ON THE RADIAL STELLAR CONTENT OF EARLY-TYPE GALAXIES AS A FUNCTION OF MASS AND ENVIRONMENT

F. La Barbera1, I. Ferreras2, R. R. de Carvalho3, P. A. A. Lopes4, A. Pasquali5, I. G. de la Rosa6,7,8, and G. De Lucia9
1 INAF-Osservatorio Astronomico di Capodimonte, Napoli, Italy
2 University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK
3 Instituto Nacional de Pesquisas Espaciais/MCT, S. J. dos Campos, Brazil
4 Observatório do Valongo/UFRJ, Rio de Janeiro, Brazil
5 Astronomisches Rechen Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstr. 12–14, 69120 Heidelberg, Germany
6 Instituto de Astrofísica de Canarias (IAC), E-38200 La Laguna, Tenerife, Spain
7 Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK
8 Departamento de Astrofísica, Universidad de La Laguna, E-38205, Tenerife, Spain
9 INAF-Osservatorio Astronomico di Trieste, via G.B. Tiepolo 11, I-34143 Trieste, Italy

Received 2011 June 28; accepted 2011 July 29; published 2011 September 29

ABSTRACT

Using optical–optical and optical–NIR colors, we analyze the radial dependence of age and metallicity inside massive ($M_*>10^{10.5} M_\odot$), low-redshift ($z<0.1$), early-type galaxies (ETGs), residing in both high-density group regions and the field. On average, internal color gradients of ETGs are mainly driven by metallicity, consistent with previous studies. However, we find that group galaxies feature positive age gradients, $\nabla t$, i.e., a younger stellar population in the galaxy center, and steeper metallicity gradients, compared to the field sample, whose $\nabla t$ ranges from negative in lower mass galaxies to positive gradients at higher mass. These dependencies yield new constraints on models of galaxy formation and evolution. We speculate that age and metallicity gradients of group ETGs result from (either gas-rich or minor-dry) mergers and/or cold-gas accretion, while field ETGs exhibit the characteristic flatter gradients expected from younger, more metal-rich stars formed inside-out by later gas cooling.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: fundamental parameters

1. INTRODUCTION

Being hot dynamical systems, early-type galaxies (ETGs) are often assumed to form from major mergers, where the progenitors can be either gas-rich disks or ETGs. The predominantly old stellar populations (SPs) found in these galaxies indicate a rapid and intense star formation history, although the detection of compact, massive ETGs at high redshift (Daddi et al. 2005) implies a change in size of a factor of 3–5 between $z\sim2$ and $z=0$ (see, e.g., Trujillo et al. 2007).

Recent studies of the size evolution of massive ETGs over the past 8 Gyr propose a number of alternative scenarios, such as minor mergers (Naab et al. 2009; Trujillo et al. 2011) or a puffing-up of the central regions caused by the baryonic mass loss (Damjanov et al. 2009; Fan et al. 2010). Alternatively, cold accretion—perhaps reminiscent of the monolithic collapse scenario (Larson 1975)—may provide an independent channel for the formation of massive galaxies, accounting for the highly efficient star formation measured in these systems at high redshift (Dekel et al. 2009). In addition, the environment can contribute as well to the star formation history. As a galaxy enters a group, its hot gas reservoir can be removed, shutting off star formation (“strangulation”). All these processes may be discerned if spatial information within galaxies is taken into account. The majority of studies on the star formation history of ETGs use observations integrated within an aperture, losing the discriminating power. Radial gradients of photometric data represent a fundamental observable to disentangle the different formation channels described above. Studies of local samples of ETGs show that the majority feature red cores (see, e.g., Peletier et al. 1990). Blue cores are less frequent, being mostly low-mass ($M_\ast \lesssim 10^{10.5} M_\odot$) ETGs (Suh et al. 2010). Radial gradients of spectral line strengths reveal a significant trend in metallicity (see, e.g., Forbes et al. 2005; Ogando et al. 2005; Spolaor et al. 2009; Koleva et al. 2011) and an intriguing dependence of the age gradients on environment (Sánchez-Blázquez et al. 2006). Extending the analysis to moderate redshift takes advantage of the look-back time, as younger populations are less affected by the age–metallicity degeneracy. The analysis of the color gradients of the GOODS sample of ETGs over a wide redshift range ($0.4 < z < 1$) confirmed a clear metallicity radial gradient for the red-cored galaxies, and a significantly younger population at the centers of the blue-cored galaxies (Ferreras et al. 2009), with an increase in the fraction of blue- versus red-cored profiles toward lower stellar masses.

Galaxy mass and environment are the two main drivers of the formation history of galaxies (see, e.g., Weinmann et al. 2009) and recent work on ETGs has revealed a significant difference between the two, with environment only playing a secondary role on the SPs (Rogers et al. 2010) although with more significant effects on dynamical relationships such as the fundamental plane (La Barbera et al. 2010b, hereafter LLD10). In this Letter, we extend the analysis by inferring age and metallicity radial gradients of low-redshift ETGs from a multi-wavelength data set in the optical and NIR. Our findings reveal a significant contribution of the environment to the formation and assembly mechanisms of ETGs.

2. SAMPLE

The SPIIDER survey consists of a volume-limited sample of 39,993 bright ETGs ($M_\ast < -20$) in the redshift range $0.05 \leq z \leq 0.095$, with $griz$ photometry from SDSS-DR6. Five thousand and eighty of these galaxies also have $YJHK$ imaging from the UKIDSS-Large Area Survey (see LLD10, 2011).
ETGs are defined as galaxies with a prominent bulge, and a passive spectrum in their central regions (within the Sloan Digital Sky Survey (SDSS) fiber). Galaxies have structural parameters, i.e., effective radius, $R_e$, mean surface brightness within that radius, $(\mu_r)_e$, and Sérsic index, $n$, homogeneously measured from $g$ through $K$ with the software 2DPHOT, by fitting galaxy images with seeing-convolved two-dimensional Sérsic models. The environment of ETGs is characterized by a friends-of-friends catalogue of 8083 groups. A shifting gapper technique is applied to this catalogue (see Lopes et al. 2009) allowing galaxies to be classified as either group members ($\sim 46\%$), non-group members (hereafter “field” galaxies, $\sim 33\%$), or unclassified ($\sim 21\%$; see LLD10). Each group galaxy has two-dimensional local density, $\Sigma_N$, estimated by its distance to the nth nearest group member, where $n$ scales as the square root of group richness.

We select only galaxies with better quality structural parameters from $g$ through $K$ ($\sim 90\%$ of the sample; see La Barbera et al. 2010a, hereafter LDD10) and stellar mass $M_*$ $\geq 3 \times 10^{10} M_\odot$, which gives an $M_*$ complete sample of ETGs. These selections result in a sample of 9285 (936) field galaxies with optical (optical+NIR) data available. For group galaxies, we select only ETGs residing in the highest density regions, $\Sigma_N \gtrsim 16.6 \text{gals Mpc}^{-2}$ ($\Sigma_N \gtrsim 6.4 \text{gals Mpc}^{-2}$) for the optical (optical+NIR) sample. These $\Sigma_N$ thresholds are chosen to emphasize the environmental dependence of galaxy color gradients, without overly reducing the number of group galaxies, which consist of 1792 (optical) and 487 (optical+NIR) ETGs. Most of the parent systems where these ETGs reside are relatively poor groups, with an average velocity dispersion of $\sim 370 \text{km s}^{-1}$. Both field and group ETGs are split among three $M_*$ bins: “low” ($3 < M_* < 5 \times 10^{10} M_\odot$), “intermediate” ($5 < M_* < 8 \times 10^{10} M_\odot$), and “high” ($8 < M_* < 45 \times 10^{10} M_\odot$), being the number of group ETGs the same in each bin.

### 3. INTERNAL COLORS VERSUS GALAXY MASS AND ENVIRONMENT

The internal color gradient of an ETG, defined as the slope of its radial color profile, written as $V_{g-r}$, where $X = r; Y, J, H, K$, is estimated as described in LDD10, using deconvolved Sérsic models of each galaxy to measure $g-X$ colors on concentric ellipses with axis ratio and position angle fixed to the $r$-band Sérsic fit. A line is fitted to the resulting $g-X$ versus log R profile, in the radial range of 0.1 to 1$R_e$ (as in, e.g., Peletier et al. 1990), where $R$ is the equivalent galactocentric distance and $R_e$ is the $r$-band effective radius. The line slope gives $V_{g-r}$. Figure 1 shows the dependence of median optical–optical and optical–NIR color gradients, $V_{g-r}$ and $V_{g-K}$, as well as central colors, $(g - r)_{0.1}$ and $(g - K)_{0.1}$ (computed at $R = 0.1R_e$), on galaxy mass and environment (i.e., field versus group). To a first approximation, optical–optical colors are more sensitive to the age of an SP than its metallicity, while optical–NIR colors are more sensitive to metallicity than age (see, e.g., de Jong 1996). Hence, the upper and lower panels of Figure 1 can be roughly seen as reflecting the behavior of age and metallicity, respectively. At a given stellar mass, group galaxies have significantly shallower optical–optical color gradients than their field counterparts, consistent with La Barbera et al. (2005), who found cluster galaxies to have systematically flatter $V_{g-r}$ (by $\sim 0.03 \text{mag dex}^{-1}$ at $z \lesssim 0.1$) with respect to galaxies in less dense environments. However, optical–NIR color gradients do not exhibit any significant environmental dependence, implying that age (rather than metallicity) gradients are changing with the environment. The small panels in Figure 1 also show that, at all masses, group galaxies have redder central colors than those in the field. On average, the color difference amounts to $\sim 0.02 \text{ mag in } g-r$ and $\sim 0.05 \text{ mag in } g-K$. This may result from both age and metallicity increasing with mass and group (relative to field) ETGs having older SPs, as found by, e.g., Thomas et al. (2005), Gallazzi et al. (2006), and Pasquali et al. (2010).

---

10 Accounting for $> 80\%$ of total light.
11 The $M_*$ limit is established with the same approach as in Figure 3 of LDD10.
12 Since optical–NIR color gradients do not depend significantly on $\Sigma_N$ (Section 3), using the same $\Sigma_N$ threshold for both optical and optical+NIR samples would not change our results. However, adopting a lower $\Sigma_N$ threshold for the optical+NIR sample allows us to effectively reduce error bars.
13 The other available colors $(g-i, g-z, g-J, g-H)$ are not shown for brevity, but are included in the stellar population analysis of Section 4.

---

**Figure 1.** Color gradients of ETGs as a function of environment and stellar mass. Group and field ETGs are plotted with empty and filled symbols, respectively. Low-, intermediate-, and high-mass galaxies are plotted with squares, triangles, and circles, respectively. Upper panel: median $V_{g-r}$ vs. median stellar mass. Error bars are 1σ confidence intervals on median values. The inset shows how central values of $g-r$, $(g - r)_{0.1}$, depend on stellar mass and environment. Lower panel: the same as upper panel but for the optical–NIR color $g-K$. 

---

**The Astrophysical Journal Letters,** 740:L41 (4pp), 2011 October 20

La Barbera et al.
4. AGE AND METALLICITY GRADIENTS VERSUS GALAXY MASS AND ENVIRONMENT

We assume that the dependence of internal colors of ETGs on mass and environment is mainly driven by the age and metallicity of the underlying SPs, which is motivated by the existence of well-established absorption-line gradients in ETGs (see, e.g., Sánchez-Blázquez et al. 2007; Rawle et al. 2010). Although a dust component may also generate color gradients (Silva & Wise 1996), so far no observational evidence has been found that dust can play a major role (Savoy et al. 2009; LDD10).

We fit simultaneously all available central colors and color gradients (as shown in Figure 1) with SP models, inferring galaxy central age and metallicity,15 as well as age and metallicity gradients,16 $V_t$ and $V_Z$ (as in, e.g., Ferreras et al. 2009). Each SP model consists of a pair of simple stellar populations (SSPs) with Chabrier (2003) initial mass function, from the S. Charlot & G. Bruzual (2011, in preparation; CB11) synthesis code. The “inner” SSP is used to model central galaxy colors, while the difference of $g−X$ between the two SSPs is fitted to $V_{g−X}$, providing $V_t$ and $V_Z$. The fitting is done in a $\chi^2$ sense by varying age and metallicity of both SSPs in the range $1 < t < 14$ Gyr and $0.2 < Z/Z_{\odot} < 2$, respectively. We found that similar results are obtained when using Bruzual & Charlot (2003) population synthesis models, or using exponentially declining star formation models. As shown in Figure 2, the age and metallicity content of ETGs depends significantly on both galaxy mass and environment, reflecting the behavior of optical–optical and optical–NIR colors of Figure 1. For all environments and mass bins, the main driver of color gradients in ETGs is a significantly negative ($<−0.3$) metallicity gradient (consistent with e.g., Peletier et al. 1990; Ferreras et al. 2009), with field galaxies having somewhat shallower $V_Z$ (by $\sim0.06$) than their group counterparts. However, age is found to play a significant role, and, perhaps more importantly, this depends on the environment where galaxies reside. Group galaxies have positive, albeit small, age gradients ($<0.1$, i.e., an age variation of $<23\%$ per radial decade), while the galaxy SPs being younger in the center than in the outskirts, while field ETGs exhibit systematically smaller, mostly negative, age gradients, consistent with Ferreras et al. (2009) based on the analysis of the evolution of the color gradients of field ETGs from GOODS data. Note, however, that at high-mass field galaxies also tend to have slightly positive $V_t$ ($\sim0.04 \pm 0.01$).

5. DISCUSSION

The analysis presented in this Letter suggests that there is a significant trend of the internal distribution of age and metallicity in massive ETGs with galaxy mass and environment. The results of Figure 2 can be qualitatively discussed in light of current formation scenarios of ETGs, considering that most ($\sim90\%$) of our sample of group galaxies consists of satellite, rather than central, galaxies (according to the definition of Yang et al. 2007).

Gas-rich mergers. The presence of a younger SP (i.e., a positive age gradient) in the center of group ETGs supports a dissipative formation picture, whereby gas-rich mergers fuel the central region with cold gas, allowing for the formation of younger, metal-enriched, stars. In a hierarchical picture of galaxy formation, the more massive ETGs start forming stars at earlier epochs (albeit assembling later, see De Lucia et al. 2006), when disk-like progenitors likely had a more turbulent and clumpy interstellar medium (Förster Schreiber et al. 2009), possibly implying a larger amount of dissipation. This might explain why age (metallicity) gradients tend to marginally increase (decrease) with stellar mass. However, this is not supported by smoothed particle hydrodynamic simulations of galaxy formation, with merging producing no correlation of metallicity gradients and mass (Kobayashi 2004). Moreover, both the light profile shape as well as the size–mass relation of ETGs at $z < 0$ provide evidence against an increasing importance of gas dissipation at high mass (Hopkins et al. 2009; Shankar et al. 2011).

Cold accretion. An alternative scenario to explain positive age gradients involves the accretion of cold (clumpy) gas from the cosmological surroundings, leading to subsequent star formation in the central region. Cold accretion is expected to be more important at high redshift ($z > 2$), being a relevant mode for the formation of galaxies as massive as $\sim10^{12} M_{\odot}$ (Dekel et al. 2009, but see also Keres et al. 2005). In a cold accretion scenario, where the formation process resembles monolithic collapse, the $V_t$ and $V_Z$ would naturally correlate with galaxy mass as star formation lasts longer in the center of more massive systems having a deeper central potential well (e.g., Kobayashi 2004; Pipino et al. 2010). This interpretation is also supported by the fact that: (1) the ages and metallicities of the SPs within and

---

15 Central age and metallicity are not discussed here, as their estimates are less robust than that of SP gradients, involving an absolute, rather than a relative, matching of model to observed colors.

16 That is, the variation of logarithmic age and metallicity per decade in galactocentric distance.
among ETGs are tightly correlated to the local escape velocity (Scott et al. 2009), and (2) the resulting gradients depend on mass (e.g., Forbes et al. 2005) and, at fixed mass, on the duration of star formation, a property that can be parameterized by the α to iron abundance ratio (LDD10). One should note, however, that the existence of a correlation between \( \nabla Z \) and mass has long been debated in the literature (see, e.g., Spolaor et al. 2009; Koleva et al. 2011, and references therein).

**Later gas accretion.** While group galaxies have their star formation quenched when entering bigger halos (through “strangulation”), field galaxies can accrete gas longer, by radiative cooling of their dark-matter hot-gas reservoir, and form a younger, more metal-rich, stellar component outward. This would lower, and eventually invert, the age gradient, making also metallicity gradients shallower, consistent with what we see for field ETGs in Figure 2.

**Stripping.** Environmental effects, such as ram pressure and/or tidal stripping, may also trigger (central) star formation in recently accreted group satellites (e.g., Bekki & Couch 2003). In general, stripping should be less important for high-mass galaxies, inconsistent with the trends seen in Figure 2.

**Dry merging.** ETGs can also form by gas-poor interactions. Minor dry mergers and stellar accretion can drive the formation of the outer envelopes of ETGs, explaining their size evolution with redshift (Naab et al. 2009). Gas-poor mergers should mix the SPs within galaxies, flattening pre-existing metallicity and age gradients (White 1980). Since \( \nabla V_1 \) and \( \nabla V_2 \) steepen with mass (see also LDD10), our data seem to reject major dry mergers as the main channel for the formation of ETGs, unless the amount of flattening is small (Hopkins et al. 2009). Minor dry mergers would lead to a deposit of metal-poor, old, stellar material in the outer regions of a galaxy, increasing (decreasing) the age (metallicity) gradients. Therefore, the trends of \( \nabla V_1 \) and \( \nabla V_2 \) in Figure 2 might also result from minor dry mergers being more important at high-mass (consistent with model predictions; see Hopkins et al. 2010; De Lucia et al. 2011) and preferentially in group, relative to field, environments. However, such a trend would be at odds with the finding of a lack of environmental dependence of the redshift evolution of ETGs on the mass–size plane (Rettura et al. 2010).

In summary, although we find that several mechanisms can contribute to the observed age and metallicity gradients in ETGs (among them, cold accretion, and minor dry mergers are the most likely ones), we do indeed detect physical differences in the formation mechanisms with respect to environment, with field (relative to group) galaxies having the characteristic flatter gradients expected from inside-out star formation induced by late gas cooling. Studies of radial gradients outside of the effective radius will shed more light into the mechanisms that drive the formation of ETGs.

We used data from the SDSS (http://www.sdss.org/collaboration/credits.html). This work is based on data obtained as part of the UKIRT Infrared Deep Sky Survey (Lawrence et al. 2007). I.G.R. acknowledges a grant from the Spanish Secretaria General de Universidades of the Ministry of Education, in the frame of its programme to promote the mobility of Spanish researchers to foreign centers. F.L.B. acknowledges support from the ASI-INAF contract I/009/10/0. G.D.L. acknowledges financial support from the European Research Council under the European Community’s Seventh Framework Programme (FP7/2007-2013)/ERC grant agreement n. 202781.