & Cameron 1993), selected to have a relatively high "nucleus strength" (details of the sample see, Paudel et al. 2010), which we define as the difference between the nucleus magnitude and the host galaxy effective surface brightness, $s_{r,\mathrm{nucleus}} = m_{r,\mathrm{nucleus}} -$

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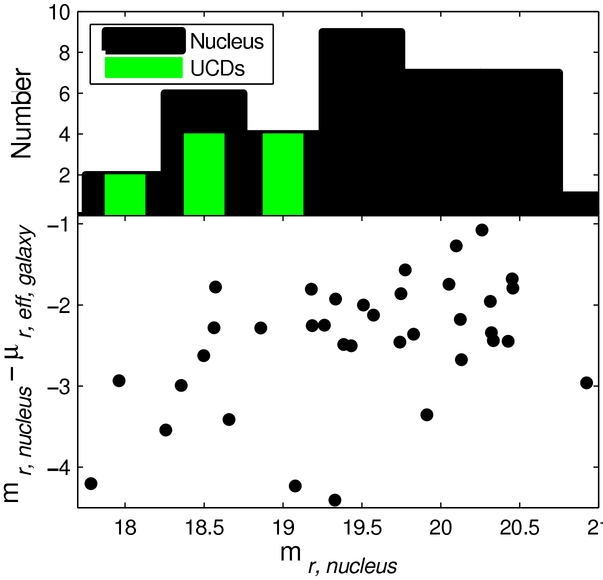

FIG. 1.— *Top:* Number distribution of dE nuclei and UCDs in our sample. *Bottom:* Our selection criteria for dE nuclei, limiting the nucleus magnitude $m_{r,\mathrm{nucleus}}$ to values brighter than 21 mag, and the "nucleus strength", i.e. the value of $m_{r,\mathrm{nucleus}} - \mu_{r,\mathrm{eff,galaxy}}$ to less than -1. Note that the nucleus sample is not complete within this parameter region, i.e. not all Virgo dE nuclei with these parameters have been observed.

$\mu_{r,\mathrm{eff,galaxy}}$, measured in SDSS r (see below). Thereby, $\mu_{r,\mathrm{eff,galaxy}}$ is a measure for the brightness of a unit area of the galaxy, determining the "contrast" between galaxy and nucleus (also see Lisker et al. 2007, their Fig. 1). We select nuclei with $s_{r,\mathrm{nucleus}} < -1$ and $m_{r,\mathrm{nucleus}} < 21$ mag (see Fig. 1).

Our UCD sample selection (see Table 1), is based on Evstigneeva et al. (2005) and Jones et al. (2006); our numbering follows the latter. Three of the nine Virgo UCDs of Jones et al. were not included in the Lick index study of Evstigneeva et al. (VUCD2, 8, and 9), so they were selected by us as targets. Three further UCDs were selected, since they fell in the same field-of-view as dE targets of our study. Due to the multi-slit observations, they could be easily included.

We also targeted a new Virgo UCD candidate, which we now indeed confirm as Virgo cluster member; it is named VUCD10 in Table 1. It was identified through a simple multiparameter selection procedure. From SDSS DR5 pipeline photometry, we obtained *ugriz* magnitudes and colors for all nine Virgo UCDs in Jones et al. (2006). When excluding VUCD7, which is clearly brighter than the others and appears to be an extended object in the SDSS images (also see Jones et al. 2006), the r-band magnitudes (SDSS "modelMag" values) lie within 18.0 to 19.1 mag. Their Petrosian radii in r, again excluding VUCD7, are below 2.2 arcsec. Their u-r colors, when excluding the much redder VUCD3, cover the range 1.8 to 2.4 mag (which includes VUCD7). Their i-z colors, again excluding VUCD3, lie between 0.1 and 0.25 mag (which again includes VUCD7). The right ascension and declination of all objects except VUCD3 and VUCD7 ranges from 187.5° to 188.1° and 11.9° to 12.7°, respectively. When querying the SDSS database for all objects fulfilling the above criteria of magnitude, radius, color, and position, 20 objects were identified that the SDSS classified as stars, among them VUCD1, 2, and 5. The same query, but for objects classified as galaxies, yielded only five objects: VUCD4, 6, 8, 9, and the new VUCD10, which we therefore included in our target sample.

With its radial velocity of 2425 km/s that we now measured from its spectrum, it is consistent with being a Virgo cluster member: in velocity space, Virgo member galaxies in the central cluster region reach velocities of 2600 km/s (Binggeli et al. 1987; Binggeli & Cameron 1993). We therefore consider VUCD10 a new Virgo cluster UCD, and include it in the following analysis.

2.2. *Photometry*

To obtain nucleus and UCD magnitudes, we use SDSS DR5 r-band images to which we applied our own sky subtraction procedure (see Lisker et al. 2007). We also correct them for Galactic extinction, following Schlegel et al. (1998), and use the flux calibration provided directly by the SDSS. A Virgo distance modulus of $m - M = 31.09$ mag (Mei et al. 2007; Blakeslee et al. 2009), corresponding to $d = 16.5$ Mpc and an SDSS pixel scale of 32 pc (80 pc/"), is adopted here and in the further analysis.

Nucleus magnitudes are derived as follows. A Sérsic fit to the radial profile of the galaxy is done, measured with elliptical annuli and using only the radial interval from 2" to 1/3 of the half-light radius, or extending it if the interval subtends less than 2.5" (200 pc). From this fit, a two-dimensional elliptical model image, taking into account the median SDSS PSF of 1.4" FWHM, is created and subtracted from the original image, leaving only the nucleus in the center. The nucleus magnitude is then measured by circular aperture photometry with $r = 2$". We estimate the magnitude error to be 0.2 mag, which is consistent with the RMS scatter of a comparison to the *Hubble Space Telescope (HST)* ACS Virgo cluster survey (Côté et al. 2006) for the 10 objects in common.[4]

The same aperture photometry is done to obtain UCD magnitudes. To be comparable to the nucleus measurements, this aperture is also applied to VUCD7, even though it is known to be extended, as mentioned previously. For the UCD magnitudes we estimate an error of 0.1 mag.

2.3. *Spectroscopy*

The spectroscopic observations were carried out at ESO Very Large Telescope (VLT) with FORS2. The 1" slit and V300 grism provide an instrumental resolution ∼11 Å FWHM. Details of the observational layout and data reduction are described in Paudel et al. (2010, hereafter P10). Our data was obtained in two observing runs, using the same instrumental setup. The first set of dEs (26 objects, see P10) was observed in the semester 2007A, and the second set (8 dEs) in 2010A. In total our sample covers the full range of local projected galaxy density that is populated by nucleated dEs in Virgo, from less than 10 to more than 100 galaxies per square degree. The UCDs were observed in 2007A together with the first set of dEs, using the same instrumental configuration. We provide the basic properties such as position

[4] Nucleus r magnitudes were converted into g by adding the $g-r$ color value of the nucleated dE's center ($r \leq 2$"), and were then compared to ACS g magnitudes, showing no systematic offset.

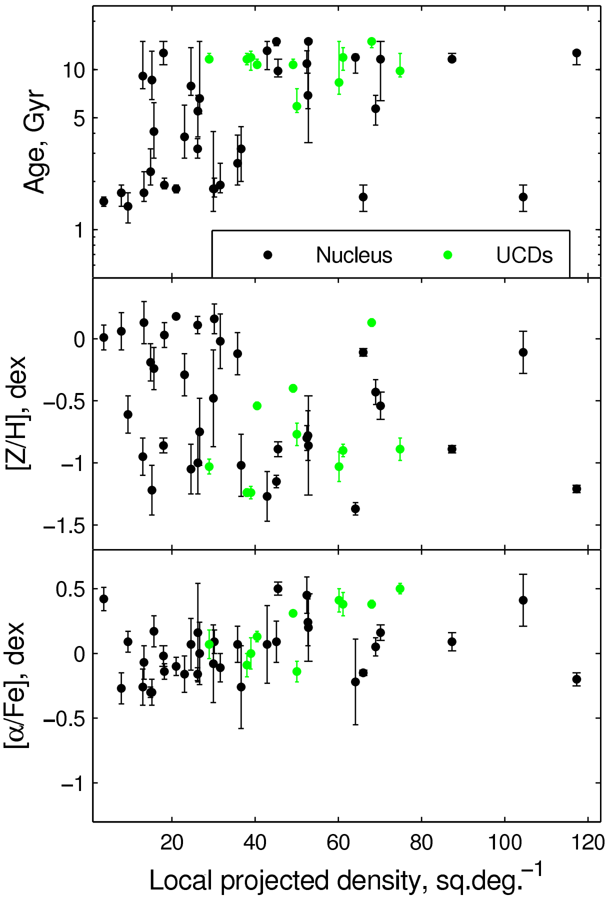

FIG. 2.— Age, metallicity, and [α/Fe]-abundance versus local projected galaxy density are shown for dE nuclei (black) and UCDs (green).

and radial velocity in Table 1 and the detailed UCD sample selection criteria in Section 2.1.

While the nucleus typically contributes the majority of light at the photometric center of the dEs, still a considerable amount of underlying galactic light of the host galaxy could alter the actual properties of the nuclei. Therefore, we attempt to subtract the galactic light from the nuclear spectra. This is done by inward extrapolation of the exponentially-fitted light profile of the host galaxy along the slit, yielding the amount of galaxy light contained in the nucleus extraction aperture of 0".75 (central 3 pixels). The galaxy spectrum is extracted in a radial interval from 3" to 8", scaled accordingly, and subtracted from the centrally extracted spectrum. Further details of this process are given in Paudel et al. (2010b, submitted to MNRAS). While certainly not being perfect, we expect that this approach removes most of the galactic light contamination and thus provides spectra that are fairly well representative for the stellar population properties of dE nuclei.

3. RESULTS

In order to derive stellar population parameters from the measured line strengths, we translate our Lick index measurements into SSP-equivalent ages, metallicities, and α-element abundance ratios by comparing them to the model of Thomas et al. (2003) by χ^2−minimization, following Proctor & Sansom (2002). We use nine well-measured indices (Hδ_F, Hγ_F, Fe4383, Hβ, Fe5015, Mgb, Fe5270, Fe5335 & Fe5406) in case of the dE nuclei. For the UCDs we use only Hβ, Mgb, Fe5270 and Fe5335, because we only find these four indices available in the literature for those three UCDs that we did not target ourselves. Moreover, due to the slit mask placement, our observations only cover the full range of indices (i.e., ∼4000 Å to ∼5600Å) for three of the observed UCDs. For completeness, we also checked whether the use of different sets of indices produces any significant discrepancy in the estimated SSP parameters. We find that the estimated SSP parameters agree well within the errors, although the use of a larger set of indices naturally leads to smaller errors in the SSP parameters. Therefore, we keep using all nine indices for the dE nuclei in the further analysis.

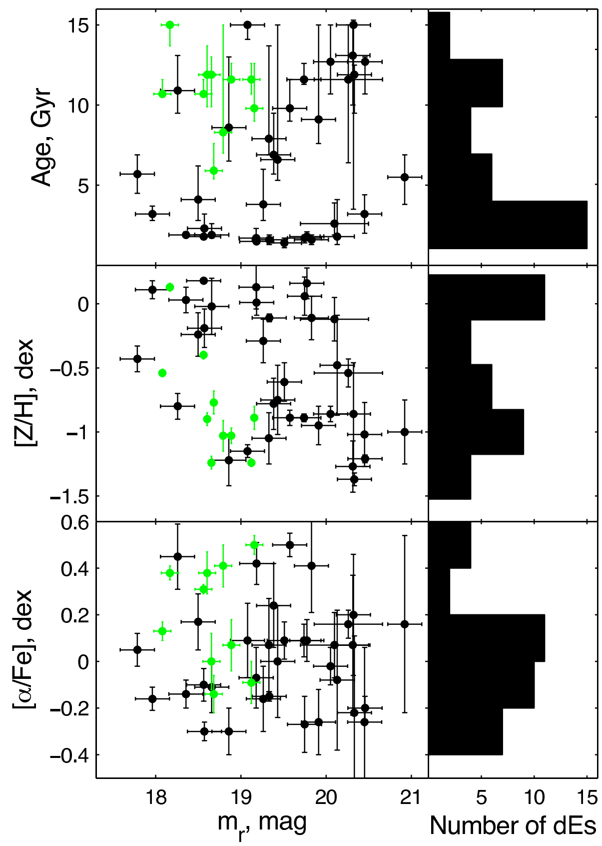

FIG. 3.— Age, metallicity and [α/Fe]-abundance versus nucleus/UCD magnitude, for dE nuclei (black) and UCDs (green).

The relation between the stellar population parameters and the local projected galaxy density is plotted in Fig. 2. The local projected density has been calculated from a circular projected area enclosing the 10th neighbor. It seems that there is a weak correlation between the local projected density and the ages of the nuclei. But, more prominent than the correlation, an age break is seen at a projected density ≈40 sq.deg.$^{-1}$. We thus use this value to divide our dE sample in two groups, located in cluster regions of lower/higher density. We find median ages of 2.6 Gyr for the low density group and 11.6 Gyr at high densities.

Almost all UCDs lie in the high density region as defined above. Their ages have a median of 11.7 Gyr,

TABLE 1
THE UCD SAMPLE. IN THE FIRST FOUR COLUMNS, WE PROVIDE UCD NUMBER, POSITION IN THE SKY (RA, DEC), AND RADIAL VELOCITY. IN THE LAST COLUMN, WE INDICATE WHETHER UCDS ARE IN COMMON WITH THE STUDIES OF E07 OR FIRTH ET AL. (2009).

UCDs name	RA (h:m:s)	Dec (^{o} :' :")	RV (kms)	Age Gyr	[Z/H] dex	[α/Fe] dex	m_r mag	Remark
VUCD1	12:30:07.61	12:36:31.10	1227.8 ± 1.7	$11.9^{+1.8}_{-2.0}$	-0.90 ± 0.05	0.38 ± 0.09	18.6	E07
VUCD2	12:30:48.24	12:35:11.10	911 ± 6	$5.9^{+1.7}_{-0.5}$	-0.77 ± 0.09	-0.14 ± 0.08	18.6	F09
VUCD3	12:30:57.40	12:25:44.8	710.6 ± 3.5	$15.0^{+0.1}_{-1.3}$	0.13 ± 0.03	0.38 ± 0.03	18.1	E07
VUCD4	12:31:04.51	11:56:36.8	919.7 ± 1.7	$11.9^{+1.1}_{-2.0}$	-1.24 ± 0.05	-0.00 ± 0.12	18.6	E07
VUCD5	12:31:11.90	12:41:01.20	1290 ± 3	$10.7^{+0.9}_{0.1}$	-0.40 ± 0.03	0.31 ± 0.02	18.5	E07
VUCD6	12:31:28.41	12:25:03.30	2101 ± 4	$8.3^{+6.7}_{-1.3}$	-1.03 ± 0.12	0.41 ± 0.09	18.7	E07
VUCD7	12:31:52.93	12:15:59.50	985 ± 5	$10.7^{+0.9}_{0.1}$	-0.54 ± 0.03	0.13 ± 0.04	18.0	E07
VUCD8	12:32:04.33	12:20:30.62	1531 ± 19	$11.6^{+1.0}_{-0.9}$	-1.24 ± 0.03	-0.09 ± 0.09	19.1	F09
VUCD9	12:32:14.61	12:03:05.40	1325 ± 5	$11.6^{+1.0}_{0.1}$	-1.03 ± 0.06	0.07 ± 0.11	18.8	F09
VUCD10	12:30:30.86	12:18:41.66	2425 ± 103	$9.8^{+2.8}_{-0.8}$	-0.89 ± 0.09	0.50 ± 0.04	19.1	New

strikingly consistent with the nuclei in the same density regime. As a statistical comparison, we performed a Kolmogorov-Smirov (K-S) test with the null hypothesis that there is no difference in the distribution of SSP parameters between the UCDs and the dE nuclei of the high density group. We find that there is a probability of 88%, 97% and 73% for having the same age, metallicity, and [α/Fe]-abundance distribution, respectively.

The metallicities of dE nuclei also show a difference between the low and high density regions: the median values differ by more than 0.5 dex, although the scatter is fairly large. The UCDs also have a fairly large scatter in metallicity, ranging from +0.1 to −1.4 dex. However, it is remarkable that only two UCDs (VUCD3 and 4) have a metallicity above −0.5 dex. The [α/Fe]-abundances are more or less consistent with solar in case of the dE nuclei, but also a slight increase with density can be recognized for the nuclei and (more clearly) for the UCDs. Although the scatter is fairly large, the Spearman's rank correlation coefficients are 0.3 and 0.7 for dE nuclei and UCDs, with the probabilities for the null hypothesis that there is no correlation being 8.5% and 1.5%, respectively. In case of the UCDs, 7 out 10 have super-solar values of [α/Fe].

The relation between the stellar population parameters and the r-band magnitudes of UCDs and nuclei is presented in Fig. 3. We do not see a relation of age and [α/Fe]-abundance with luminosity, both for nuclei and UCDs. Unlike that, the metallicity of both UCDs and dE nuclei tends to increase with increasing luminosity, following the well known metallicity-luminosity relation. However, bimodal peaks of the age and metallicity distributions of dE nuclei can be seen as a striking feature in Fig 3 (right panel). This indicates the inhomogeneous nature of dE nuclei, which can be divided into two different groups of stellar population characteristics: a young metal-rich group and an old metal-poor group. Brighter nuclei predominantly have metal-rich stellar populations consistent with solar values. The metal-poor nuclei (metallicity <-0.5 dex) have an average of −1.0 dex, and most of them are less luminous than $m_r = 19.2$ mag ($M_r = -11.9$ mag).

4. SUMMARY AND DISCUSSION

We have derived stellar population parameters of Virgo cluster UCDs and nuclei of early-type dwarf galaxies, through fitting measured Lick absorption line strengths to models of Thomas et al. (2003). Since we use simple stellar population models, it must be noted that our estimated parameters are interpreted as *SSP-equivalent.*

Indications that the UCDs in the Virgo cluster more likely have formed via dE destruction in dense cluster regions than in the Fornax cluster have already been presented in the literature (Mieske et al. 2006; Côté et al. 2004, 2006). An explanation could be the higher mass of the Virgo cluster, which provides a deeper potential well with stronger tidal forces than in the Fornax cluster. Virgo UCDs were also found to be significantly different from GCs in colors and sizes, as they are bluer and larger than GCs (Haşegan et al. 2005). E07 showed that Virgo UCDs have structural properties similar to the Fornax UCDs. Furthermore, De Propris et al. (2005) showed with the *HST* that Fornax UCDs are more extended and have higher surface brightnesses than typical dwarf nuclei. That is not necessarily inconsistent with the stripping scenarios, because the stripping process can alter structural parameters of the embedded nuclei. Therefore, a direct comparison of structural parameters may not be able to constrain the formation scenarios of UCDs properly.

In the light of our new age and metallicity estimates in the previous section, we want to address the possibility of formation of Virgo UCDs via tidal destruction of nucleated dEs. We observe that UCDs exhibit significantly older and more metal deficient stellar populations as compared to dE nuclei *on average*. However, if we compare the ages of UCDs and nuclei only in high density regions, where most of the UCDs are located, we do not find any significant difference in their age and metallicity distribution. Only two dE nuclei (VCC0965 and VCC1122) out of 13 from the high density group have ages less than 5 Gyr and metallicities above -0.2 dex. Note, however, that due to projection effects, a number of objects that are actually located in the outskirts of the cluster must fall into regions of high *projected* density, lying in front or behind the center along the line of sight. If we consider the low density group of our sample to be representative for nuclei of dEs outside of the (three-dimensional) cluster center, then we actually *expect* to have a few objects with young ages and high metallicities in the high density group, consistent with what we observe. Moreover, even without taking this effect into account, our statistical tests already show that the age distributions of UCDs and dE nuclei are similar when considering only the group of nuclei in the high density.

This supports the idea of the threshing of dEs in high density environments to form the UCDs.

At low densities, a certain fraction of dEs probably still retained some central gas and transformed it into stars (some dEs are still doing this, see Lisker et al. 2006). Consequently, their nuclei today would indeed show a younger stellar population than a UCD, the latter being an "old nucleus". For such dEs, not only the orbital average should be located in the outskirts, but they should also not have passed right through the center (e.g. on an eccentric orbit), otherwise the gas would have been stripped by ram pressure and tidal forces. This would explain the fact that we do not see young UCDs: a dE destruction is only possible if the galaxy really goes through the center and experiences the strongest tidal forces. If we assume that the *full* destruction, i.e. the complete removal of the dE's main body, takes significantly more orbital time than the gas stripping, then nucleated dEs with an orbit leading through the center first lost their gas, halting any star formation, and then became destroyed. Therefore, we have no young UCDs.

In any case, young and bright dE nuclei have either late or prolonged star formation activity. We assess this by modeling spectra of composite stellar populations through superposition of a young and an old component, using the model spectra of Vazdekis et al. (2010). We fix the old population at an age of 11 Gyr and a metallicity of -1.2 dex, and add a component with solar metallicity and exponentially declining star formation rate, starting from an age of 11 Gyr. We find that spectra like those of the young nuclei (with an SSP-equivalent age of $\sim$3 Gyr) can be achieved when the exponentially declining component formed stars until 2 Gyr ago, at which point it is truncated. This means, if we assume our model to represent the observed young nuclei, their star formation activity would have stopped 9 Gyr later than that of the old nuclei.

On the one hand, the estimated ages and metallicities of UCDs nicely agree with the ages and metallicities of nuclei of dEs from the dense cluster regions. On the other hand, most of the old nuclei are fainter than the UCDs. However, the UCD discoveries might suffer a selection effect: if a *faint* nucleus was stripped, it would now be automatically counted into the globular cluster system of M87. We can hardly estimate how many nucleated dEs have already been destroyed and transformed into UCDs during the lifetime of the cluster. Thus we cannot rule out or confirm any scenario *just by counting* the number of bright nuclei or that of UCDs. Only detailed future simulations can resolve this issue.

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