Compact Elliptical Galaxies in Different Local Environments: A Mixture of Galaxies with Different Origins?

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Received 2020 March 20; revised 2020 August 11; accepted 2020 August 11; published 2020 November 2

Abstract

We present the stellar populations of 138 compact elliptical galaxies (cEs) in the redshift range of $z < 0.05$ using the Sloan Digital Sky Survey (SDSS) DR12. Our cEs are divided into those with [cE(w)] and without [cE(w/o)] a bright ($M_r < -21$ mag) host galaxy. We investigated the stellar population properties of cEs based on the Lick line indices extracted from SDSS spectra. [cE(w)] show $[Z/H]$ and $[α/Fe]$ distributions skewed toward higher values compared to those of the [cE(w/o)]. No statistically significant difference in age distribution was found between the [cE(w)] and [cE(w/o)]. In the mass–metallicity distribution, [cE(w)] deviate from the relation observed for early-type galaxies at a given stellar mass, whereas [cE(w/o)] conform to the relation. Based on the different features in the stellar populations of [cE(w)] and [cE(w/o)], we can propose two different cE formation channels tracing different original masses of the progenitors. [cE(w)] would be the remnant cores of the massive progenitor galaxies whose outer parts are tidally stripped by a massive neighboring galaxy (i.e., a nature origin). In contrast, [cE(w/o)] are likely the faint end of early-type galaxies maintaining in situ evolution in an isolated environment with no massive galaxy nearby (i.e., a nurture origin). Our results reinforce the propositions that cEs comprise a mixture of galaxies with two types of origins depending on their local environment.

Unified Astronomy Thesaurus concepts: Compact objects (288); Compact galaxies (285); Compact dwarf galaxies (281); Elliptical galaxies (456); Galaxy evolution (594); Galaxy formation (595); Tidal interaction (1699); Stellar populations (1622)

1. Introduction

Compact elliptical galaxies (cEs) are relatively rare objects in the local universe, characterized by very small effective radii (a few hundred parsecs), low stellar masses ($10^8$–$10^{10} M_\odot$), and high central surface brightnesses (Faber 1973; Norris et al. 2014). Therefore, cEs are located in the low-mass end of massive early-type galaxies and differ from diffuse low-mass galaxies such as dwarf early-type galaxies (dEs) in their mass-size distribution. While several scenarios have been suggested (Faber 1973; Bekki et al. 2001; Martinović & Micic 2017; Du et al. 2019), questions regarding the origin of cEs remain unanswered.

Most cEs deviate from the mass–metallicity relation observed in classical early-type galaxies in that cEs are more metal-rich than galaxies of comparable masses; however, they have metallicities appropriate to more massive galaxies (Chilingarian & Zolotukhin 2015; Janz et al. 2016). Furthermore, cEs are most likely to be associated with an adjacent massive host galaxy in galaxy clusters or groups (Norris et al. 2014; Chilingarian & Zolotukhin 2015; Janz et al. 2016). These facts suggest a formation scenario in which cEs are the tidally stripped remnants of larger, more massive galaxies (Faber 1973; Bekki et al. 2001; Choi et al. 2002; Graham 2002). According to this scenario, an early-type disk galaxy with a compact bulge loses a large fraction of its initial disk mass through dissipative tidal interactions with a more massive host galaxy and only the central bulge component survives (e.g., Bekki et al. 2001; Chilingarian et al. 2009). The outcome is a metal-rich and low-mass cE that is in line with observational results (Norris et al. 2014; Chilingarian & Zolotukhin 2015; Janz et al. 2016).

Indeed, the discovery of tidal streams around a few cEs can be considered a direct evidence for cE formation through tidal stripping (Huxor et al. 2011; Paudel et al. 2013; Chilingarian & Zolotukhin 2015; Ferré-Mateu et al. 2018). Further, supporting evidence of the cE formation through stripping is that cEs should contain a central black hole (BH) with mass appropriate for becoming a massive progenitor (see Kormendy et al. 1997; van der Marel et al. 1997; Forbes et al. 2014; Paudel et al. 2016, for details on the observational hints of central BHs existing in cEs).

An alternative cE formation scenario proposes that cEs are instead the natural extension of classical luminous elliptical galaxies to lower luminosities. This is supported by the fact that cEs follow the scaling relations of giant elliptical galaxies at the low-mass end (e.g., Wirth & Gallagher 1984; Kormendy et al. 2009; Kormendy & Bender 2012, see also Saulder et al. 2015 for more massive cEs with stellar masses in the range of $10^{10}$–$10^{11} M_\odot$). Kormendy & Bender (2012) argue against the stripping scenario since not all cEs are companion galaxies of bright galaxies. The discovery of isolated cEs is conclusive evidence that cEs may not be formed by appreciable environmental effects, suggesting an alternative channel to the tidal stripping for the cE formation (Huxor et al. 2013; Paudel et al. 2014). It has been suggested that isolated cEs might have originated through an earlier merger between smaller objects, as in typical massive elliptical galaxies (e.g., Kormendy et al. 2009; Paudel et al. 2014).

From their large sample of cEs identified in various environments including 11 isolated cEs, Chilingarian & Zolotukhin (2015) found that the dynamical and stellar
population properties of isolated cEs might be similar to those in more dense environments. They suggested that isolated cEs originally formed by tidal stripping in clusters or groups and then were ejected from the host galaxy via three-body encounters. Therefore, this finding has simplified the formation scenarios of cEs, eliminating the need for an additional formation channel for the isolated cEs.

In the context of current galaxy formation scenarios, most compact galaxies formed at high-$z$ will evolve into classical massive galaxies through hierarchical merging, rather than retaining their compact morphology by $z = 0$ (Damjanov et al. 2009; de la Rosa et al. 2016; Huang et al. 2016; Rodriguez-Gomez et al. 2016). However, according to cosmological simulations, some compact galaxies formed at high-$z$ are likely to survive in the local universe (e.g., Wellons et al. 2016; Martinović & Micic 2017). In this case, these galaxies might not have acquired ex situ stellar mass over time, owing to the lack of mergers with other galaxies. Such intrinsic cEs are not have acquired ex situ stellar mass over time, owing to the fact that they are expected to follow the same trend as compact galaxies formed at high-$z$.

The properties of the two subsamples. In Section 3.3, we present the mass–metallicity relation in terms of their predicted population properties. CEs are ubiquitous in a wide variety of environments (Chilingarian et al. 2009; Norris et al. 2014; Chilingarian & Zolotukhin 2015; Janz et al. 2016; Zhang & Bell 2017; Ferré-Mateu et al. 2018). While most cEs exist in a dense cluster environment, some are also found in loose environments of galaxy groups and fields. All previous studies have concentrated on large-scale, global environments containing cEs (e.g., Norris et al. 2014; Chilingarian & Zolotukhin 2015; Janz et al. 2016). However, small-scale environments of galaxies also have an impact on the various properties of the galaxies (e.g., Park et al. 2008; Park & Choi 2009; Geha et al. 2012; Robotham et al. 2014; Alpaslan et al. 2015). Therefore, it is important to study the dependence of cE properties on the local environment relative to their neighboring massive galaxy.

In this regard, most recently, Ferré-Mateu et al. (2018) studied various properties of 25 cEs at different evolutionary stages according to possible interactions with their massive neighbor galaxy. Although the number of cEs has grown over the last few years, a more extensive and homogenous sample of cEs in different local environments is required (e.g., Chilingarian et al. 2009; Chilingarian & Zolotukhin 2015). This would allow a more systematic investigation of properties of cEs to obtain further insights regarding cE formation. Hence, in this study, we searched for a large sample of cEs at $z < 0.05$ from the Sloan Digital Sky Survey (SDSS) DR12. We studied the stellar population properties of cEs depending on the local environment related to their host galaxy. In particular, we focused on comparing stellar population properties between two cE subsamples, namely those associated or not associated with a close host galaxy. The implications for different properties of cE subsamples are discussed in terms of rivaling cE formation scenarios.

This paper is organized as follows. In Section 2, we describe the cE sample construction. In Section 3.1, we present the environmental parameterization of cEs and the classification of cEs into subsamples with or without nearby massive host galaxy. In Section 3.2, we compare the stellar population properties of the two subsamples. In Section 3.3, we present the mass–metallicity distributions of the cEs. Finally, we discuss the formation scenarios of cEs and summarize the results in Section 4. Throughout this study, we assumed the cosmological parameters to be $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $h_0 = 0.73$.

2. Sample Selection

While cEs show luminosities similar to bright dEs, the effective radii of cEs are smaller than those of dEs. Moreover, cEs also have larger velocity dispersions compared to dEs at the same luminosity (Kormendy 1985). Following the selection criteria of Chilingarian & Zolotukhin (2015), we created a list of cE candidates in the redshift range of $z < 0.05$ using the SDSS DR12. The distances of these galaxies are estimated using radial velocities extracted from the SDSS based on the linear relationship between the radial velocity and distance. We initially chose low-luminosity ($M_r > −18.7$ mag) galaxies with a small Petrosian effective radius. Following the selection criteria of Chilingarian & Zolotukhin (2015), we created a list of cE candidates in the redshift range of $z < 0.05$ using the SDSS DR12. In particular, we selected galaxies with high-velocity dispersion ($\sigma > 60$ km s$^{-1}$) to accurately exclude dEs of similar brightnesses. The selected cE candidates included a total of 2352 galaxies. Three members of our team (S.K., H.J., and Y.L.) independently performed visual inspection of the images of all galaxies. The morphology of each galaxy was finalized if the classification of two or more classifiers agreed. Most galaxies show an underlying disk or central irregularity (see the top panels of Figure 1). We secured 403 cE candidates with only compact elliptical shapes (see the bottom panels of Figure 1).

We used the $R_{\text{eff,petro}}$ provided by the SDSS DR12 for selection of the cE candidates. However, the $R_{\text{eff,petro}}$ does not consider the seeing effect. The effective radius would be buried in the seeing size when the actual effective radius is smaller than the seeing size of the SDSS image. Hence, we redetermined the sizes of galaxies from SDSS r-band images using GALFIT (Peng et al. 2002), a two-dimensional galaxy-fitting code. For each galaxy image, GALFIT creates a convolution of a Sérsic model with the point-spread function from a set of point sources within the image field. GALFIT
finally provides the model effective radius ($R_{\text{eff, model}}$) of all cE candidates from a single-component Sérsic fit determined by comparing the convolved image with the SDSS image of the galaxy (see also Trujillo et al. 2006; Huxor et al. 2013).

Figure 2 shows a comparison between $R_{\text{eff, petro}}$ and $R_{\text{eff, model}}$ of the galaxies. The crosses are early-type galaxies in the Virgo cluster (crosses). The dotted line is the 1:1 relation to guide the eye. The vertical and horizontal solid lines show the typical seeing size of the SDSS r-band image (∼1.4 arcsec). Red circles denote 138 cEs with sizes less than 600 pc as the final sample for our analysis.

3. Results

3.1. Environments of Compact Ellipticals

We quantified the small-scale, local environment of our cE sample using the projected distances from each cE to the nearest luminous galaxy in the redshift range of $z < 0.05$ were chosen; these have the same luminosity range ($M_r > -18.7$ mag) as that of the cEs, but larger sizes ($R_{\text{eff}} > 600$ pc) and bluer colors ($g - r < 0.3$ and $NUV - r < 2$). The nearest luminous galaxies of blue dwarf galaxies were defined with the same criteria as those used for the cEs. As shown in Figure 3, most blue dwarf galaxies exist beyond one $R_{\text{vir}}$ of the luminous galaxy. This is consistent with the findings that the gas-rich, star-forming dwarf galaxies preferentially lie at larger distances from the massive galaxy (e.g., Mateo 1998; Tolstoy et al. 2009; Weisz et al. 2011, 2015 for the Local Group). Geha et al. (2012) also demonstrated that most of the dwarf galaxies located beyond 4
environments of EEs into a cluster, group, and the structure of the group catalog to classify the global dispersion of the group. We used the number of galaxies in between the EE and group is smaller than the velocity (R_vir) of a neighboring massive galaxy exhibit star formation (see the arrow in Figure 3). It is interesting to note that a large fraction of our EE(w/o) sample overlap with the distribution of blue dwarf galaxies in which approximately 63% of EE(w/o)s are located beyond four R_vir. This could imply that most EE(w/o) share low-density local environments with star-forming dwarf galaxies.

Additionally, we estimated the global environment of EEs using the group catalog of Tempel et al. (2014). We defined the host structure surrounding a EE if the EE is located within two R_vir of the nearest group and the radial velocity difference between the EE and group is smaller than the velocity dispersion of the group. We used the number of galaxies in the structure of the group catalog to classify the global environments of EEs into a cluster, group, and field following Norris et al. (2014): a cluster has more than 40 galaxies, a group has 10–40 galaxies, and a field has fewer than 10 galaxies. Furthermore, regardless of the number of the structure, if a EE is located beyond two R_vir of the nearest structure, the environment of the EE was considered to be the field. In our EE sample, 23, 24, and 91 EEs are found in the cluster, group, and field, respectively.

Figure 4 shows the location of our EE sample (circles) in the size-stellar mass space relative to other galaxies, including early-type galaxies (E/S0s, green boxes), dEs (crosses), and EEs (stars) compiled from literature (Bender et al. 1993; Ferrarese et al. 2006; Misgeld et al. 2008, 2009; Norris et al. 2014; Guérou et al. 2015). The stellar masses of our EEs are measured using the relation between the SDSS g − r color and the stellar mass-to-light ratio based on the i-band luminosity (Bell et al. 2003) assuming the initial mass function of Kroupa et al. (1993). The dotted line represents the linear best fit to E/S0s. The dEs differ from E/S0s in that dEs show small size variations over the large mass range, whereas E/S0s exhibit a steeper distribution. It is clear that most of the EEs in our sample are found in the same region as that occupied by previously known EEs. EEs locate below the distribution of dEs at a given mass, characterized by systematically smaller sizes than the diffuse low-mass galaxies with comparable masses. They instead fall on the extension of the relation defined by more massive E/S0s or lie in between the relations of E/S0s and dEs (Kormendy et al. 2009; Misgeld & Hilker 2011). In Figure 4, we cannot see distinct different distributions between the EE(w/s) (red circles) and EE(w/o)s (blue circles), implying that the size and stellar mass of EE are in a similar range regardless of the environment.

### 3.2. Stellar Populations of EEs

We investigated the stellar population properties of EEs based on Hβ, Mg b, Fe 5270, and Fe 5335 Lick indices extracted from the OSSY catalog (Oh et al. 2011). The OSSY catalog provides an improved database of absorption and emission-line measurements for all SDSS galaxies at z < 0.2 using the gandalf line-fitting code (Sarzi et al. 2006).

Figure 5 shows the observed line indices of EEs in comparison with the simple stellar population (SSP) model grid with various values of age, [Z/H], and [α/Fe] provided by Thomas et al. (2003). The red and blue circles represent EE(w/s) and EE(w/o)s, respectively. For comparison, we also present the distribution of early-type galaxies from the OSSY catalog (Oh et al. 2011) as contours. In Figure 5(a), we present the distribution of EEs in the plane of Hβ versus [MgFe]′ overlaid with the model grids with a fixed [α/Fe] value of 0.3. Hβ is an age indicator and the composite index [MgFe]′ is a good metallicity tracer (Thomas et al. 2003). While the majority of EEs show a similar [Z/H] distribution for early-type galaxies, a fraction of the EEs show smaller [Z/H] values. Most EEs also exhibit old ages similar to early-type galaxies. Interestingly, the metallicity distributions between the EE(w/s) and EE(w/o)s appear different in the sense that EE(w/s) are more biased toward higher [MgFe]′ values than EE(w/o)s (see the red and blue open squares for the median values of line indices of EE(w/s) and EE(w/o)s, respectively).

Figure 5(b) displays line indices of (Fe)8 and Mg b with the model grids for a representative age of 10 Gyr. It is clear that EEs show higher dispersion in [Z/H] values compared to early-type galaxies. Furthermore, the difference between the EE(w/s) and EE(w/o)s in terms of their metallicities is prominent; EE(w/s) are more metal-rich than EE(w/o)s (see the red and blue open squares for the median values of line indices of EE(w/s) and EE(w/o)s, respectively).

We derived the age, [Z/H], and [α/Fe] values of EEs by comparing the observed Lick indices with the SSP model grids of Thomas et al. (2003). In the model grid of Hβ−[MgFe]′, we need an [α/Fe] value for accurate estimation of the age and [Z/H] values because the dependence of this grid on [α/Fe] is not negligible. The (Fe)−Mg b grid also requires an age value for accurate estimation of [Z/H] and [α/Fe] values. Thus, to determine accurate age, [Z/H], and [α/Fe] values, we applied

\[
[MgFe]′ = Mg b(0.72 \times Fe 5270 + 0.28 \times Fe 5335)
\]  
(Thomas et al. 2003).

\[
(Fe) = (Fe 5270 + Fe 5335)/2
\]  
(Gorgas et al. 1990).
the iteration between two grids following the technique described in Puzia et al. (2005). For cEs located outside the model grids, we used the extreme grid value.

Figure 6 shows the distributions of derived age, [Z/H], and [α/Fe] values of cE(w) (red curve) and cE(w/o) (blue curve). The most notable feature is that the [Z/H] distribution of cE(w) s appears to be different from that of cE(w/o) s; cE(w) s show a skewed distribution toward higher [Z/H] values, whereas cE(w/o) s have a lower peak in the distribution. In the [α/Fe] distribution, cE(w/o) s exhibit a high fraction of relatively small [α/Fe] values, whereas cE(w) s show a rather flat distribution. As for the age distribution, a distinct difference is not shown between the cE(w) s and cE(w/o) s. We performed a K-S test to quantify the statistical significance of the differences in stellar population properties between the cE(w) s and cE(w/o) s. The test yields probabilities of <0.05, rejecting the null hypothesis of the same parent distribution between the cE(w) s and cE(w/o) s for [Z/H] and [α/Fe]. However, in the case of age, the probability is higher than 0.1, accepting the null hypothesis of the same underlying distribution. This indicates no statistically significant difference in the age distributions between the cE(w) s and cE(w/o) s.

In the metallicity versus age distribution obtained by Chilingarian & Zolotukhin (2015), there appears to be a difference in metallicities between cEs in isolated and dense environments (see Figure 2 of Chilingarian & Zolotukhin 2015). Of the 11 isolated cEs, 8 appear to be slightly more metal-poor than the majority of their counterparts in dense environments at a given age. However, they concluded that the metallicities of their isolated cEs do not show a statistically significant difference from those of nonisolated cEs. In Figure 7, we present the [Z/H] versus age distribution of our cE sample. We also overplot mean loci of cE(w) s (red curve) and cE(w/o) s (blue curve) by calculating the running average values of [Z/H] along the age, where the bin size and the step size of the age are 4 Gyr and 2 Gyr, respectively. It is clear that the distribution of cE(w) s (red circles) is well separated from that of cE(w/o) s (blue circles) in that cE(w) s are systematically more metal-rich than cE(w/o) s at any age. This result is in contrast to that obtained by Chilingarian & Zolotukhin (2015), which could be attributed to the small sample size of their isolated cEs compared to ours.

3.3. Mass–Metallicity Relation

It is well known that metallicity correlates with stellar mass in the sense that high-mass galaxies show higher metallicity. In this context, it is interesting to investigate the mass–metallicity distribution of cEs regarding their possible connection with galaxies in the higher-mass regime. Moreover, this would provide information on the mass of the progenitors, which can be used to constrain their formation.

In Figure 8(a), we present the distributions of cE(w) s (red circles) and cE(w/o) s (blue circles) in the plane of [MgFe]′ versus stellar mass. For comparison, we also plot early-type galaxies from the OSSY catalog (black small circles; Oh et al. 2011). The stellar masses of the early-type galaxies are also measured using the relation between the SDSS g – r color and the stellar mass-to-light ratio based on the i-band luminosity (Bell et al. 2003). The solid line is the linear best fit for early-type galaxies and dotted lines denote its 1σ deviation. We also overplot mean loci of cE(w) s (red curve) and cE(w/o) s (blue curve) by calculating the running average values of [MgFe]′ along the stellar mass, where the bin size and the step size of the log(stellar mass) are 0.4 $M_\odot$ and 0.2 $M_\odot$, respectively. cEs exhibit a large range of [MgFe]′ values at any given stellar mass compared to early-type galaxies. The most prominent feature is that cE(w) s have systematically higher [MgFe]′ values than the majority of cE(w/o) s at a fixed mass. Furthermore, cE(w) s are located mostly above the ±1σ of the linear best-fit line. In contrast, most cE(w/o) s follow the relation corresponding to early-type galaxies and are well
confined within 1σ lines (also see the blue curve for the mean locus of cE(w/o)s). This implies that cEs in different local environments are clearly separated with respect to their mass–metallicity relation in that cEs associated with a host galaxy are more metal-rich than their isolated counterparts at a given mass.

Further, to examine the features of cEs with respect to the large-scale, global environment (see Section 3.1), we also present the distributions of cEs in dense (i.e., cluster and group, Figure 8(b)) and sparse (i.e., field, Figure 8(c)) environments. As expected, most (80%) cEs residing in the cluster and group environments are associated with a host galaxy (i.e., cE(w)s). These galaxies show large deviations from the mass–metallicity relation of early-type galaxies. Most of the cEs in the field environment are those with no host galaxy (i.e., cE(w/o)s); these galaxies conform to the mass–metallicity relation of early-type galaxies. However, it is interesting to note that, contrary to our expectation, a non-negligible fraction (31%) of cEs in the field environment also have a plausible host galaxy nearby. Furthermore, even in the field environment, the [MgFe]′ versus mass distribution of cE(w)s is also clearly different from that of cE(w/o)s, similar to that shown in dense environments.

In Figure 8(d), we present the distribution of Δ[MgFe]′, which is the difference between the observed [MgFe]′ values and expected ones from the mass–metallicity relation of early-type galaxies at a given mass of cE(w)s (red histogram) and cE(w/o)s (blue histogram) in the field environment. It is clear that the Δ[MgFe]′ distributions between the cE(w)s and cE(w/o)s are different. While the Δ[MgFe]′ distribution of cE(w/o)s is very similar to that of early-type galaxies (gray histogram), the distribution of cE(w)s shows offsets from those of cE(w/o)s and early-type galaxies. This is confirmed by the statistical significance of the K–S test: the probabilities of Δ[MgFe]′ distributions of the early-type galaxies versus cE(w/o)s and of the early-type galaxies versus cE(w)s are 0.051 and 0.001, respectively. Moreover, the distribution of cE(w)s in the field is very similar to that of cE(w)s in the cluster and group environments (red dashed histogram).

4. Discussion and Conclusions

In this study, we explored the environmental dependence of the population properties of a large sample of cEs at z < 0.05 using the SDSS DR12. Examination of the distance from a neighboring luminous galaxy suggests the existence of a distinct population of cEs that is beyond the Rvir of a luminous galaxy (i.e., cEs with no host galaxy; cE(w/o)s) in addition to the population that is located close to a luminous galaxy (i.e., cEs with a host galaxy; cE(w)s) (see Figure 3). Our classification of cEs in this small-scale, local environment shows reasonable agreement with that for the large-scale, global environment. Most cEs in dense environments such as clusters and groups are present in the vicinity of a host galaxy (see Figure 8(b)). However, contrary to our expectation, some fraction of cEs in the field environment also show a plausible host galaxy nearby (see Figures 8(c) and (d)). The existence of a non-negligible fraction of cE(w)s in the field environment suggests that the local environment associated with a nearby
massive galaxy may also be essential for investigating the properties and formation of cEs depending on the environment.

Our most important result is that the metallicity distributions between the two cEs samples, cE(w/s) and cE(w/o)s, are significantly different. cE(w/s) show a skewed distribution toward higher metallicities compared to that of cE(w/o)s (see Figures 6 and 7), which is statistically confirmed by the K–S test (see Section 3.2). Most of the cE(w/s) deviate from the mass–metallicity relation of early-type galaxies, being more metal-rich than metallicities that could be expected from their low masses (see Figure 8(a)). Therefore, cE(w/s) lie to the left (i.e., lower stellar mass) of early-type galaxies in the plane of the [MgFe] vs. mass. This indicates that the metallicities of cE(w/s) are rather similar to those of more massive early-type galaxies. However, the bulk of cE(w/o)s follow the mass–metallicity relation of early-type galaxies in the low-mass regime. Metallicity can be a measure of the original mass of the progenitor of a cE in terms of the mass–metallicity relation; this reinforces our conclusion that cE(w/s) and cE(w/o)s are distinct classes of cEs.

The high metallicities of cE(w/s) suggest that cE(w/s) are initially larger, more massive galaxies but stripped down by a nearby host galaxy through a stripping process. Therefore, in the mass–metallicity distribution, high-mass progenitors of cE(w/s) can move to remnant galaxies with lower stellar mass but preserving their high metallicities. According to the [Z/H] versus mass relation determined by De Masi et al. (2018) and mean mass of our cE(w/s) ~10^{9.25} M_\odot, the progenitors of cE(w/s) would initially have a mean stellar mass of 10^{10.34} M_\odot. This indicates that cE(w/s) lost more than 90% of their original masses in the stripping process (see also Chilingarian et al. 2009; Norris et al. 2014; Ferré-Mateu et al. 2018). On the other hand, the existence of cE(w/o)s and their stellar populations with lower metallicities underlines the necessity of an additional channel for the formation of present-day cEs. In this case, cE(w/o)s might be rather bona fide low-mass classical early-type galaxies.

We also observed a possible difference in the [\alpha/Fe] distributions between the cE(w/s) and cE(w/o)s, although its significance is lower than that of metallicity (see Figure 6). The [\alpha/Fe] distribution of cE(w/o)s is skewed toward lower values and cE(w/o)s have a slightly higher (~0.15 dex) mean value of [\alpha/Fe] than cE(w/s). In general, [\alpha/Fe] traces the star formation history (SFH), reflecting the efficiency and timescale

**Figure 8.** (a) [MgFe] vs. stellar mass distributions of cE(w/s) (red circles) and cE(w/o)s (blue circles). The small black circles are early-type galaxies from the OSSY catalog (Oh et al. 2011). The solid line is the linear best fit for early-type galaxies and dotted lines denote its 1σ deviation. The red and blue curves represent the mean loci of cE(w/s) and cE(w/o)s, respectively. (b) Same as (a), but for cEs in cluster and group environments. (c) Same as (a), but for cEs in the field environment. (d) Distributions of Δ[MgFe], which is the difference between observed [MgFe] values and expected ones from the mass–metallicity relation of early-type galaxies at a given mass, of cE(w/s) (red histogram) and cE(w/o)s (blue histogram) in the field environment. The gray histogram is for early-type galaxies. The red dashed histogram denotes the distribution of cE(w/s) in cluster and group environments. The vertical solid and dotted lines correspond to the linear best fit for early-type galaxies and its 1σ deviation in [MgFe] vs. stellar mass distribution, respectively.
of star formation in galaxies (Thomas et al. 2005). Moreover, \([\alpha/Fe]\) correlates with the galaxy mass; rapid (< 1 Gyr) and efficient star formation occurred in the massive galaxies, while low-mass galaxies experience an extended (> 1 Gyr) and less efficient star formation (e.g., Spolaor et al. 2010 and references therein). In this context, our result is naturally compatible with the mass-dependent SFH at the early star-forming epoch. A higher mean \([\alpha/Fe]\) of CE(w)s implies an SFH with rapid star formation in their massive progenitors. In contrast, a lower \([\alpha/Fe]\) of CE(w/o)s is indicative of an extended SFH with relatively long star formation timescale (a few Gyr), which is consistent with genuine low-mass galaxies (see also Ferré-Mateu et al. 2013). Therefore, the difference in \([\alpha/Fe]\) between the CE(w)s and CE(w/o)s is an additional evidence supporting the existence of different original masses of progenitors corresponding to their different formation channels.

Our results strengthen the suggestion that CEs are mixtures of galaxies with two types of origins depending on their environment (e.g., Ferré-Mateu et al. 2018 and references therein). One contains remnants of larger galaxies with bulges tidally stripped by a neighboring massive host galaxy (i.e., stripped CEs). The other comprises real low-mass classical early-type galaxies in an isolated environment with no massive galaxy nearby (i.e., intrinsic CEs). On the observational side, these two scenarios cannot be reliably distinguished in parameter spaces (e.g., size versus mass diagrams) owing to the similarity in the structural parameters of all CEs. However, we can strongly suggest that the metallicity of CEs may be one of the key parameters responsible for discriminating between rival formation scenarios of CEs, because there should be residual metallicity signatures pertaining to different origins. In combination with other diagnostic tools based on high-quality spectroscopic observations, we can further infer the evolutionary stages and progenitor types for a large sample of CEs in future works.

We are grateful to the anonymous referee for helpful comments and suggestions that improved the clarity and quality of this paper. S.K. acknowledges support from the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2019R1I1A1A01061237). S.C.R., acting as the corresponding author, acknowledges support from the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2020R1I1A1A01055595).