Coordinated Assembly of Brightest Cluster Galaxies

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Abstract

Brightest Cluster Galaxies (BCGs) in massive dark matter halos are shaped by complex merging processes. We present a detailed stellar population analysis in the central region of Abell 3827 at z = 0.1, including five-nucleus galaxies involved in a BCG assembly. Based on deep spectroscopy from the Multi Unit Spectroscopic Explorer, we fit the optical spectra of 13 early-type galaxies (ETGs) in the central 70 kpc of the cluster. The stellar populations in the central R = 1 kpc of these ETGs are old (>6 Gyr). Their [Fe/H] increases with σ and stellar mass. More importantly, [α/Fe] of galaxies close to the cluster center do not seem to depend on σ, or stellar mass, indicating that the cluster center shapes the [α/Fe]–σ, and [α/Fe]–Mσ relations differently than other environments where [α/Fe] is observed to increase with increasing σ and Mσ. Our results reveal the coordinated assembly of BCGs: their building blocks are different from the general low-mass populations by their high [α/Fe] and old ages. Massive galaxies thus grow by accreting preferentially high [α/Fe] and old stellar systems. The radial profiles also bear the imprint of the coordinated assembly. Their declining [Fe/H] and flat [α/Fe] radial profiles confirm that the accreted systems have low metallicity and high [α/Fe] stellar contents.

Key words: galaxies: clusters: individual (Abell 3827) – galaxies: evolution – galaxies: stellar content

1. Introduction

According to the Λ–Cold Dark Matter model, galaxy assembly is closely linked to the hierarchical growth of dark matter structures. Local massive early-type galaxies (ETGs) are considered to have evolved from the compact “red nuggets” at z ≈ 2 by doubling their stellar masses and increasing their effective radii by a factor of 3–5 (e.g., van Dokkum et al. 2010; Patel et al. 2013). Recent simulations describe this transformation by the two-phase scenario (e.g., Naab et al. 2009; Oser et al. 2010, 2012), in which massive ETGs experience strong dissipational processes that lead to rapid and concentrated mass growth at high redshifts, and accrete low-mass systems at later times to build up the outer envelopes. Brightest cluster galaxies (BCGs) are a special class of ETGs at the extreme high-mass end of the stellar mass function and in the densest environments. They have diffuse and extended envelopes (e.g., Schombert 1988) that can be explained by a series of merging events (e.g., Ostriker & Tremaine 1975; Hausman & Ostriker 1978; Dubinski 1998).

It is still ambiguous whether the low-mass galaxies we observe today are intrinsically different from the building blocks of massive galaxies, or their surviving counterparts. One useful approach is to compare the abundance trends of their stellar contents, especially the ratio between α–elements to iron. [α/Fe] is used to indicate the star formation timescales due to its sensitivity to the time delay between SNe II and SNe Ia (e.g., Tinsley 1979). SNe II from massive stars yield both α-elements and Fe, while SNe Ia from low-mass binary systems contribute mostly Fe on longer timescales. High [α/Fe] in old stellar population suggests short star formation timescales in the past. Stellar population analysis has revealed correlations between stellar population properties and stellar mass or stellar velocity dispersion (e.g., Trager et al. 2000; Worthey & Collobert 2003; Thomas et al. 2005; Schiavon 2007; Thomas et al. 2010; Conroy et al. 2014; McDermid et al. 2015) in a way that massive galaxies are older, more metal-rich, and more α-enhanced compared to low-mass galaxies. If these trends are universal for all environments and epochs, an apparent tension under the hierarchical assembly paradigm would emerge: the building blocks of massive galaxies, especially the BCGs would have “diluted” the [α/Fe] at the high-mass end, and/or would produce steep [α/Fe] gradients. This would make it difficult to reconcile with the general observational facts that more massive galaxies are more α-enhanced.

The Milky Way satellite dwarf galaxies were once thought to be the surviving counterparts of Galactic building blocks until studies revealed their stellar populations occupy different locations from Milky Way halo stars on the [α/Fe] versus [Fe/H] diagram (e.g., Tolstoy et al. 2009). Looking beyond the Milky Way, Liu et al. (2016) showed that the [α/Fe] of low-mass ETGs in the Virgo cluster depend on the distance to the cluster center and the [α/Fe]–σ relation in this cluster has larger scatter, indicating that the densest environments quench low-mass galaxies earlier than other environments. From these studies, it seems that the assembly of massive galaxies are coordinated in a way that their building blocks have early truncated star formation histories, making them a particular sample with high [α/Fe] among the low-mass systems.

In this Letter, we present stellar population analysis on 13 ETGs in Abell 3827. Five of these are involved in a rarely observed BCG assembly from multiple mergers; therefore, we are fortunate to directly analyze the building blocks of a prospective BCG. [Mg/Fe] is used as a tracer of [α/Fe]. We compare the stellar population scaling relations in this special environment to the general samples in previous work. We assume a flat ΛCDM cosmology with h = 0.73, Ω_m = 0.27, Ω_Λ = 0.73. The redshift of Abell 3827 is cz = 29,500 km s^{-1} (Struble & Rood 1999). The distance is assumed to be 433 Mpc. This corresponds to a distance modulus of 38.18 mag and a scale of 1.74 kpc arcsec^{-1}. All magnitudes in this paper are in the AB system. The mass center of Abell 3827 is assumed to be at R.A. =22^h 01^m 52.90, decl. = −59^d 56′ 44′′ 89
2. Data and Methods

We use the datacube obtained by the Multi Unit Spectroscopic Explorer (MUSE) Integral Field Unit spectrograph (Bacon et al. 2010; Le Fevre et al. 2013) on the European Southern Observatory (ESO) Very Large Telescope (VLT). Abell 3827 was observed in 2015 (ESO programme 295.A-5018(A), PI: Richard Massey, Massey et al. (2015, 2017)), centered at R.A. = 22°03′14″.65, decl. = −59°56′43″.19. We reduce and combine the data using MUSE Pipeline muse-2.2 (Weilbacher et al. 2014, 2016). According to Massey et al. (2017), observations were taken in dark time with seeing around 0″7. The total integration time in the final datacube is 3.2 hr. The field of view (FoV) is 1′ × 1′. The wavelength coverage is 475–935 nm, sampled at 1.25 Å/pixel, with mean spectral resolution ~3000 at the optical wavelength range. The spatial pixel size is 0″2 × 0″2. Due to the small FoV, we limit the sky regions during the data reduction, by setting skymodel_fraction to 0.01. As a result, the surface brightness profiles in of the MUSE datacube are consistent with the Hubble Space Telescope (HST)/ACS image out to $μ_{H606W} = 24$ mag arcsec$^{-2}$, with $Δμ_{H606W} \approx 0.22$ mag arcsec$^{-2}$ at $μ_{g5056W} = 24$ mag arcsec$^{-2}$.

Galaxies in Abell 3827 and foreground stars are identified using SExtractor (Bertin & Arnouts 1996). Thirteen ETGs in Abell 3827 are selected for further analysis. They are all confirmed spectroscopically and are shown in Figure 1. We mask out foreground stars and background lensed galaxies (white hatched region). To study the radial profiles of stellar populations, we analyze the spectra by binning spaxels in radial directions for N1–N4 and N9. The binning scheme is shown in the right panel of Figure 1.

To model galaxies spectra, we use the absorption line fitter (alf; Conroy & van Dokkum 2012; Conroy et al. 2014, 2018). alf enables stellar population modeling of the full spectrum for stellar ages >1 Gyr and for metallicities from $∼$−2.0 to +0.25. Parameter space is explored using a Markov Chain Monte Carlo algorithm (emcee; Foreman-Mackey et al. 2013). alf adopts the MIST stellar isochrones (Choi et al. 2016) and uses a new spectral library (Villaume et al. 2017) that includes continuous wavelength coverage from 0.35 to 2.4 μm over a wide range in metallicity, which taken from new IRTF NIR spectra for stars in the MILES optical spectral library (Sánchez-Blázquez et al. 2006). Theoretical elemental response functions were computed with the ATLAS and SYNTHE programs (Kurucz 1970, 1993). They tabulate the effect on the spectrum of enhancing each of the individual elements. With alf in “full” mode, we fit for parameters including a two-burst star formation history, the redshift, velocity dispersion, overall metallicity, 18 individual element abundances, and several IMF parameters (Conroy et al. 2018). Throughout this paper, we use alf with the IMF fixed to the Kroupa (2001) form. We use flat priors within these ranges: $−10^3$ to $10^5$ km s$^{-1}$ for recession velocity, $100$–$1000$ km s$^{-1}$ for velocity dispersion, 1.0–14 Gyr for age and $−1.8$ to +0.3 for metallicities. For each spectrum, we fit a continuum in the form of a polynomial to the ratio between model and data. The order of polynomial is $(λ_{max} − λ_{min})/100$ A. During each likelihood call, the polynomial divided input spectrum and model are matched. The continuum normalization occurs in three separate wavelength intervals, 4300–5080 Å, 5080–5700 Å, and 5700–6700 Å.

Five galaxies have central velocity dispersion smaller than the resolution of the models (100 km s$^{-1}$): N5, N6, N11, N12, and N15. Their spectra are smoothed by convolving a wavelength dependent Gaussian kernel with $σ = \sqrt{100^2 − σ_i^2}$ prior to the modeling, where $σ_i$ is the wavelength dependent instrumental resolution.

To study the spatial distribution of stellar population parameters, spectra in adjacent spaxels are binned by Voronoi tessellation (Cappellari & Copin 2003). The mean signal-to-noise

Figure 1. Left panel: overview of the locations of ETGs studied in this paper on a SDSS−r−iz composite image derived from the MUSE datacube. Red circles enclose $R = 2$ kpc. Right panel: zoomed-in SDSS−r band surface brightness map derived from the MUSE datacube. Solid lines enclose stacked regions for radial profiles. White hatched regions highlight masked out spaxels.

(Massey et al. 2015). We assume the r-band solar absolute magnitude to be 4.76 mag (Blanton et al. 2003).
ratio \( (S/N) \) in observed frame 4500–5000 Å of this binning scheme is shown in the top left panel of Figure 2. The \( S/N \) is between 40 and 110 Å\(^{-1}\). In addition to foreground stars and lensed galaxies, we also exclude bins where foreground and background galaxies overlap with each other, e.g., some spaxels between N4 and N2. Only bins where the best-fit spectra and residuals are visually consistent with data and data uncertainties are shown here. The low \( S/N \) at the outskirts (\( R > 3 \) kpc) of low-mass ETGs makes it hard to derive a reliable mass-to-light ratio \( (M/L) \). Therefore, we assume a constant \( M/L \) as a function of radius and adopt the \( M/L \) measured within \( R = 1 \) kpc. The stellar masses within \( R = 5 \) kpc of the 13 ETGs are derived by multiplying the rest-frame \( r \)-band total integrated luminosity within \( R = 5 \) kpc, by the best-fit \( M/L \) in \( r \) band within \( R = 1 \) kpc.

### 3. Results and Discussion

We present results in this section. Objects N1, N2, N3, N4, and N9 have the closest projected distances to the mass center (\( \leq 18 \) kpc). Their recession velocities relative to the cluster center \( (cz = 29,500 \text{ km s}^{-1}) \) are \( cz = -45_{-2}^{+3} \text{ km s}^{-1}, 167_{-3}^{+1} \text{ km s}^{-1}, 359_{-3}^{+1} \text{ km s}^{-1}, -830_{-3}^{+1} \text{ km s}^{-1}, \) and \( 452_{-3}^{+1} \text{ km s}^{-1} \), respectively. Given their small projected distances to the cluster center and very similar velocities, they are on their way to form a massive BCG in the near future. If we estimate the time it would take based the dynamical friction time (Binney & Tremaine 1987), the five ETGs will merge within 1 Gyr. Therefore, we assume N1–N4 and N9 are building blocks of a prospective BCG with \( \log (M_{*}/M_{\odot}) \approx 11.7 \).

Spatial distribution of the following parameters are shown in Figure 2: \( cz, \sigma_{*}, \) stellar age, \([\text{Fe/H}]\) and \([\text{Mg/Fe}]\), focusing on \( D \approx \pm 25 \) kpc around the cluster center. The \( cz \) distribution shows that the five ETGs are all members of the cluster. The \( \sigma_{*} \) map shows that \( \sigma_{*} \) declines outwards from the center of N1–N4 within \( R < 2 \) kpc, and rises toward the outskirts, reaching \( \sim 400–500 \text{ km s}^{-1} \). This shows that the stars in the outskirts are tracing the gravitational potential of the cluster, instead of any individual galaxy, and describes the formation of the cD envelope, or the intracluster light component that have been measured in other galaxy clusters (e.g., Kelson et al. 2002).

Due to the large \( \sigma_{*} \), the typical errors of \( \log(\text{age}/\text{Gyr}) \), \([\text{Fe/H}]\) and \([\text{Mg/Fe}]\) are \( \sim 0.1 \) dex in bins with \( S/N \approx 50 \) Å\(^{-1}\). The stellar age distribution shows this region is uniformly old. From the \([\text{Fe/H}]\) distribution, we see declining \([\text{Fe/H}]\) from the galaxy centers outwards, indicating that the inner regions of the galaxies are more metal-rich than the cD envelop where the stellar content is likely from disrupted low-mass systems. The distribution of \([\text{Mg/Fe}]\) shows that the \( \alpha \)-abundance in this region is generally high, with no particular pattern of differences between the galaxy centers and the cD envelope, indicating that the stellar content has short star formation timescales in general.

Figure 3 shows the main result. We compare the median stellar population parameters within \( R = 1 \) kpc, including \([\text{Fe/H}]\), stellar ages, and \([\text{Mg/Fe}]\) as a function of galaxy velocity dispersion \( \sigma_{*} \) and galaxy stellar mass. Colors indicate the projected distance to the cluster mass center. Previous studies found scaling relations between stellar population properties and the central \( \sigma_{*} \): the stellar components in galaxies with higher central \( \sigma_{*} \) are older, more metal-rich, and more \( \alpha \)-enhanced (e.g., Trager et al. 2000; Thomas et al. 2005; Schiavon 2007; Graves et al. 2009; Conroy et al. 2014). We compare our results to previous studies in Figure 3, including a large sample of morphologically selected SDSS ETGs in Thomas et al. (2005) (red dashed–dotted line), ETGs in ATLAS3D by
McDermid et al. (2015) (blue circles), and 12 ETGs in the Coma cluster by Trager et al. (2008) (green triangles). We estimate [Fe/H] in the above works using Equation (4) in Thomas et al. (2003) assuming the factor A = 0.94 (Trager et al. 2000). We also compare to stacked SDSS ETGs that are binned in σ*, and stellar mass in Conroy et al. (2014), except that they are fit with the updated response functions.

For stellar age and [Fe/H], our results agree with the trends found in the general ETG populations: galaxies with high central stellar velocity dispersion or larger stellar mass are older and more metal-rich. For [Mg/Fe], our results are distinctly different from ETGs in the field. The [Mg/Fe] of galaxies within ~40 kpc to the cluster center have high [Mg/Fe], even indicating a trend that smaller galaxies are more [Mg/Fe] enhanced. If we assume the variation of [Mg/Fe] is due to the differences of star formation timescale (e.g., Thomas et al. 2005), Figure 3 illustrates that compared to galaxies in all environments, the ETGs with lower σ*, or stellar masses within ~40 kpc in Abell 3827 are quenched as early (if not more), more massive galaxies. Our results highlight the effect of “environmental quenching” (e.g., Peng et al. 2010) on low-mass galaxies, possibly due to the complex interplay between processes such as ram pressure stripping and strangulation. The high [α/Fe] and old stellar ages make the building blocks very different from low-mass galaxies in general and are possibly due to early quenching by the dense environment.

As described earlier, N1–N4 and N9 are very likely building blocks of a BCG in the future. Although multiple nuclei are rarely observed, it has been predicted by recent simulations that major mergers play an important role in the build-up of massive galaxies (e.g., Rodriguez-Gomez et al. 2016). We estimate the Stellar population properties of the prospective BCG through weighting the properties of the five ETGs by luminosity. The lower limit of its stellar mass is estimated using the total stellar mass of N1–N4 and N9 within R = 5 kpc: log(M*/M⊙) ≈ 11.7. The diffuse component is not included due to the contamination from the lensed galaxies and the foreground stars. The predictions are shown as black stars in Figure 3. This prospective BCG would fall on all of the empirical trends between stellar population parameters and stellar mass.

The coordinated assembly picture can be described by the schematic diagrams in Figure 4: the building blocks of BCGs are low-mass galaxies in a special environment–cluster centers.

**Figure 3.** Top panel: relationships between σ, and stellar population parameters: [Fe/H], stellar ages and [Mg/Fe]. Bottom panel: relationships between stellar mass measured within R = 5 kpc and stellar population parameters measured within R = 1 kpc. Colors indicate the projected distance from the center of galaxies to the mass center of the cluster. Thirteen ETGs in our sample are compared to a large sample of morphologically selected SDSS ETGs in Thomas et al. (2005; red dashed-dotted line), ETGs in ATLAS3D by McDermid et al. (2015; blue circles), 12 ETGs in the Coma cluster by Trager et al. (2008; green triangles), and updated results from stacked SDSS ETGs that are binned in σ*, and stellar mass (Conroy et al. 2014).

**Figure 4.** Schematic diagrams for scaling relations of [α/Fe] or log(age) vs. log(M*) or log(age) of a massive ETG would build up (right) if it accreted systems randomly in all environments (blue), or coordinately from a sample of low-mass galaxies that are quenched early on by the dense environments (red).
They follow a relatively flat relation between [\(\alpha/Fe\)] or stellar age and stellar mass (red box), which are distinct from the relations followed by galaxies in the fields (blue box). The right panel shows the expected radial profiles of the massive ETGs: as the low-mass systems in the cluster center accrete onto the outskirts of massive ETGs, the coordinated assembly produces flat radial profiles of stellar age and [\(\alpha/Fe\)] (red), whereas if the accreted systems are random draws from the low-mass galaxy sample in all environments, the profiles of stellar age and [\(\alpha/Fe\)] would decline with radius.

The radial profiles of stellar population properties confirm the coordinated assembly picture. Figure 5 shows the radial profiles of velocity dispersion \(\sigma_v\), stellar ages, [Fe/H], and [Mg/Fe] for N1–N4 and N9. The binning schemes are shown in the right panel of Figure 1. These profiles are compared to those of six ETGs in van Dokkum et al. (2017a). Note that we only show the combined profiles from both sides of the six ETGs. Due to the contamination of the foreground stars and background lensed galaxies, we are not able to extend the radial trends beyond 14 kpc. However, we can already see rising velocity dispersion profiles built up for N1–N3, which is consistent with the expected cD galaxy profiles (e.g., Kelson et al. 2002). The stellar ages profiles indicate that the ages of the five ETGs are generally old from the center to the outskirts. [Fe/H] declines with the radius and seems to depend on the central velocity dispersions within \(R = 2\) kpc. This is consistent with the two-phase formation scenario (e.g., Naab et al. 2009; van der Wel et al. 2014) that the inner regions are mostly built up by the dissipational process at high redshifts and thus are strongly dependent on the central stellar velocity dispersions, and the outskirts are dominated by accretion of small stellar systems. [Mg/Fe] profiles are generally flat. Flat [\(\alpha/Fe\)] profiles have also been observed previously (e.g., Sánchez-Blázquez et al. 2007; Greene et al. 2015). This is consistent with the coordinated assembly picture.

4. Summary

We have presented detailed stellar population studies for 13 ETGs in Abell 3827 using the optical spectra from MUSE on the VLT. The sample includes five ETGs that are involved in an ongoing assembly of a BCG. Our conclusions are summarized as follows:
1. The 13 ETGs are spectroscopically confirmed members of Abell 3827. Their stellar age and [Fe/H] fall on empirical trends that galaxies with higher \( \sigma \), or stellar mass are older and more metal-rich. However, ETGs within 40 kpc from the cluster center show higher [Mg/Fe] compared to the [Mg/Fe]–\( \sigma \), and [Mg/Fe]–\( M \), relations in the field.

2. From the spatial distribution in the central region of the cluster, the stellar populations in the diffuse stellar light of Abell 3827 are generally old and \( \alpha \)-enhanced.

3. We show the radial profiles of \( \sigma \), stellar age, [Fe/H], and [Mg/Fe] that are consistent with previous studies. The flat stellar age and [Mg/Fe] profiles confirm the coordinated assembly picture.

4. Our results highlight the effect of “environmental quenching”, and reveal the coordinated assembly of BCGs: the building blocks of the prospective BCG in Abell 3827 are distinct from the general low-mass systems by high [\( \alpha/\text{Fe} \)] due to early quenching by the dense environment.

Future spectroscopic observations of cluster centers will place constraints on the formation history of massive galaxies and will shed additional light on the general picture of coordinated assembly.

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