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The Cosmic Evolution of Early-type Galaxies

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Abstract. The latest observational results on the formation and evolution of early-type galaxies are reviewed by focusing on the issues of mass assembly and *downsizing* scenario.

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1. Introduction

Early-type galaxies (ETGs) are important probes that can be used to investigate the cosmic history of galaxy mass assembly. Although ETGs at $z \sim 0$ are rather "simple" and homogeneous systems in terms of morphology, colors, stellar population content and scaling relations (Renzini 2006), their formation and evolution is still a debated question. In the modern scenario of ΛCDM cosmology, it is expected that galaxies assembled their mass gradually through hierarchical merging, with most of the ETG stellar mass assembled at $0 < z < 1$ (De Lucia *et al.* 2006). The modern generation of galaxy surveys can test the different predictions on the evolution of the number density, colors, merger types and rates, luminosity and mass functions, and provide a crucial feedback to improve the theoretical simulations.

Several observational tests on ETG evolution have been performed in the past years, and the recent advent of wide-field surveys ($\geqslant$1 square degrees) made it possible to reduce the "cosmic variance" which affects ETG surveys due to their strong clustering. However, a general consensus has not been reached yet. For instance, recent results based on optically-selected, moderately deep ($R < 24$) samples of "red sequence" ETGs (e.g. COMBO-17, DEEP2) (Bell *et al.* 2004, Faber *et al.* 2005) suggest a strong evolution, with the number density increasing by a factor of ∼6 from $z \sim 1$ to $z \sim 0$, and a corresponding increase by a factor of 2 of their stellar mass density since $z \sim 1$. However, other wide-field surveys do not support these finding and claimed a weaker evolution, with the rest-frame B-band luminosity function of ETGs being consistent with passive evolution up to $z \sim 1$ and a ∼40% decrease of the number of bright ETGs from $z \sim 0$ to $z \sim 1$ (Zucca *et al.* 2006, Yamada *et al.* 2005, Brown *et al.* 2006, Scarlata *et al.* 2006). Moreover, the evolutionary scenario has been made more controversial by the results indicating a weak evolution of the stellar mass function (Fontana *et al.* 2004, Caputi *et al.* 2006, Bundy *et al.* 2006, Borch *et al.* 2006). Also the mechanism with which ETGs assemble their mass is unclear. On the one hand, dissipationless ETG–ETG merging (also called "dry" merging) has been advocated as an important mechanism to build up the masses of ETGs at $0 < z < 1$ (Bell *et al.* 2005, van Dokkum 2005), on the other hand this possibility seems unlikely based on the evolution of the stellar mass function (Bundy *et al.* 2006) and the properties of the small-scale clustering of ETGs at $0.16 < z < 0.36$ selected from the SDSS (Masjedi *et al.* 2005).

2. The *downsizing* evolutionary scenario

Many of the above discrepancies can be reconciled within the scenario proposed by Cowie *et al.* 1996 (see also Gavazzi & Scodeggio 1996) known as *downsizing*: galaxy evolution depends on the mass, with the most luminous and massive systems reaching the completion of star formation first, while less massive ones have a more prolonged star formation till later cosmic times. Several observations now support this scenario.

For instance, the typical $\mathcal{M}/L$ of luminous ETGs is significantly larger than that of the fainter ones at low and intermediate redshifts. This implies that, while the $\mathcal{M}/L$ of the luminous population is consistent with either very short star-formation time-scales (τ) or high formation redshifts ($z_f \geqslant 3$) (and some objects appear to require both), the less luminous population experienced a more recent history of assembly, as indicated by the larger τ and lower z_f required to reproduce the typical $\mathcal{M}/L$ (Fontana *et al.* 2004). Additional support to *downsizing* comes from (1) the star formation histories of ETGs at $z \sim 0$ (Thomas *et al.* 2005), (2) the Fundamental Plane (FP) up to $z \sim 1$ showing a mass-dependent evolution of the mass-to-light ratio, and indicating that the stellar populations formed at $z_f > 2$ and $z_f \sim 1$ for high- and low-mass ETGs respectively, and that the fraction of stellar mass formed at recent times ranges from <1% for $M > 10^{11.5} M_\odot$ to 20%–40% below $M \sim 10^{11} M_\odot$ (with no significant difference between the evolution of massive field and cluster ETGs) (Treu *et al.* 2005), (3) the bright–end of the field colour-magnitude relation has been built all the way down to the present-day, but the build-up at the faint end has not started yet (Tanaka *et al.* 2005), (4) the differential and mass-dependent evolution of the stellar mass function, nearly constant from $z \sim 0.7$–0.8 to $z \sim 0$ for massive galaxies, but much faster for low-mass systems (Fontana *et al.* 2004, Drory *et al.* 2005, Caputi *et al.* 2006, Bundy *et al.* 2006, Pannella *et al.* 2006, Franceschini *et al.* 2006, Cimatti *et al.* 2006, (5) the evolution of the specific star formation rate (SSFR = $SFR/\mathcal{M}$), with lower mass galaxies showing larger SSFR than higher mass galaxies at all redshifts, and the SSFR for massive galaxies increasing by a factor of ~10 at $z > 2$ (Feulner *et al.* 2005, Juneau *et al.* 2005), (6) the strong decrease of the number density of massive galaxies with strong Hδ absorption from $z \sim 1$ to $z \sim 0$ (Le Borgne *et al.* 2006), (7) the existence of old, massive, nearly passively evolving ETGs up to $z \sim 2.5$ (Cimatti *et al.* 2004, McCarthy *et al.* 2004, Saracco *et al.* 2005, Daddi *et al.* 2005a, Kriek *et al.* 2006).

3. The case for *mass – downsizing*

Recent results suggest that the scenario of *downsizing* could be extended from star formation (i.e. stars in more massive galaxies are older) to the stellar mass assembly itself (i.e. massive galaxies were the first to assemble). For instance, the ETG luminosity and stellar mass function evolution shows that while the number density of luminous (massive) ETGs with $M_{\rm B}(z = 0) < -20.5$ ($\mathcal{M} > 10^{11}$ M$_\odot$) is nearly constant since $z \sim 0.8$, less luminous galaxies display a deficit which grows with redshift and that can be explained with a gradual population of the ETG "red sequence" by the progressive "quenching" of star formation in galaxies less massive than $\sim 10^{11} M_\odot$. At each redshift there is a critical mass above which virtually all ETGs appear to be in place (Cimatti *et al.* 2006, Bundy *et al.* 2006). Note that these results are now supported from other studies based on wide-surveys (Borch *et al.* 2006, Brown *et al.* 2006, Scarlata *et al.* 2006).

While *downsizing* in star formation may be a natural expectation in a hierarchical galaxy formation scenario, provided that a suitable mechanism is found to "quench" star formation at earlier times in more massive galaxies (De Lucia *et al.* 2006), the above evolutionary trend is not reproduced by some of the most recent theoretical simulations even when they successfully reproduce the star formation *downsizing*.

4. ETGs beyond $z \sim 1$ and ETG progenitors

The recent spectroscopic surveys of near-infrared–selected galaxy samples unveiled a substantial population of ETGs at about $1 < z < 2.5$. These galaxies are very red (e.g. $R - K > 5 - 6$, Vega) show the spectral features of passively evolving old stars with ages of 1–4 Gyr, have large stellar masses with $\mathcal{M} > 10^{11} M_{\odot}$ and dominate the high-luminosity and high-mass tails of the total luminosity and stellar mass functions (Cimatti *et al.* 2002a, Cimatti *et al.* 2003, Pozzetti *et al.* 2003, Cimatti *et al.* 2004, Fontana *et al.* 2004, McCarthy *et al.* 2004, Saracco *et al.* 2005, Daddi *et al.* 2005a, Kriek *et al.* 2006, Bundy *et al.* 2006). The stellar masses of these galaxies are estimated by fitting their multi–band photometric SEDs with stellar population synthesis models, and are in reasonable agreement with the dynamical masses estimated from the absorption line velocity dispersion (Rettura *et al.* 2006). Due to the strong cosmic variance, the number density of high-z ETGs is still so poorly constrained that the current data at $1 < z < 2$ are consistent with a range from 10% to 100% of the local density of luminous ETGs (Cimatti *et al.* 2004, Daddi *et al.* 2005a, Saracco *et al.* 2005).

The properties of these distant, old ETGs can be explained only with a star formation history characterized by: (1) strong (>100 $M_{\odot}$ yr^{-1}), (2) short-lived (τ ~0.1-0.3 Gyr) starbursts (where SFR$\propto$ $exp(t/\tau)$), (3) the onset of star formation occurring at high redshift ($z_f > 2 - 3$), (4) a passive–like evolution after the major starburst. Recent near-IR – to – millimeter surveys have indeed uncovered galaxies matching the above requirements. Examples are given by BzK–selected galaxies at $1.4 < z < 2.5$ (Daddi *et al.* 2004a, Daddi *et al.* 2004b, Daddi *et al.* 2005b, de Mello *et al.* 2004, Kong *et al.* 2005, Dannerbauer *et al.* 2006), submm/mm-selected galaxies (Chapman *et al.* 2005, Dannerbauer *et al.* 2004, Swinbank *et al.* 2004, Greve *et al.* 2005), "Distant Red Galaxies" selected with $J - K_s > 2.3$ (Franx *et al.* 2003, van Dokkum *et al.* 2004, Papovich *et al.* 2006), optically-selected BM/BX/LBG systems with bright K-band fluxes (Adelberger *et al.* 2005, Reddy *et al.* 2005, Shapley *et al.* 2004), IRAC Extremely Red Objects (IEROs) (Yan H. *et al.* 2004), HyperEROs (Totani *et al.* 2001), and a fraction of dusty EROs (Yan *et al.* 2005).

The next steps will be to perform detailed studies of these progenitor candidates in order to understand what are the main mechanisms capable to assemble massive galaxies with short timescales. A promising avenue is provided by near-IR Integral Field Spectroscopy coupled with Adaptive Optics. The first example is given by a BzK–selected star-forming galaxy at $z = 2.38$ observed with the ESO VLT + SINFONI reaching an angular resolution of $\sim 0.15''$ (1.2 kpc) and showing the case for a massive rotating disk which may become unstable and lead to the rapid formation of a massive spheroid (Genzel *et al.* 2006).

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Discussion

Alfonso Aragon-Salamanca: When applying the luminosity evolution correction determined from FP, that is luminosity dependent, how would that affect your results?

Andrea Cimatti: We applied the luminosity evolution correction valid for massive early-type galaxies¡; It is a conservative choice. While it is certainly valid for massive galaxies, it is conservative for the low-mass ones, because the application of a luminosity-dependent correction would amplify the evolution of the number density of low luminosity (low mass) early-type galaxies.