Probing the mass assembly of massive nearby galaxies with deep imaging

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Abstract. According to a popular scenario supported by numerical models, the mass assembly and growth of massive galaxies, in particular the Early-Type Galaxies (ETGs), is, below a redshift of 1, mainly due to the accretion of multiple gas–poor satellites. In order to get observational evidence of the role played by minor dry mergers, we are obtaining extremely deep optical images of a complete volume limited sample of nearby ETGs. These observations, done with the CFHT as part of the ATLAS^{3D}, NGVS and MATLAS projects, reach a stunning 28.5 – 29 mag.arcsec^{-2} surface brightness limit in the g' band. They allow us to detect the relics of past collisions such as faint stellar tidal tails as well as the very extended stellar halos which keep the memory of the last episodes of galactic accretion. Images and preliminary results from this on-going survey are presented, in particular a possible correlation between the fine structure index (which parametrizes the amount of tidal perturbation) of the ETGs, their stellar mass, effective radius and gas content.

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1. Introduction

Early-Type Galaxies play a key role in modern cosmology: according to the standard hierarchical cosmological model, galaxies build up from successive mergers, associated by a series of morphological transformations. The massive ETGs we see today are the end-product of this process. *At high redshifts*, few ETGs are observed, but surprisingly they have not all disappeared, raising questions on how they formed so quickly in the traditional merging scenario. They appear to be also very compact (e.g. Buitrago *et al.*, 2008). *At low redshift*, the early-type galaxies are observed to be larger but also to be much more complex and lively that once believed. As shown in the presentations of the ATLAS^{3D} results in this volume, a large fraction of them contain in particular gas, some with non-regular kinematics, and thus may still be involved in active transformation processes.

Simulations indicate that while the global light profile of ETGs can be rather easily obtained with various processes, getting their total mass and large radius is much more

challenging and may require multiple collisions in the recent past. Several recent papers have highlighted the role of minor mergers in the growth of galaxies (e.g., Johansson *et al.*, 2012; Newman *et al.*, 2012). These late mergers impact the properties of the stellar populations mostly at large galactocentric radii. In particular minor mergers bring low metallicity stars from the infalling dwarf satellites, and create radial color gradients. On the other hand, a major merger induces large radial mixing, leading to a washing up of metallicity/age and thus color gradients.

Furthermore, the mass assembly of galaxies leaves various imprints in their surroundings, such as shells, streams and tidal tails. The frequency, shape and properties of these fine structures depend on the mechanism driving the mass assembly (see the review by Duc & Renaud, 2011). Any analysis of the fine structures around galaxies, however, should take into account (1) that the resulting stellar debris have a very low surface brightness, (2) that such debris fade with age, or may be dispersed by the local environment, and (3) that galaxies may have formed by multiple processes.

Deep imaging surveys coupled with numerical simulations done in cosmological context can now address these issues. Several studies have quantified the importance of fine structures around massive galaxies and their variation with environment and redshift (Tal *et al.*, 2009; Bridge *et al.*, 2010; Adams *et al.*, 2012) but were restricted to the census of luminous tidal features. So far, the surface brightness limit required to apply a genuine galactic archeology technique has been reached for only local galaxies for which stellar counts may be done. As however shown, among others, by Martinez-Delgado *et al.* (2010) and Duc *et al.* (2011), deep optical images obtained under specific conditions can also reveal the diffuse light associated with very low-surface brightness structures.

2. Observations and data reduction

Our targets are the 260 nearby ETGs located at distances below 42 Mpc from the ATLAS^{3D} survey (Cappellari *et al.*, 2011). Very deep optical images in the g',r' and i' bands are currently being obtained with the large field of view camera MegaCam installed on the CFHT. The observations are carried out as part of several projects: ATLAS^{3D}, the Next Generation Virgo Cluster Survey (NGVS, covering the full Virgo Cluster area; Ferrarese *et al.*, 2012), and the recently accepted CFHT MATLAS Large Programme. The typical integration time is about one hour per band. The limiting sensitivity is outstanding with respect to previous generations of optical images: about $28.5 - 29$ mag.arcsec^{-2} in the g'–band. This could be achieved using dedicated observing strategies and data reduction softwares. On traditional images obtained by MegaCam, the presence of scattered light patterns masks extended features below surface brightness of 27 mag.arcsec^{-2}. Investigations motivated by the NGVS have shown that this problem can be overcome carrying out a sequence of observations with large offsets between the images, as it is usually done with infrared observations. A sky is then computed and subtracted from the individual images, before they are stacked.

The majority of the fine structures disclosed by the survey are very extended and directly show up on surface brightness or color maps. To disclose those located more towards the inner regions, several methods were used: unsharp masking, best at revealing sharp-edged structures such as shells or narrow filaments; subtraction of the ETGs modeled by an ellipse fitting or by a multi-component GALFIT model, which helps to detect extended asymmetric features. As a first step to quantify the amount of tidal perturbations, a fine structure index was determined, counting by eye the number of structures, and weighting them according to their nature.
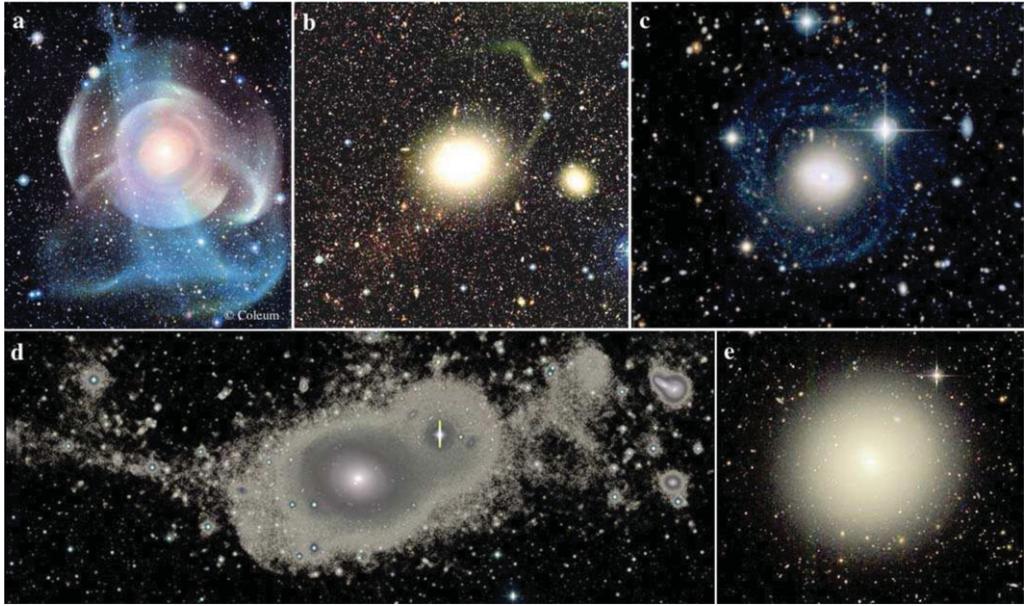
Figure 1. Deep optical images of a sub-sample of nearby Early-Type Galaxies obtained with MegaCam on the CFHT as part of the ATLAS^{3D} and Next Generation Virgo Cluster Survey. The figure illustrates the variety of low surface brightness structures that show up around these galaxies: long tidal tails and shells, telling us about past major mergers (a,d); narrow stellar filaments associated with disrupted dwarf satellites, revealing future minor mergers (b); regular low surface brightness star–forming disks (c); extended featureless stellar halos (e).

3. Preliminary results

Figure 1 illustrates the variety of low surface brightness structures detected around the ETGs: 200 kpc long tidal tails revealing past 2-3 Gyr old major merger (for instance around NGC 5557; Duc *et al.*, 2011), narrow filaments around a disrupted dwarf, with their typical S-shape and wrapping around the host, diffuse halos, some remaining regular even up to large radii.

At time of writing, more than half of the ATLAS^{3D} ETGs benefit from deep Mega-Cam images. This initial sub-sample is however somehow biased towards the most massive ETGs, those that are slow rotating and/or gas–rich. In such conditions, providing the percentage of disturbed galaxies is premature. Nevertheless some initial trends were found.

First of all, statistically, the galaxies that contain atomic hydrogen, in particular in their outskirts, have a higher fine structure index. This is a strong indication that the HI clouds are associated with collisional debris. A rather large fraction of ATLAS^{3D} ETGs contain detectable molecular gas, as traced by CO. Those for which the CO is kinematically misaligned with respect to the stellar component and for which an external origin of the molecular gas had been proposed (Davis *et al.* 2011), exhibit collisional debris, just as expected. Finally one of the most promising results is the trend with mass and size, two fundamental parameters in the scaling laws of galaxies. As shown on Figure 2, the more massive and the more extended† the galaxy is, the higher its fine structure index. Conversely, many, usually fast rotating low–mass, ETGs do not show

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† As mentioned a number of times during the symposium, the measure of the effective radius, the radius containing half of the stellar light, is tricky at high redshift. Our study indicates that this is even the case at low redshift. For the ATLAS^{3D} ETGs showing on MegaCam images a
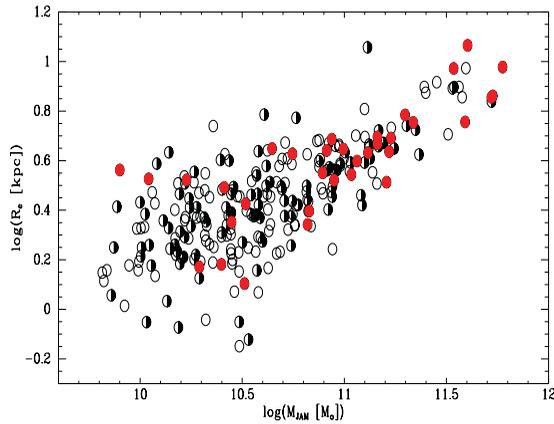
Figure 2. Effective radius, R_e^{max}, vs M_{JAM}, a proxy of the stellar mass, for the full sample of ATLAS$^{\mathrm{3D}}$ ETGs (open circles, Cappellari *et al.*, 2012). The galaxies shown with the half filled circles have already deep MegaCam images available from either the ATLAS$^{\mathrm{3D}}$ or NGVS surveys. The images for the other galaxies will be obtained as part of the MATLAS CFHT Large Programme. Those that have a high fine structure index, i.e. galaxies that are either strongly tidally perturbed, or have multiple stellar streams in their vicinity, are shown with the red filled circles.

any sign of external perturbation. This tells that the most massive galaxies in the local Universe have had a rich recent mass accretion history. At which level it accounts for their mass/size growth remains to be determined. Since the optical images only reveal structures brighter than 29 mag.arcsec^{-2}, simulations will be key to extrapolate from the observations the quantity of accreted material since $z = 1$. Another crucial parameter will be the survival time of tidal features, which likely depends on the environment. The study of the fine structure index as a function of the local density – our volume limited sample covers a large range of environments: field, groups and the Virgo Cluster – will give interesting constrains on that matter.

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very extended low surface brightness halo, the value had to be revised, with differences with earlier published values reaching factors up to 2.