Evolution of the colour-magnitude relation of early-type galaxies in cosmological numerical simulations

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Resumen / En este trabajo estudiamos la evolución con el *redshift* de la relación color-magnitud (CMR) de galaxias de tipo temprano. Esta evolución es analizada a partir de simulaciones numéricas cosmológicas, desde $z = 2$ hasta $z = 0$. Los resultados preliminares mostrados aquí representan el punto de partida de un estudio apuntado a identificar los procesos que originaron la CMR de galaxias de tipo temprano observada a $z = 0$.

Abstract / In this work, we study the evolution with redshift of the colour-magnitude relation (CMR) of early-type galaxies. This evolution is analyzed through cosmological numerical simulations from $z = 2$ to $z = 0$. The preliminary results shown here represent the starting point of a study aimed at identifying the processes that originated the observed CMR of early-type galaxies at z = 0.

Keywords / Galaxies: evolution — Galaxies: elliptical and lenticular, cD — Cosmology: theory

1. Introduction

In the colour-magnitude diagram (CMD), early-type (ET) galaxies trace a welldefined sequence from dwarfs to giants, where brighter galaxies tend to be redder (e.g., Chen et al., 2010; Smith Castelli et al., 2013). This colour-magnitude relation (CMR) is considered as universal, in the sense that it is observed with similar slopes in rich groups and clusters in the local Universe ($z \sim 0$). This sequence is interpreted as a mass-metallicity relation, with brighter and redder galaxies tending to be more massive and more metal-enriched (Sánchez-Blázquez et al., 2006; Conroy et al., 2014). Nevertheless, processes that establish and define it are not yet totally known for certain (e.g., Roediger et al., 2011; Janz et al., 2017).

In this work, we present a preliminary study that extends a previous analysis of the CMD for ET galaxies extracted from cosmological numerical simulations, studying the behaviour of the diagram as function of redshift. Our main goal is to provide clues in order to explain the origin of the CMR, studying its evolution since the formation times of these galaxies until today.

2. Simulated galaxies

2.1. The EAGLE simulations

In this work, we use simulations of the EAGLE (Evolution and Assembly of GaLaxies and their Environments) project (Schaye et al., 2015; McAlpine et al., 2016), a suite of cosmological, hydrodynamical simulations of a standard ΛCDM universe, that were performed by using a modified version of the GADGET-3 code (Springel, 2005; Schaller et al., 2015). The cosmological parameters used for the EAGLE simulations are those of the Planck Collaboration (Planck Collaboration et al., 2016): $\Omega_\Lambda = 0.693$, $\Omega_m = 0.307$, $\Omega_b = 0.048$ and $h = 0.6777$. We started working with the reference, intermediate-resolution simulation Ref-L0100N1504, which has a box size of 100 cMpc, with an initial baryonic particle mass of 1.81×10^6 M$_\odot$ and a maximum proper softening length of 0.70 pkpc. Due to its volume, with this simulation we are able to obtain a significant number of galaxies (in particular, galaxies of intermediate and high masses) at the analyzed redshifts.

The identification of galaxies in the simulations were carried out by applying a Friends-of-Friends technique (Davis et al., 1985), combined with the SUBFIND algorithm (Springel et al., 2001). The subgrid physics in EAGLE simulations implement prescriptions on radiative cooling and heating, star formation, chemical enrichment, supernovae and active galactic nuclei feedbacks, and interactions and fusions, among other processes (see Schaye et al., 2015 for details).

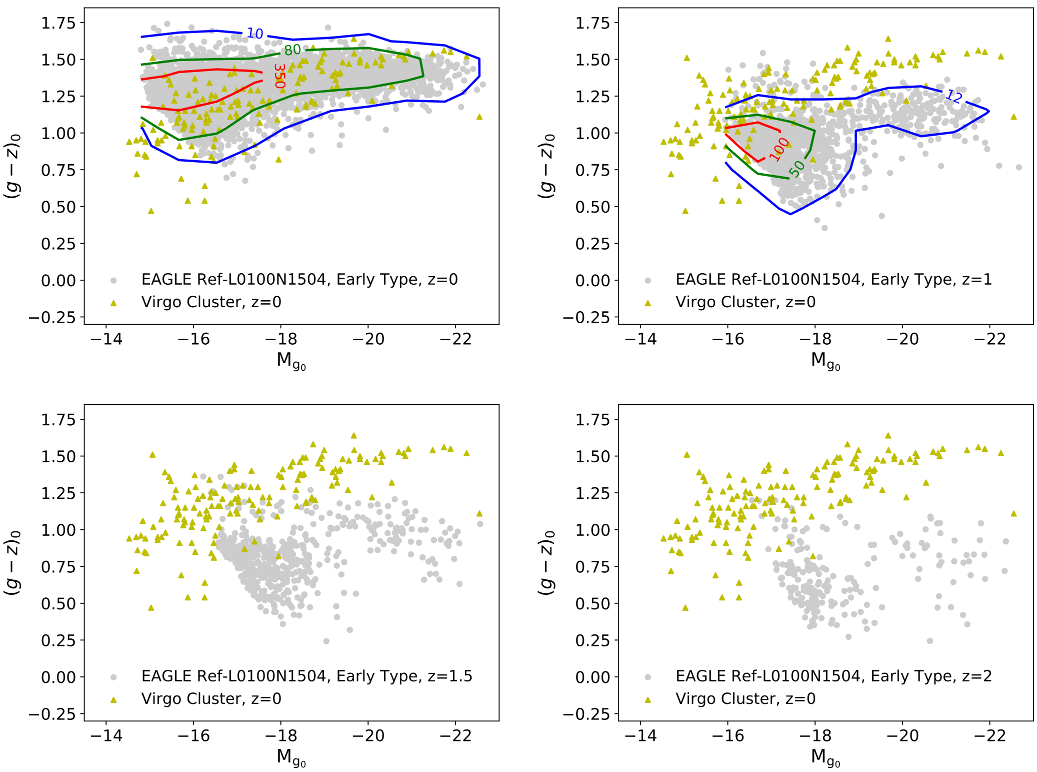

Figure 1: Color-magnitude diagrams of early-type galaxies at different z. Grey circles are simulated galaxies, extracted from the EAGLE Ref-L0100N1504 simulation using the selection criteria stated in Section 2.2.. Yellow triangles are galaxies of the Virgo Cluster (Chen et al., 2010; Sánchez-Janssen et al., 2019). Here are shown the CMD at $z = 0$ (top left), $z = 1$ (top right), $z = 1.5$ (bottom left), and $z = 2$ (bottom right). Three contours of constant number of galaxy are shown for $z = 0$ and $z = 1$.

2.2. Galaxy selection

From the Ref-L0100N1504 EAGLE simulation, we extracted galaxies with stellar mass $M_\star \geqslant 10^9$ $M_\odot$, a star formation rate (SFR) such as $\log(SFR/M_\star) \leqslant -11$ yr^{-1}, and star forming gas fraction $M_{SF\ gas}/(M_{SF\ gas} + M_\star) \leqslant 0.1$ (Zenocratti et al., 2018). Galaxies fulfilling these conditions are defined as our simulated sample of ET galaxies. To check our selection criteria, we compared the CMD of that sample at $z = 0$ with the corresponding to ET galaxies in the Virgo Cluster (Chen et al., 2010; Sánchez-Janssen et al., 2019). The CMD of the simulated sample at $z = 0$ agrees with the observed one (see Fig. 1).

3. Results

3.1. CMR at different z

Panels of Fig. 1 show the simulated $(g - z)_0$ vs. M_{g_0} CMD from $z = 0$ to $z = 2$ (grey circles); for comparison, galaxies of the Virgo Cluster (which are at $z = 0$) are shown in every panel (yellow triangles). As can be seen, the simulated sample and the observed one at $z = 0$ are located in the same region of this colour-magnitude diagram, therefore our selection criteria are consistent with observed trends. Also, some contours of constant number of simulated galaxies are plotted in the first two panels (i.e., at $z = 0$ and $z = 1$), in order to identify which region of the $(g - z)_0$ vs. M_{g_0} plane is more densely populated. As can be seen, when z decreases the number of ET galaxies increases in both luminosity extremes. That increment seems to be higher in the less luminous region of the CMD. Also, at lower z the bulk of galaxies in the CMD is located in redder regions, indicating that simulated ET galaxies (with our selection criteria) are reddened. Lastly, it can be seen that the brightest region of the CMD is always populated.

3.2. Distributions of magnitudes and colours at different z

The panels of Fig. 2 show the distributions of magnitude M_{g_0} and colour $(g-z)_0$ for redshifts from $z = 0$ to $z = 2$, for the simulated sample of ET galaxies. With respect to the distribution in magnitude, the low-magnitude peak moves towards less luminous magnitudes at lower z, which is due to the increment of low-luminosity ET galaxies at lower z. Also, at $z = 2$ a bimodality in the distribution can be seen, with a peak at $M_{g_0} \approx -18$ and another (less prominent) peak at $M_{g_0} \approx -21$, hence there are two population of simulated ET galaxies at that time. The properties of simulated galaxies around both peaks will be studied in a future work, but due to

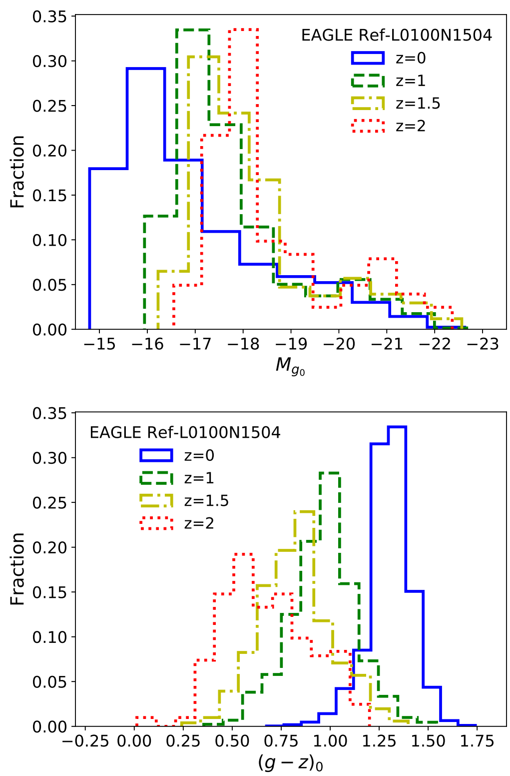

Figure 2: Distribution of M_{g_0} magnitude (top) and $(g-z)_0$ color (bottom) at different redshifts z for the simulated sample of ET galaxies, extracted from the EAGLE Ref-L0100N1504 simulation. The histograms correspond to $z = 0$ (blue solid), $z = 1$ (green dashed), $z = 1.5$ (yellow dot-dashed), and $z = 2$ (red dotted).

the cosmic time corresponding to $z = 2$ (≈ 3 Gyr), the brightest systems might be ET galaxies still in development.

The distribution of colour $(g-z)_0$ shows that at lower z, the maximum of the distribution moves towards redder colours, being this maximum more pronounced, i.e., the scatter in colour seems to decrease towards lower z. This means that simulated ET galaxies (selected with our criteria) tend to be bluer in the past, showing them colours in a little broader range than observed today. In particular, the bluest galaxies at high redshift might be ET galaxies going through their final stages of star formation, or as mentioned before, ET galaxies still in development. The shift of the maximum with z might be due to an increasing in the average age, while the lower scatter towards $z = 0$ might indicate that $g-z$ colour is not sensitive to age variations within the population. Specific properties of galaxies that populated our simulated sample (such as masses, ages, SFRs, metallicities, among others) will be studied exhaustively in a forthcoming work.

4. Summary and future work

We started studying the evolution with redshfit of the CMR for simulated ET galaxies, extracted from the EAGLE Ref-L0100N1504 simulation. Our selection criteria give us a sample at $z = 0$ consistent with the observed CMD for ET galaxies in the Virgo Cluster, hence we also used these criteria to extract ET galaxies up to $z = 2$. In the CMD, ET galaxies are placed in bluer regions with increasing z. At lower z, more low-luminosity systems appear, and ET galaxies tend to be redder, with a decreasing scatter in the colour distribution. Bluer and brighter ET galaxies present at higher z might be systems still in development.

In a future work, properties of the selected sample of ET galaxies (mass, metallicities, SFRs, etc.) will be studied in detail. Also, other EAGLE simulations with variations in the subgrid physics will be used, in order to determine how variations in parameters affect the CMR. Lastly, evolution of galaxies in the CMD will be analysed.

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