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ABSTRACT

We have revisited the ACS Virgo Cluster Survey (ACSVCS), a Hubble Space Telescope program to obtain ACS/WFC g and z bands imaging for a sample of 100 early-type galaxies in the Virgo Cluster. In this study, we examine 51 nucleated early-type galaxies in the ACSVCS in order to look into the relationship between the photometric and structural properties of stellar nuclei and their host galaxies. We morphologically dissect galaxies into five classes. We note that (1) the stellar nuclei of dwarf early-type galaxies (dS0, dE, and dE,N) are generally fainter and bluer with $g > 18.95$ and $(g - z) < 1.40$ compared to some brighter and redder counterparts of the ellipticals (E) and lenticular galaxies (S0), (2) the g-band half-light radii of stellar nuclei of all dwarf early-type galaxies (dS0, dE, and dE,N) are smaller than 20 pc and their average is about 4 pc, and (3) the colors of red stellar nuclei with $(g - z)$ > 1.40 in bright ellipticals and lenticular galaxies are bluer than their host galaxies colors. We also show that most of the unusually "red" stellar nuclei with $(g - z) > 1.54$ in the ACSVCS are the central parts of bright ellipticals and lenticular galaxies. Furthermore, we present multi photometric band color - color plots that can be used to break the age-metallicity degeneracy particularly by inclusion of the thermally pulsing-asymptotic giant branch (TP-AGB) phases of stellar evolution in the stellar population models.

Key words : Galaxies: nuclei — Stars: AGB and post-AGB — Stars: evolution

1. INTRODUCTION

Clear understanding of the central parts of galaxies has become an important issue in galactic and extragalactic astronomy. It appears that most galaxies have either massive black holes or stellar nuclei or both at their centers (e.g., Carollo 1999; Côté et al. 2006; Seth et al. 2010). In this context, it is highly interesting to find that there are important correlations between those massive compact central objects and their host galaxies; for instance, in terms of mass fraction (e.g., Ferrarese et al. 2006b).

In the last decade, using high resolution photometric capabilities (down to a few parsec level at the Virgo cluster distance) of the *Hubble Space Telescope (HST)*, Côté et al. (2004) surveyed the 100 early-type galaxies in the Virgo Cluster, spanning a range of ∼460 in blue luminosity, with widely separated bandpasses (F475W ∼ g and F850LP ∼ z). This is the ACS Virgo Cluster Survey (ACSVCS). From this ACSVCS, Côté et al. (2006) and Ferrarese et al. (2006a) showed that (1) the massive early-type galaxies with $M_B < -20.5$ appear to have supermassive black holes in their center, (2) about 50 ∼ 80% of early-type galaxies with $-20.5 < M_B < -15$ in the Virgo cluster have stellar nuclei at or near their projected photocenters, and (3) the stellar nuclei are, on average, 3.5 mag brighter than a typical globular cluster.

In this study, we revisit the earlier studies of the ACSVCS, especially those on stellar nuclei in the centers of the relatively low mass early-type galaxies. We dissect early-type galaxies into their morphological classes and look into the relationship between the photometric and structural properties of stellar nuclei and their host galaxies.

2. LUMINOSITIES, COLORS, AND SIZES OF STELLAR NUCLEI OF THE ACSVCS

Table 1 lists photometric and structural data of 51 Type Ia* stellar nuclei of the ACSVCS from Côté et al. (2006) and some properties of their host galaxies from Ferrarese et al. (2006a). We have categorized the ACSVCS early-type galaxies into five morphological classes. The five morphological classes in Table 1 are ellipticals, nucleated dwarf ellipticals (dE,N), non-nucleated dwarf ellipticals (dE), dwarf lenticulars (dS0), and lenticular galaxies (S0s), respectively, and they are listed in order of increasing B_T, the integrated B-band magnitude of host galaxies. Among six classes in the Table 2 of Côté et al. (2004), we have combined

*Type Ia stellar nuclei show unambiguous evidence for a nucleus at or near their photocenters and are of reliable photometric and structural parameters.

Table 1.
Data of type Ia stellar nuclei of early-type galaxies in the ACSVCS

VCC	Type	B_T	g,Gal	$(g-z)$,Gal	g,Nuc	$(g-z)$,Nuc	$r_{h,g}$,Nuc	Other Name
Ellipticals								
828	E5	12.84	12.71	1.48	18.53	1.57	16.64	NGC 4387
1630	E2	12.91	12.54	1.50	17.39	1.68	40.08	NGC 4551
1146	E1	12.93	12.70	1.36	15.37	1.42	62.40	NGC 4458
1913	E7	13.22	12.90	1.43	17.55	1.60	47.76	NGC 4623
1422	E1,N:	13.64	13.60	1.27	20.22	1.22	3.04	IC 3468
1871	E3	13.86	14.13	1.45	18.73	1.25	10.00	IC 3653
1488	E6:	14.76	14.78	0.88	23.71	0.72	2.00	IC 3487
1545	E4	14.96	14.77	1.34	21.93	1.05	4.00	IC 3509
1192	E3	15.04	14.48	1.52	19.09	1.19	9.60	NGC 4467
1627	E0	15.16	15.11	1.42	18.83	1.44	15.76	
1440	E0	15.20	14.67	1.26	19.70	1.32	5.04	IC 798
538	E0	15.40	15.91	1.16	21.27	1.13	2.64	NGC 4309A
1199	E2	15.50	15.74	1.56	19.75	1.36	6.00	
dE,N								
1261	d:E5,N	13.56	13.29	1.20	19.50	1.22	3.28	NGC 4482
1910	dE1,N	14.17	14.12	1.41	19.82	1.19	3.04	IC 809
856	dE1,N	14.25	14.25	1.22	18.97	1.12	13.04	IC 3328
1355	dE2,N	14.31	14.44	1.19	21.10	1.03	3.44	IC 3442
1087	dE3,N	14.31	13.87	1.29	20.22	1.33	2.16	IC 3381
1861	dE0,N	14.37	14.22	1.33	20.11	1.04	10.96	IC 3652
1431	dE0,N	14.51	14.29	1.42	19.66	1.13	19.04	IC 3470
437	dE5,N	14.54	13.82	1.26	20.00	1.00	7.12	UGC 7399A
2019	dE4,N	14.55	14.42	1.19	20.31	1.12	2.96	IC 3735
33	d:E2,N:	14.67	15.03	1.10	22.18	0.91	2.64	IC 3032
200	dE2,N	14.69	14.79	1.21	22.86	0.92	4.24	
1075	dE4,N	15.08	14.96	1.20	21.07	0.96	3.20	IC 3383
230	dE4:,N:	15.20	15.45	1.17	20.31	1.09	3.04	IC 3101
2050	dE5:,N	15.20	15.12	1.16	22.38	0.97	5.84	IC 3779
1828	dE2,N	15.33	15.09	1.25	21.50	1.00	4.80	IC 3635
1407	dE2,N	15.49	15.03	1.23	20.39	0.98	11.60	IC 3461
1886	dE5,N	15.49	15.29	1.00	22.05	1.01	2.88	
1185	dE1,N	15.68	15.24	1.28	20.86	0.95	4.56	
1539	dE0,N	15.68	15.15	1.21	20.93	1.11	18.48	
1826	dE2,N	15.70	15.51	1.16	20.10	1.19	(1.92)	IC 3633
1489	dE5,N?	15.89	15.89	1.08	22.38	0.87	4.08	IC 3490
1661	dE0,N	15.97	14.55	1.28	20.30	1.05	6.32	
dEs								
543	dE5	14.39	14.12	1.24	22.56	1.36	12.56	UGC 7436
1528	d:E1	14.51	14.34	1.29	22.27	0.96	(1.20)	IC 3501
1895	d:E6	14.91	14.88	1.11	23.48	0.88	(1.84)	UGC 7854
dS0s								
2048	d:S0(9)	13.81	13.82	1.22	21.45	1.15	2.96	IC 3773
1695	dS0:	14.53	14.23	1.15	22.61	1.38	(1.76)	IC 3586
751	dS0	15.30	14.64	1.33	21.22	1.05	3.68	IC 3292
S0s								
1720	$S0_{1/2}(4)$	12.29	11.75	1.44	18.40	1.57	6.80	NGC 4578
1619	$E7/S0_1(7)$	12.50	12.18	1.42	17.13	1.55	25.84	NGC 4550
1883	$RSB0_{1/2}$	12.57	11.76	1.32	18.74	1.14	(1.92)	NGC 4612
1242	$S0_1(8)$	12.60	12.19	1.46	19.84	1.70	2.80	NGC 4474
784	$S0_1(2)$	12.67	12.19	1.43	18.34	1.66	12.88	NGC 4379
1250	$S0_3(5)$	12.91	12.40	1.21	19.73	1.55	2.08	NGC 4476
1125	$S0_1(9)$	13.30	12.85	1.42	20.48	0.97	4.80	NGC 4452
1283	$SB0_2(2)$	13.45	13.02	1.47	20.65	1.58	4.24	NGC 4479
698	$S0_1(8)$	13.60	13.04	1.38	19.93	1.32	3.28	NGC 4352
140	$S0_{1/2}(4)$	14.30	14.08	1.22	22.09	0.91	2.40	IC 3065

NOTE.—1. Data are from Table 1 of Côté et al. (2006) and Tables 3 and 4 of Ferrarese et al. (2006a). Each category is listed in order of increasing B_T. 2. Galaxy type in the second column is from Binggeli, Sandage, & Tammann (1985). 3. The g-band half-light radii of stellar nuclei in the 8th column are in parsec and calculated with $0.1'' = 8$ pc. 4. Binggeli & Cameron (1991) noted that VCC 1422 and VCC 1545 are *misclassified dwarf ellipticals* (see their Fig. 11 and 12).

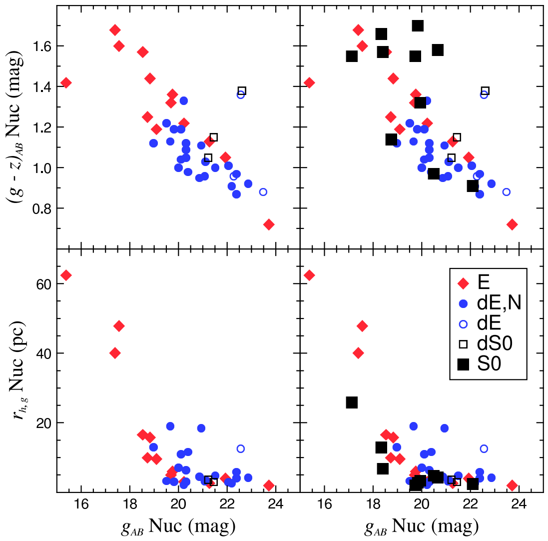

Fig. 1.— Stellar nuclei of Type Ia data from Côté et al. (2006) are plotted. Symbols for host galaxies are noted in the bottom right panel. Right panels additionally show the stellar nuclei of lenticular galaxies (S0).

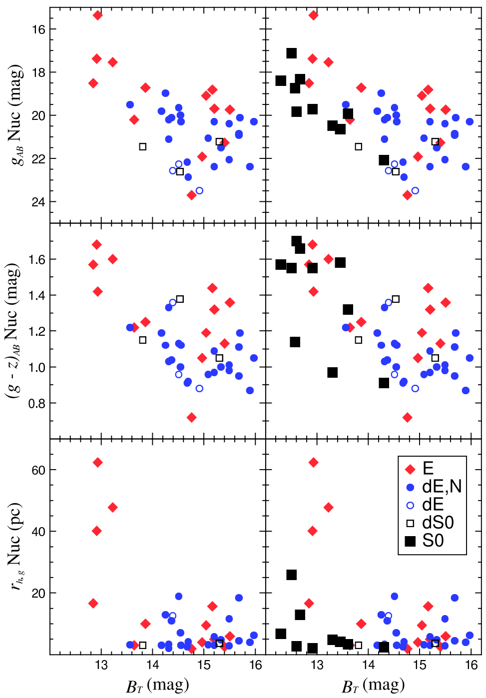

Fig. 2.— Stellar nuclei of Type Ia data from Côté et al. (2006) are plotted against the host galaxy B-band magnitude. Right panels additionally show the stellar nuclei of lenticular galaxies (S0). Symbols are same as in Figure 1.

E/S0[†] and S0 types and assigned them as S0 in this study.

[†]Among 7 E/S0, only VCC 1619 is of type Ia stellar nuclei.

Galaxy type in the second column of Table 1 is from Binggeli, Sandage, & Tammann (1985)[‡]. The 3rd and 4th columns of Table 1 are the integrated magnitudes of the host galaxies in B and g-band, respectively and the 5th column lists the $(g-z)_{AB}$[§] of the host galaxies. The 6th, 7th and 8th columns of Table 1 (g_{AB}, $(g-z)_{AB}$, and $r_{h,g}$) are the photometric and structural properties of the stellar nuclei from Côté et al. (2006). The g-band half-light radii in the 8th column are calculated by adopting $0.1'' = 8$ pc from Côté et al. (2006) with the common distance to the Virgo cluster being 16.5 Mpc from Tonry et al. (2001). The core ellipticals with supermassive black holes are not included in this study.

The Type Ia stellar nuclei of early-type galaxies among the ACSVCS sample from Côté et al. (2006) are plotted in Fig. 1. The five classes of the early-type galaxies are depicted here with different symbols as noted in the bottom right panel. The right panels of Fig. 1 *additionally* show the stellar nuclei of the lenticular galaxies (S0). In the top panels, the $(g-z)$ colors of stellar nuclei of early-type galaxies in the ACSVCS are compared with their g-band magnitudes and in the bottom panels the g-band half-light radii of the stellar nuclei are contrasted with their g-band magnitudes.

It is seen in the top panels of Fig. 1 that the stellar nuclei of dwarf ellipticals (dS0, dE, and dE,N) are generally fainter and bluer with $g > 18.95$ and $(g-z) < 1.40$ as compared to some brighter and redder counterparts of the ellipticals (E) and lenticular galaxies (S0). It is further noted from the top right panel of Figure 1 that six of the stellar nuclei of lenticular galaxies and three of that of ellipticals, respectively, are rather of unusual red colors with $(g-z) > 1.54$. The bottom panels of Fig. 1 show that the g-band half-light radii of stellar nuclei of all dwarf ellipticals (dS0, dE, and dE,N) are smaller than 20 pc and their average is about 4 pc.

Fig. 2 contrasts the B_T, the integrated B-band magnitude of host galaxies, with their stellar nuclei's g-band magnitues (top panels), $(g-z)$ colors (middle panels), and g-band half-light radii (bottom panels). Similar to Fig. 1, the right panels additionally show the stellar nuclei of lenticular galaxies (S0). It becomes clear from the right panels of Fig. 2 that the S0s are mostly brighter entities with $B_T \leq 13.6$ (except VCC 140 with $B_T = 14.3$). There appears to be no close correlation between host galaxy luminosity and their stellar nuclei's photometric and structural parameters as suggested by Côté et al. (2006).

The colors of stellar nuclei are compared with those of their host galaxies in Fig. 3. It is seen that the colors of red stellar nuclei with $(g-z) > 1.40$ in bright ellipticals and lenticular galaxies with $B_T < 13.6$ are bluer than their host galaxies colors. On the contrary,

[‡]According to Binggeli & Cameron (1991), two relatively faint elliptical galaxies, VCC 1422 and VCC 1545, are *misclassified dwarf ellipticals* (see their Figures 11 and 12).

[§]The photometry is in AB system.

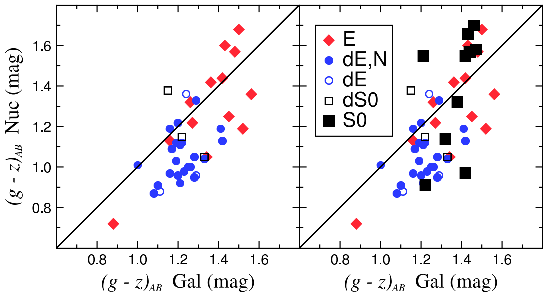

Fig. 3.— The colors of stellar nuclei are compared with that of their host galaxies. Right panels additionally show the stellar nuclei of lenticular galaxies (S0). Symbols are same as in Fig. 1.

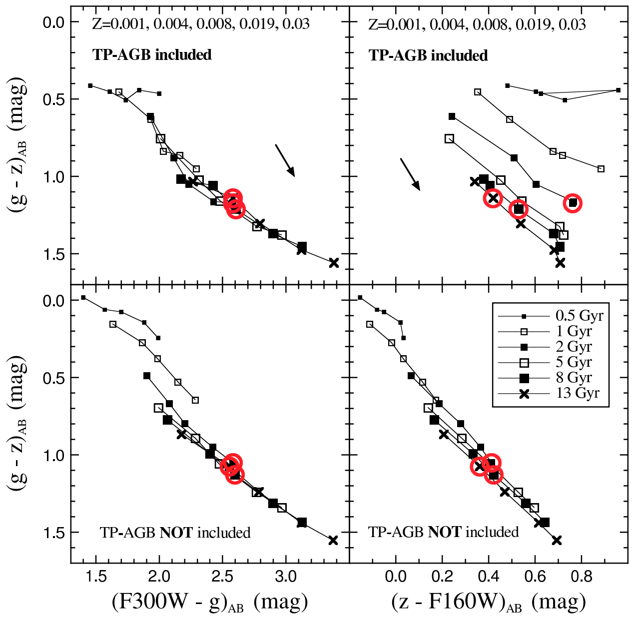

Fig. 4.— Theoretical color - color plots are shown. Top panels present models with TP-AGB stars, while bottom panels show that without TP-AGB stars (see text). Three circles in each panel demonstrate the age-metallicity degeneracy. The arrows in the top panels indicate $A_V = 0.3$ mag. At six given ages, five metallicities are connected by lines.

the colors of comparably bluer stellar nuclei with $(g-z)$ < 1.40 in faint early-type galaxies are mostly redder than those of their host galaxies.

3. MULTI-BAND COLOR - COLOR PLOTS

Once we have the optical photometry (g- and z-band) of stellar nuclei of early-type galaxies in hand from the ACSVCS, supplementing UV (e.g., WFPC2/ F300W) and IR (e.g., NICMOS/F160W) photometry will be very useful in order to understand their star formation and chemical enrichment history. Fig. 4 shows theoretical color - color plots for the case when we have multi-band photometry. Here we have calculated the integrated simple stellar population (SSP) photometric properties by employing the latest Padova stellar models¶ (Marigo et al. 2008) using the evolutionary population synthesis code that has been developed to study the stellar populations of star clusters and galaxies (Lee et al. 2002, 2004, 2007, 2010). Left panels are $(F300W - g)$ vs. $(g - z)$ and right panels are $(z - F160W)$ vs. $(g - z)$. Top panels present SSP models with TP-AGB stars, while bottom panels show that the same without TP-AGB stars. The arrows in the top panels indicate $A_V = 0.3$ mag. At six given ages with 0.5, 1, 2, 5, 8, and 13 Gyr, five metallicities with Z = 0.001, 0.004, 0.008, 0.019, and 0.03 are connected by lines. It is interesting to see from the top panels of Figure 4 that the only plausible age-metallicity combination for the $(g - z) > 1.54$ that we have noted in Figure 1 is 13 Gyr and Z = 0.03.

In Fig. 4, three points are circled in order to demonstrate the well-known age-metallicity degeneracy (which is clear in the top left panel) and its potential breaking. They are 13 Gyr with Z = 0.004, 8 Gyr with Z = 0.008, and 2 Gyr with Z = 0.03, respectively. Top right panel of Fig. 4 shows that the age-metallicity degeneracy can be broken with the supplement of near-IR photometry (e.g., F160W, equivalent of H-band). A very old, metal-poor stellar population (13 Gyr with Z = 0.004) shows the same *optical* color as a young, metal-rich one (2 Gyr with Z = 0.03), but the latter has a significantly redder color in the near-IR region because of the dominantly prevalent TP-AGB stars (Lee et al. 2007, 2010). Bottom right panel of Fig. 4, however, shows that the degeneracy breaking will not be possible unless the TP-AGB stars are properly engaged in the models.

4. CONCLUSIONS AND DISCUSSION

In this study, by employing Binggeli et al. (1985)'s morphological classification scheme within early-type galaxies, we have revisted the properties of the stellar nuclei of the early-type galaxies among the ACSVCS. We have noted that the stellar nuclei of relatively fainter early-type galaxies with $B_T > 13.5$ are comparably fainter with $g > 18.6$, bluer with $(g - z) < 1.45$, and smaller with g-band half-light radii < 20 pc than that of the brighter early-type galaxies. Moreover, we have shown that some of the unusually "red" stellar nuclei with $(g - z) > 1.54$ in the ACSVCS are the central parts of the bright ellipticals and S0 galaxies. The structural and photometric parameters for these nuclei are admittedly very hard to measure, because they are very extended and they do not have much contrast against their host galaxies. We have also presented a useful multi-band color - color plots that can potentially break the age-metallicity degeneracy with

¶http://stev.oapd.inaf.it/cgi-bin/cmd

the addition of near-IR photometry once the TP-AGB stars are properly employed in the models.

It is tempting to speculate that the stellar nuclei are the merger products of globular clusters (GCs) by dynamical friction (e.g., Tremaine et al. 1975; Oh & Lin 2000; Lotz et al. 2001; Capuzzo-Dolcetta & Miocchi 2008; Agarwal & Milosavljević 2010). The VCC 1422, VCC 856, VCC 1087, VCC 1545, VCC 1407, and VCC 1539's stellar nuclei clearly show comparatively larger sizes than that of their GCs within them (Fig. 25, 29, 30, 39, 46, and 48 of Ferrarese et al. 2006a, respectively). The larger dwarf elliptical galaxies (e.g., VCC 1261, VCC 1910, VCC 1087, VCC 1431) are presumably of the brighter and redder stellar nuclei in the upper left panel of Fig. 1 because they are perhaps the merger products of several massive red star clusters that used to inhabit the region near the center. Maybhate et al. (2010) recently note that the number of red globular clusters associated with bulges in early-type spirals generally increases with the bulge luminosity similar to elliptical galaxies (e.g., Rhode & Zepf 2004; Peng et al. 2005).

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