The eventful life of galaxies in low density environments Mapping rejuvenation episodes in nearby early-type galaxies

UVOIR Surveyor: The need for high resolution, wide field, deep multi-wavelength imaging and IFU spectroscopy

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Background Nearby ($z < 0.02$) early-type galaxies (Es + S0s = ETGs) are the fossil record of galaxy evolution. Understanding their detailed properties is essential to *pinpoint their evolution* and retrace their history. The combination of the far-UV view provided by GALEX (Martin et al., 2005) with the Sloan Digital Sky Survey (Stoughton et al., 2002, SDSS hereafter) has greatly transformed our view of ETGs as passively evolving galaxies. Statistical studies (e.g. Kaviraj et al., 2007; Schawinski et al., 2007) found that about 30% of ETGs show signatures of residual, ongoing star formation. Only a small percentage of ETGs, about 5%, show the classical UV-upturn (Yi et al., 2005, 2011; Hernández-Pérez & Bruzual, 2014). The largest incidence of rejuvenation episodes have been detected in low density environments, still scantly studied.

In the Far UV - SDSS-r color magnitude diagram, galaxies show a strong morphological segregation: most of spirals galaxies lie in the blue cloud, ETGs are mainly located in the red sequence, some bona fide Es and Sps occupy an intermediate zone called "Green Valley" (e.g. Yi et al., 2005). Mazzei et al. (2014a) provided a description of the galaxy photometric and morphological evolution in the $(NUV - r)$ $vs.$ M_r color magnitude diagram (CMD) plane exploiting smoothed particle hydrodynamics simulations (SPH) with chemo-photometric implementation to trace ETG evolution in two groups in the Leo II cloud. Major merging as well as galaxy-galaxy interactions are the mechanisms considered by the simulations. ETGs spend between 3 to 5 Gyrs, according to their luminosity, to cross the Green Valley before they reach the red sequence. Simulations suggest that bright ETGs formed before these groups collapsed, indicating that both in groups, and *a fortiori* in clusters, mature ETG systems fall. *We thus concentrate our interest in low density environments where the largest fraction of signatures of the transition from star forming to passively evolving ETGs is detected.*

Mapping the transition **In the galaxy nuclear region** GALEX revealed that ETGs with signatures of recent accretion episode, like shell structures, may have a "rejuvenated" nucleus in the far-UV (Rampazzo et al., 2007; Marino et al., 2009). Similar results come from Lick line-strength index analysis (e.g. Longhetti et al., 2000; Annibali et al., 2007) and, more recently, from mid-infrared Spitzer-IRS spectra. A large fraction of the latter present Polycyclic Aromatic Hydrocarbon (PAHs) emission, indicating the presence of episodes of residual star formation with ages of a few Gyr (depending on the metallicity) corresponding to a redshift coverage $z \lesssim 0.2$.(Bressan et al., 2006; Kaneda et al., 2008; Vega et al., 2010; Panuzzo et al., 2011; Rampazzo et al., 2013; Nanni et al., 2013). ETGs hosting AGN may also show PAHs. The star formation episode involves *a small fraction of nuclear mass (e.g.* $\sim 1.5\%$ *in Panuzzo et al. (2007)). Nuclear rejuvenation episodes* may be correlated to the AGN feedback. However, the fraction of MIR spectra showing PAHs is $34^{+10}_{-8}\%$ and $51^{15}_{-12}\%$ in Es and S0s, respectively (Rampazzo et al., 2013). These percentages are difficult to explain within the AGN feedback framework only. Such episodes are *independent of the galaxy kinematics*, i.e. they apply to both fast and slow rotators as well as to *the core/cuspy nuclear shapes* detected by HST (Rampazzo et al., 2014). **In the galaxy ourskirts** GALEX detected also ETGs with far-UV bright extended structures (e.g. rings, arm-like features, tails), sometimes extending much further than the optical galaxy body, *often associated with HI emission* (Jeong, 2009; Thilker et al., 2010; Kaviraj, 2010; Marino et al., 2011; Marino et al., 2011a; Salim & Rich, 2010; Rampazzo et al., 2011; Salim et al., 2012). Simulations suggested that such kind of UV bright ring/arm-like structures may be either a transient byproduct of a major merger (Mazzei et al., 2014b) or to result from the accretion of a small, gas rich companion (see Mapelli et al., 2015). *The fraction of FUV bright rings/arm-like structures in ETGs is unknown.* Some indication may come from Serra et al. (2014) who found that about 1/4 of ETGs in low density environments has an extended HI disk of the order of 10^9 $M_\odot$. The presence of an HI disk is independent of the inner stellar galaxy kinematics (fast and slow rotators) characterizing the galaxy.

Summarizing, FUV, optical and MIR observations and simulations concur in indicating that *both nuclear and/or galaxy-scale rejuvenation* processes recently occurred in a significant fraction of ETGs, mainly S0s. Studies of nearby ETGs is of overwhelming importance to understand distant galaxies.

Open issues *Which are the main rejuvenating mechanisms: external accretion, merging, interaction, AGN feedback, secular evolution? What has been the evolutionary path of these rejuvenated ETGs, with respect to the "red and dead" ETGs present at the same epoch and in the same environment?*

The importance of small missions and UVOIR Surveyor to study rejuvenated ETGs in low density enviroments

High resolution, wide field imaging and image field unit (IFU) spectroscopy, from Far UV to MIR, of these ETGs will be crucial to address the above issues.

•**Detailed star formation maps** The main limitations in the Far UV study of nearby galaxies are the low spatial resolution (GALEX, SWIFT-UVOT) and/or the lack of wide field (HST cameras). The GALEX wide field has been instrumental to unveil low level star formation regions in the outskirts of galaxies, HST to map nuclear shapes.

An intermediate step to reach our goals is building an UV/Optical telescope like CASTOR (1m-diameter unobscured Three Mirror Anastigmat telescope HST-like image quality of ≈0.15" over 1.16° × 0.58° Field of View) (see Côté et al., 2012). *Wide field, Far UV to NIR wavelength coverage, with narrow band imaging capabilities* can map nearby galaxies up their outskirts with unprecedented resolution, showing the 2D distribution of the atomic lines (and molecular species, including H_2 emission lines when present) providing the full scale and shape of the star forming regions.

The 8-10m class UVOIR Surveyor sensitivity and spatial resolution, although with more limited field of view, will extend our possibility to obtain stellar CDM for galaxies and their substructures well beyond the Local Group (LG) and to model them in terms of stellar populations. The derived ages and metallicities will constrain the origin and evolution of the substructures as in the LG galaxies.

•**Kinematics and gas physical properties in the nucleus and in the substructures of ETGs** Present IFUs on 8m class ground based telescopes have a limited field of view and wavelength range. IFUs with FUV-MIR wavelength coverage will boost the 8-10m class UVOIR Surveyor capabilities providing both spectroscopic (e.g. line strength indices) and kinematics information on the same area. This data-set will complement the imaging information in particular obtaining the galaxy substructures kinematics. The wide wavelength spectroscopic information will increase sensibly our diagnostic capability e.g. about the gas physical properties (e.g. abundances) as well as about ionization mechanisms (frustrating degeneracies are present using either optical or MIR bands only) (see e.g. Annibali et al., 2010; Panuzzo et al., 2011; Rampazzo et al., 2013).

•**Connection with other wavelengths** The confirmation of younger populations in these UV-bright structures might also come from X-ray observations. Chandra provided a first example from the study of NGC 1291, an S0 with a prominent UV bright ring, where excess emission is detected and the X-ray luminosity function of the X-ray sources detected there (X-ray binaries) is consistent with a different population than in the bulge, with brighter sources and a flatter overall shape (Luo et al., 2012). While searches for more examples and a better characterization of the X-ray properties of these features has just begun (Trinchieri et al., 2015), we believe that the potential discovery space is big and worth pursuing.

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