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The fundamental plane of early-type galaxies in different environments

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Abstract The study of Early-Type Galaxies (ETGs) in different environments is a strong tool to understand their star formation history and their evolution. The Fundamental Plane (FP) of ETGs has been studied in different environments in the nearby universe such as in groups, clusters and the field. We found that our sample of ETGs in different environments shows a good agreement with the FP of Coma cluster, except for a scatter of some galaxies. A major part of the scatter in the FP is due to variations in mass to light ratio as a result of metallicity or age trends in the stellar populations and structural or dynamical properties of galaxies. We noticed that the most deviant galaxies from the FP show many fine structures as tidal tails, shells, dust and a kinematically distinct core which indicates a past merger involving at least one gas-rich progenitor.

1. Introduction

Early-Type galaxies (ETGs) represent a group which includes both elliptical (E0–E7) and lenticular (S0) galaxies. They represent a class of well studied objects both because of their homogeneous properties and their high luminosities ($-24 \leqslant M_B \leqslant -20$) which allows to detect them at large distances. They are specifically important as they contain most of the visible mass in the universe (for a detailed review, see Renzini, 2006, and references therein). Therefore, by understanding their evolution, we can understand the evolution of galaxies in general, and the evolution of the universe as a whole.

Although ETGs seem to be a nearly homogeneous class, the data collected in the last 30 years showed that there are significant departures from the general properties found in the form of large quantities of gas and dust (Capaccioli and Longo, 1994; Goudfrooij et al., 1994a,1994b), counter rotating nuclei and polar rings (Bender, 1988; Whitmore et al., 1987), shells, ripples, and disky or boxy components (e.g. Malin and Carter, 1980; Schweizer, 1980; Schweizer et al., 1990) and distinctive tidal tails (Fort et al., 1986; Schweizer and Seitzer, 1992; Michard and Prugniel, 2004; Bennert et al., 2008; Tal et al., 2009; Janowiecki et al., 2010). These morphological

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structures are explained in most of the theoretical models as a result of past merging in early stages of galaxy formation or of tidal interactions with close neighbors (e.g., de Zeeuw and Franx, 1989; Franx et al., 1989).

The role that environment plays in shaping the properties of ETGs is still an open issue in our understanding of galaxy formation and evolution (see Conselice et al., 2013 as a recent review). It is accepted that galaxy encounters, merging and interaction with inter cluster medium (ICM) are all processes that affect on the properties of galaxies to some extent. The influence of environment on the evolution of galaxies is testified by the presence of the well-known morphology-density relation (Dressler, 1980), according to which ETGs are preferred to be found in high density environments (Postman and Geller, 1984; Dressler et al., 1997; Postman et al., 2005; Bamford et al., 2009), while late-type galaxies are more found in low density environments. This distribution was proved in many studies: for example, Calvi et al. (2012) showed that there is a smooth increase in the fraction of ETGs when going from single galaxies, to pairs, to groups. Another relation that shows the influence of environment is the star formation-density relation (Lewis et al., 2002; Gómez et al., 2003; Haines et al., 2007).

The study of galaxies in different environments is a robust tool to understand their evolution and star formation history (e.g., Kuntschner et al., 2002; Sánchez-Blázquez et al., 2003, 2006; Thomas et al., 2005; Collobert et al., 2006). ETGs display a relation in the 3-dimensional parameter space among their effective radius r_e, the central velocity dispersion σ_o and the luminosity L (or equivalently the effective surface brightness expressed as I_e in linear flux units, where $I_e = L/(2\pi r_e^2)$, or μ_e in magnitudes). They are concentrated on a plane called the fundamental plane (FP, Dressler et al., 1987; Djorgovski and Davis, 1987) with,

$$r_e \propto \sigma_o^a \langle I_e \rangle^b \quad (1)$$

Which can be written as,

$$\log r_e = a \log \sigma_o + b\langle \mu_e \rangle + c \quad (2)$$

where a and b are the slopes and c is the offset (intercept) of the FP. $\langle \mu_e \rangle$ is the mean effective surface brightness enclosed by r_e (simply referred to as the mean surface brightness). The exponents a and b depend on the specific band used for measuring the luminosity. This indicates that, besides being in virial equilibrium, ETGs show striking regularity in their structures and stellar populations (Renzini and Ciotti, 1993; Borriello et al., 2003).

The FP can be understood as a demonstration of the virial plane predicted for relaxed systems (Binney and Tremaine, 2008), with assuming that galaxy mass-to-light ratios (M_{dyn}/L) are constant or smoothly varying for galaxies. If M_{dyn}/L is constant and if the structures were homologous for all ETGs, then the FP would be equivalent to the virial plane which takes the form $r_e \propto \sigma^2 \langle \mu_e \rangle^{-1}$ with coefficients of $a = 2$ and $b = -1$ (Faber et al., 1987). Otherwise, the FP is rotated from the virial plane and the tilt of the FP is the difference between the observed coefficients of the plane, a and b, and those from the virial plane. Jørgensen et al. (1996) found that $r_e \propto \sigma^{1.24} I_e^{-0.82}$ for the FP of local cluster ETGs. Also Pahre et al. (1998) found that the slopes, $a \sim 1.53$ and $b \sim -0.79$ for ellipticals observed in the near-infrared. The FP represents an important tool to study the properties of early type and dwarf galaxies and compute cosmological parameters. It is also an important diagnostic tool for galaxy evolution and mass-to-light (M/L) variations with redshift.

Although the FP relation is quite tight, there is a significant scatter around the plane and there is some contradiction in the literature regarding the source of this scatter. Some studies found that the scatter could be due to some reasons, such as variations in the formation times of galaxies, differences in the dark matter content of galaxies or metallicity trends in stellar populations. According to observations, the scatter around the FP is very low, and the position of a galaxy above or below the plane is independent of galaxy flattening, velocity anisotropy and isophotal twisting.

Faber et al. (1987) found that deviations from the FP can be formed by M/L variation due to e.g. metallicity or age trends in stellar populations, dynamical or structural properties, and relative distribution of dark matter. In fact, each of these effects may also introduce a tilt into the FP if they represent a function of elliptical galaxy mass.

The origin of the scatter around the FP has been investigated by many authors. Jørgensen et al. (1996) could not reduce the scatter around the FP by introducing additional parameters, such as isophotal shape of the galaxies or ellipticity. Other studies found that variations in stellar populations in ETGs are partially responsible for the intrinsic scatter (e.g. Gregg, 1992; Guzmán and Lucey, 1993; Guzmán et al., 1993). Forbes et al. (1998) found that the scatter of the FP for a sample of non cluster galaxies is partly due to variation in galaxy age at a given mass, and to variations in the time of the last starburst. Also Reda et al. (2005) found the same results by studying a sample of isolated galaxies. They found that some galaxies deviate from the FP having lower M/L ratio and they explained this as due to younger stellar populations of those galaxies, probably induced by recent gaseous merger. Other studies showed that a major part of the scatter in the FP is due to variations in M/L ratio (e.g., Cappellari et al., 2006; Bolton et al., 2008; Auger et al., 2010; Cappellari et al., 2013).

On the other hand, some studies (e.g., Magoulas et al., 2012) found that the age of galaxies is the most important source of offset from the FP and may drive other trends through its correlation with environment, morphology and metallicity.

The FP appears to be the same in all environments (universal), in the sense that the coefficients are similar for galaxies in environments ranging from high density clusters to the low-density field (de la Rosa et al., 2001; Reda et al., 2005; Holden et al., 2010). On the other side, there are suggestions in the literatures that there are moderate, but significant, environmental variations (e.g. Lucey et al., 1991; de Carvalho and Djorgovski, 1992; Bernardi et al., 2003; La Barbera et al., 2010a, 2010b; Ibarra-Medel and López-Cruz, 2011). On the other side, Cappellari et al. (2013) showed that the larger scatter in the FP is due to stellar population effects. They also confirmed that the deviation of the FP coefficients from the virial plane is due to M/L variation.

The aim of this study was to investigate the effect of local environment on the properties of early-type galaxies, in particular their scaling relations using a sample of ETGs in different environments such as in groups, clusters and in the field. In Section 2, we present the data used in this study that comes from photometric and spectroscopic observations of galaxies

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