Evolutionary paths among different red galaxy types at 0.3 < z < 1.5 and the late buildup of massive E-S0s through major mergers

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ABSTRACT

Some recent observations seem to disagree with hierarchical theories of galaxy formation about the role played by major mergers in the late buildup of massive E-S0s. We re-address this question by analysing the morphology, structural distortion level and star formation enhancement of a sample of massive galaxies (M* > 5 × 10^{10} M_☉) lying on the Red Sequence and its surroundings at 0.3 < z < 1.5. We have used an initial sample of ~1800 sources with K_s < 20.5 mag over an area ~155 arcmin^2 on the Groth Strip, combining data from the Rainbow Extragalactic Database and the Galaxy Origins and Young Assembly survey. Red galaxy classes that can be directly associated with intermediate stages of major mergers and with their final products have been defined. We report observational evidence of the existence of a dominant evolutionary path among massive red galaxies at 0.6 < z < 1.5, consisting in the conversion of irregular discs into irregular spheroids, and of these ones into regular spheroids. This result implies: (1) the massive red regular galaxies at low redshifts derive from the irregular ones populating the Red Sequence and its neighbourhood at earlier epochs up to z ~ 1.5; (2) the progenitors of the bulk of present-day massive red regular galaxies have been discs that seem to have migrated to the Red Sequence mostly through major mergers at 0.6 < z < 1.2 (these mergers thus starting at z ~ 1.5) and (3) the formation of E-S0s that end up with M* > 10^{11} M_☉ at z = 0 through gas-rich major mergers has frozen since z ~ 0.6. All these facts support that major mergers have played a dominant role in the definitive buildup of present-day E-S0s with M* > 10^{11} M_☉ at 0.6 < z < 1.2, in good agreement with hierarchical scenarios of galaxy formation.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: interactions – galaxies: luminosity function, mass function – galaxies: structure.

1 INTRODUCTION

Studies based on data from the Sloan Digital Sky Survey have revealed the existence of a colour bimodality in the mass distribution of local galaxies (Strateva et al. 2001; Kauffmann et al. 2003a;
Baldry et al. 2004). The most-massive systems (basically spheroids) accumulate into a well-defined Red Sequence in colour–magnitude diagrams, while the less-massive blue ones (mostly discs) reside into a more spread Blue Galaxy Cloud (Strateva et al. 2001; Kauffmann et al. 2003b; Baldry et al. 2004). Although this colour–mass bimodality is observed up to \( z \sim 1 \), observational data evidence a strong evolution in it for both field and cluster environments (Couch et al. 1998; van Dokkum et al. 2000; van Dokkum & Franx 2001; Bell et al. 2004b). In fact, the mass limit isolating the Red Sequence from the Blue Cloud rises as the redshift increases, and the stellar mass harboured by the former has nearly doubled since \( z \sim 1 \) (whereas that of the Blue Cloud has remained nearly constant; see Arnouts et al. 2007; Lotz et al. 2008a; Stutz, Papovich & Eisenstein 2008; Taylor et al. 2009). This points to a progressive buildup of the Red Sequence during the last \( \sim 9 \) Gyr, associated with the migration of discs from the Blue Cloud to the Red Sequence through mechanisms that are still poorly understood, but that must be responsible for their star formation quenching and morphological transformation (Brinchmann & Ellis 2000; Faber et al. 2007, F07 hereafter).

According to hierarchical models of galaxy formation, the mechanism governing this evolution in the most-massive systems has been major mergers (i.e. with mass ratios from 1:1 to 1:4; see Somerville & Primack 1999; Steinmetz & Navarro 2002). Present-day massive spheroids (E-S0s) are expected to be the result of the most-massive and violent merging sequences in the Universe, also being the latest systems to be completely in place into the cosmic scenario (at \( z \lesssim 0.5 \), see De Lucia et al. 2006; Hopkins et al. 2008b; Oser et al. 2010). However, this prediction conflicts directly with recent data indicating that massive galaxies seem to have been in place before their less-massive counterparts (a phenomenon known as downsizing; see Bundy et al. 2006; Cimatti, Daddi & Renzini 2006; Pérez-González et al. 2008a; Mortlock et al. 2011).

Also this assembly epoch seems to depend strongly on the galaxy mass and its environment (di Serego Alighieri et al. 2005; Thomas et al. 2005; di Serego Alighieri, Lanzoni & Jørgensen 2006a,b; Pérez-González et al. 2008b; Cooper et al. 2010; Niemi et al. 2010; Vikram et al. 2010). The wide range of ages found for E-S0s (\( \sim 2-15 \) Gyr) and the disagreement between optical and near-infrared (NIR) age estimators (sometimes, of up to \( \sim 6 \) Gyr for a given galaxy) indicate that E-S0s have been built up at different epochs and through different mechanisms, basically depending on their masses (Trager et al. 2000; Bregman, Temi & Bregman 2006; López-Corredoira 2010). It is generally accepted that the time period at \( 1 < z < 2 \) is a transition era in which an increasing fraction of galaxies end their star formation activity and move on to the Red Sequence (Arnouts et al. 2007, but see also Ellis 1997; Cristóbal-Hornillos et al. 2003; Eliche-Moral et al. 2006b; Taylor et al. 2009; Brammer et al. 2011; Domínguez Sánchez et al. 2011). Nevertheless, there are conflicting views on the number evolution experienced by massive E-S0s at \( z \lesssim 1 \), with studies reporting from a negligible evolution to an increase by a factor of up to \( \sim 3 \) in these systems (Ilbert et al. 2006; F07; Scarlata et al. 2007; Cool et al. 2008; Nicol et al. 2011).

Moreover, the Red Sequence is not made of a homogeneous galaxy population, but of a mixing of different galaxy types that has evolved strongly with redshift (Cimatti et al. 2002; Gilbank et al. 2003; Yan & Thompson 2003; Moustakas et al. 2004; Franzetti et al. 2007; Hempel et al. 2011). In the past few years, different studies have analysed the number evolution of the Red Sequence from colour- and morphologically selected samples, but the conclusions derived from the former do not apply to the latter ones in general (Franzetti et al. 2007; Bundy et al. 2010; Hempel et al. 2011). Recently, Ilbert et al. (2010) have considered simultaneously both the morphological and star-formation properties of red galaxies to analyse their buildup. These authors confirm that the bulk of massive quiescent galaxies is rapidly created at \( 1 < z < 2 \), this mass assembly becoming negligible at later epochs. As in many previous studies, they also propose major mergers as drivers of this buildup.

Several estimates, assuming that most of the mass growth in quiescent galaxies is due to mergers, indicate that this mechanism is capable of explaining at least 50 per cent of the number density evolution of massive galaxies (see e.g. Eliche-Moral et al. 2010a, hereafter EM10; Eliche-Moral et al. 2010b; Brammer et al. 2011). However, no direct observational evidence has been found up to the date on the existence of a cause-and-effect link between major mergers and the definitive assembly of massive quiescent galaxies (F07; Sobral et al. 2009, 2011; Lin et al. 2010; Bernardi et al. 2011a,b; Chuter et al. 2011).

This study tries to advance in the understanding of the formation and evolution of massive galaxies by analysing the physical properties of red galaxies at \( 0.3 < z < 1.5 \) with stellar masses \( M_\ast > 5 \times 10^{10} \odot \). The novelty of our study over previous ones is two-fold. First, we include information about the structural distortion of each galaxy to trace merger remnants (besides considering morphology and star formation properties). And secondly, as most objects in their evolution towards the Red Sequence must have gone over nearby Green Valley locations transitorily (F07), we have analysed the red galaxies both lying on the Red Sequence and at close positions on the Green Valley. Therefore, red galaxies in the context of this paper include both the galaxies on the Red Sequence and at its neighbourhood. The galaxy classes resulting from the combination of morphological, structural and star-formation activity properties allow us to trace the evolution of intermediate stages of major mergers and of their final remnants since \( z \sim 1.5 \). Finally, the observed number density evolution experienced by each galaxy type is used to carry out a set of novel observational tests defined on the basis of the expectations of hierarchical models, which provide observationally and for the first time main evolutionary paths among the different red galaxy types that have occurred in the last \( \sim 9 \) Gyr.

The paper is organized as follows. In Section 2, we provide a brief description of the survey. Section 3 is devoted to the definition of the mass-limited red galaxy sample. In Section 4, we define the galaxy classes according to the global morphology, structural distortion level and star formation enhancement of the red galaxies. In Section 5, we comment on the sources of errors and uncertainties. Section 6 presents three novel tests to check the existence of any evolutionary links between the different red galaxy types, based on the expectations of hierarchical models of galaxy formation. The results of the study are presented in Section 7. In particular, the results of the three tests proposed for the hierarchical scenario of E-S0 formation can be found in Section 7.3. The discussion and the main conclusions of the study are finally exposed in Sections 8 and 9, respectively. Magnitudes are provided in the Vega system throughout the paper. We assume the concordance cosmology (\( \Omega_m = 0.3, \Omega_\Lambda = 0.7 \) and \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\); see Spergel et al. 2007).

2 THE SAMPLE

We have combined multiwavelength data from the Rainbow Extragalactic Database\(^1\) (Barro et al. 2011a,b) and the Galaxy

\(^1\)Rainbow Extragalactic Database: https://rainbowx.fis.ucm.es/Rainbow_Database/Home.html
Origins and Young Assembly (GOYA) photometric survey\(^2\) (see Balcells et al. 2002) over an area of \(\sim 155 \text{ arcmin}^2\) in the Groth Strip (\(\alpha = 14^h 16^m 38.8^s\) and \(\delta = 52^\circ 16' 52''\); see Groth et al. 1994; Ratnatunga, Griffiths & Ostrander 1999; Simard et al. 2002). The Rainbow Extragalactic Database compiles multiwavelength photometric data from the ultraviolet (UV) to the far-infrared (FIR) (and, in particular, in Spitzer/MIPS 24 \(\mu\)m band) over this sky area, providing analysis of spectral energy distributions (SEDs) of nearly 80 000 IRAC Spitzer 3.6-4.5 \(\mu\)m-selected galaxies. This study considers the photometric redshifts available in the Rainbow Database, which have a typical photometric redshift accuracy of \((\Delta z/(1 + z)) = 0.03\) (Barro et al. 2011b), as derived for the sources with spectroscopic redshifts available in the DEEP2 galaxy redshift survey (Davis et al. 2003, 2007). The GOYA survey is a survey covering the Groth Strip compiling photometry in four optical bands (\(U, B, F606W\) and \(F814W\)) and in two NIR ones (\(J\) and \(K_s\)) with visual classifications available, reaching similar depths to the Rainbow data in similar bands (\(U \sim 25, B \sim 25.5, K \sim 21\) mag; see Cristóbal-Hornillos et al. 2003; Eliche-Moral et al. 2006b; Abreu et al. 2007; Domínguez-Palmero et al. 2008).

We have performed the sample selection starting from a \(K\)-band-selected catalogue in the field, reaching a limiting magnitude for 50 per cent detection efficiency at \(K \sim 21\) mag. Several cuts have been performed to the original catalogue to obtain a mass-limited red galaxy sample. First, red galaxies are selected as detailed in Section 3. This selection determines the redshift interval of the study, as it is restricted to the redshifts where the obtained number of red galaxies is statistically significant (i.e. to \(0.3 \lesssim z \lesssim 1.5\); see Section 4.3).

According to the \(M_k-z\) distribution of the red galaxies sample, the faintest absolute magnitude for which the catalogue is complete in luminosity up to \(z \sim 1.5\) corresponds to \(M_{K,\text{lim}} \sim -24\) mag. According to the redshift evolution of the mass-to-light relation (assuming a Salpeter initial mass function (IMF)) derived by Arnouts et al. (2007) for a sample of quiescent bright galaxies, a red passive galaxy with this \(K\)-band absolute magnitude at \(z \sim 1.5\) has a stellar mass of \(M_{\ast,\text{lim}} \sim 5 \times 10^{10} \text{M}_\odot\). Therefore, we have selected red galaxies with masses higher than \(M_\ast \sim 5 \times 10^{10} \text{M}_\odot\) at each \(z\) just considering all galaxies with \(M_{K,\text{cut}}(z) = -23.3\) to 0.45\(z\) to account for their luminosity evolution. This luminosity cut is very similar to the one obtained by Cirasuolo et al. (2007). Analogously, the equivalent luminosity cut to obtain a complete red galaxy sample for \(M_{K,\text{lim}} = 10^{11} \text{M}_\odot\) would be: \(M_K = -24\) to 0.45\(z\) (we will use this selection for comparing our results with those reported in other studies, see Section 3.3). The detection efficiency in the \(K\) band drops below 0.9 for \(m_K > 20.5\) mag (Cristóbal-Hornillos et al. 2003), so we have checked that all galaxies in our mass-limited red sample exhibit apparent magnitudes brighter than this limit.

We have used the colour–color diagram shown in Fig. 1 to remove stars from the sample. It represents the \(I - K_s\) versus \(V - I\) distribution for all the sources in the mass-limited red galaxy sample. Stars typically exhibit NIR colours bluer than galaxies, so they populate the lower region in the diagram. Attending to this bimodality of star–galaxy colours, we have defined a colour–color cut to isolate galaxies from stars (see the solid line in the figure). The marked points include the stars and compact objects in the sample. We have checked that the stars identified according to it include all the objects at lower redshifts that have been classified as ‘stars’ in the morphological classification performed in

\(^2\)GOYA project (Galaxy Origins and Young Assembly): http://www.astro.ufl.edu/GOYA/home.html
3.1 Color cuts for red galaxies selection

Following previous studies, we have selected red galaxies according to their rest-frame $U-B$ colour (see, e.g., F07; Kriek et al. 2008). This colour traces the 4000 Å breakup, a spectral feature characteristic of evolved stellar populations. However, the rest-frame $U-B$ estimates derived from the present data set exhibit high uncertainties due to photometry and redshift-determination errors that we have used instead the observed colour that samples the rest-frame $U-B$ more closely at the centre of the three wide-redshift bins covering the complete redshift range ($0.3 < z < 0.7, 0.7 < z < 1.1$ and $1.1 < z < 1.5$).

The top panels of Fig. 3 show the colour distribution of all galaxies in our $K$-band-selected catalogue in the colours that sample more closely the rest-frame $U-B$ at these three redshift bins ($U-V$, $B-I$ and $V-K$ for the low-, middle- and high-redshift intervals, respectively). Typical colour errors of the galaxy sample are indicated with a horizontal bar at the upper-left corner of each frame. The figure shows the well-known bimodal distribution of galaxies into red and blue populations at all redshifts up to $z \sim 2$ (see references in Section 1). These bimodal distributions have been modelled as the addition of two Gaussian functions (also plotted in the figure).

In order to include the galaxies located at nearby positions on the Red Sequence in the red sample (and not just the galaxies lying within $1\sigma$ scatter of the red peak), we have adopted the colours at which both Gaussian distributions cross as the colour cuts for isolating red from blue galaxies at each redshift bin. The resulting cuts are $(U-V) = 1.4$ mag for $0.3 < z < 0.7$, $(B-I) = 2.7$ mag for $0.7 < z < 1.1$ and $(V-K) = 4.5$ mag for $1.1 < z < 1.5$.

In the bottom panels of Fig. 3, we show the histograms of the rest-frame $U-B$ colour in the same redshift bins. The dashed red and dotted blue histograms show the distribution of red and blue galaxies selected according to the criteria based on the apparent colours commented above. In the $1.1 < z < 1.5$ redshift range, the red and blue galaxy distributions appear quite mixed, probably due to the high errors associated with rest-frame $U-B$ colours (see the horizontal bar in the upper-left corner of each frame). These high errors in the rest-frame $U-B$ colour inhibited us to perform the red galaxies selection on the basis of rest-frame $U-B$ colours.

Previous studies report a negligible dependence of the rest-frame $U-B$ colour cut isolating the Red Sequence from the Blue Cloud with the galaxy mass for both the mass and redshift range considered in this study (the $U-B$ colour cut varies $\sim 0.3$ mag at most; see Taylor et al. 2009; Nicol et al. 2011). Therefore, any dependence of our colour cuts on mass (or, equivalently, on luminosity) has been overridden.

3.2 Galaxy populations in the red galaxy sample

We have analysed the kind of galaxy populations selected at each redshift interval with the colour cuts defined in Section 3.1 to find out if the selection is homogeneous at each redshift bin. In Fig. 4, we show the colour-redshift distributions of all the galaxies in the $K$-band-selected catalogue, for the colour indices nearest to the rest-frame $U-B$ colour in the three wide-redshift bins considered in the study ($0.3 < z < 0.7, 0.7 < z < 1.1$ and $1.1 < z < 1.5$). The colour cuts to distinguish between red and blue galaxies at each redshift bin are marked in their corresponding panels with horizontal lines. The red galaxies selected at each redshift bin are those above the colour cut and enclosed between the redshift limits associated with the colour index in each panel.

We have overplotted the theoretical evolution followed in each colour-redshift plane by different galaxy types. These trends have been modelled using the IRAF package COSMOPACK (Balcells, Cristóbal-Hornillos & Elliche-Moral 2003), which uses the SEDs predicted by the stellar population synthesis models by Bruzual & Charlot (2003) to obtain the evolution of colour indices with $z$. The galaxy types plotted in the figure include E’s and spirals formed at different redshifts, an S0, a star-forming irregular and a dust-reddened star-forming galaxy. Standard star formation histories (SFHs), metallicities and dust extinction values are assigned to each galaxy type, accordingly to observations (Kennicutt 1989; Gallazzi et al. 2005; Muñoz-Mateos et al. 2009). The modelling parameters assumed for each simulated galaxy type are listed in Table 1. We must remark that we have adopted for the ellipticals a finite burst instead of the traditional single stellar population model. Although both SFHs provide similar colours and magnitudes evolution, the finite burst model can account for the short initial phases of star formation observed in these systems (Kannappan, Guie & Baker 2009; Huertas-Company et al. 2010).

Different formation redshifts have been considered for all the types. Nevertheless, as the redshift evolution of colours for S0s and their values were quite independent of $z_l$, we have just plotted the S0 track for $z_l = 3$ in Fig. 4 for the benefit of clarity. As Irr’s with different $z_l$ are basically located below the spirals region in the plots, we only plot the case with $z_l = 3$ for the same reason. We have also simulated several cases of dust-reddened star-forming galaxies with different dust extinction levels. Their tracks basically overlap with...
Evolution among different red galaxy types

Figure 3. Color histograms of all galaxies in the $K$-band-selected catalogue in the three wide-redshift bins under consideration (0.3 < $z$ < 0.7, 0.7 < $z$ < 1.1 and 1.1 < $z$ < 1.5). Top panels: histograms of the apparent colour nearest to the rest-frame $U - B$ at each redshift interval. Red and blue solid lines: Gaussian functions fitted to match the bimodal colour distributions at each redshift. Vertical dashed lines in top panels: colour cuts used to isolate red from blue galaxies in each redshift bin (see the text). Bottom panels: histograms of the rest-frame $U - B$ in the same redshift bins. The horizontal bar in the upper-left corner of each frame represents the average colour error of one galaxy in the sample in each case. The dashed red and dotted blue histograms in these panels show the distributions of red and blue galaxies, respectively, selected according to the criteria based on the apparent colours of the top panels. The red galaxies are selected on the basis of apparent colours just attending to the low uncertainties associated with them compared to the typical errors of the rest-frame $U - B$ colours at all redshifts.

Figure 4. Color–redshift distributions for all galaxies in the $K$-band-selected catalogue, in the observed colours closest to the rest-frame $U - B$ colour in the three wide-redshift bins of the study. Panel a: $U - V$ colour (used for red galaxy selection at 0.3 < $z$ < 0.7). Panel b: $B - I$ colour (used for red galaxy selection at 0.7 < $z$ < 1.1). Panel c: $V - K$ colour (used for red galaxy selection at 1.1 < $z$ < 1.5). Dots: observational data. Lines: theoretical trends in the colour–$z$ space for different galaxy types according to standard SFHs and physical properties of different galaxy types (more details in the text). Red: ellipticals with different $z_f$. Magenta: SO galaxy with $z_f = 3$. Yellow: spirals with different $z_f$. Blue: star-forming irregular. Green: dust-reddened star-forming galaxy with $\tau_{V, \star} = 3$. Horizontal black lines: colour cuts defined to isolate red from blue galaxies, according to Fig. 3. Vertical solid lines: limits of the redshift interval associated with the colour plotted in each panel. Red galaxies in each redshift bin are those enclosed between the vertical lines and above the horizontal line marking the colour cut.
those of the ellipticals in the plots, so we only show the model with τ < \tau_0 = 3 mag.

To assume different or equal epoch for the formation of spirals have a negligible effect on both their colour evolution and location in the colour–z plane. They differ basically in their e-folding time-scales, metallicities, and gas and dust contents. However, a similar conclusion cannot be derived for ellipticals. If we assume that all ellipticals have formed at an early epoch (e.g. \tau_0 ≥ 2, as supported by some studies, see Section 1), the observed colour–z space of real red galaxies cannot be reproduced with the tracks modelled for \tau_0 > 2.0, unless there is a large population of dust-reddened star-forming objects at all redshifts at 0.4 < z < 2 (Kitzbichler & White 2006; EM10). A wide range of values for the formation redshift of ellipticals reproduces more properly the observed colour–z distribution of red galaxies (see the mesh of red lines in each panel of the figure), a fact that does not exclude the existence of relevant populations of dust-reddened objects at different redshifts.

The models for Es, S0s and dust-reddened star-forming galaxies lie all above the colour cuts in the three panels and that no spiral track enters the region of red galaxies in Fig. 4. This proves that the colour cuts used in this study select quite homogeneous samples of galaxy populations in the whole redshift interval, basically galaxy types earlier than Sa and dust-reddened star-forming galaxies.

### 3.3 Comparison with other studies

The red galaxy selection made in this study cannot be directly compared to the red galaxy samples obtained by most studies in the literature because, first, we have included red galaxies adjacent to the Red Sequence to study objects at transitory stages of their evolution towards it (which is not usual, see Section 1), and secondly, we have estimated masses using the M/LK–z relation derived by Arnouts et al. (2007) for different redshifts, whereas most authors use the M/LV–colour relation derived by Bell & de Jong (2001) or an equivalent relation. Moreover, most studies report the number evolution of red galaxies for masses M* > 10^{11} M_⊙, instead of for masses M* > 5 × 10^{10} M_⊙ (as our case). In order to check our results, we have made alternative red galaxy selections for M* > 10^{11} M_⊙, adopting the colour cuts and/or the mass-to-light relation used by other authors.

The three panels of Fig. 5 compare the redshift evolution of the number density of red galaxies derived from our data with the results of different authors, for analogous mass and colour selections in each case. In panel a, we have assumed the U–B colour evolution derived by van Dokkum & Franx (2001) to select red galaxies (following F07), and the masses are estimated using the M/LV–colour relation by Bell & de Jong. Only red galaxies with M* > 10^{11} M_⊙ at each redshift are considered in this panel. Panel b of
the figure also assumes the colour cut by van Dokkum & Franx for selecting red galaxies, but the mass estimates assume the $M_*/L_K$ relation by Arnouts et al., which includes evolutive corrections (it is equivalent to the one derived by Cirasuolo et al. 2007). The number densities of red galaxies shown in panel b are also for galaxies with $M_*>10^{11}\, M_\odot$ at each redshift. Finally, panel c of the figure uses the same selection criteria as panel b, but the number densities of red galaxies have been computed for $M_*>5\times10^{10}\, M_\odot$. Note that the results of our colour selection (including galaxies on the Red Sequence and at nearby locations) are not plotted in this figure (see Section 7 and Table 4).

The data from Arnouts et al. (2007), Cirasuolo et al. (2007) and F07 have been obtained by integrating their red galaxy luminosity functions at each redshift for $\log(M_*/M_\odot)>11$. In this case, the absolute magnitudes have been transformed into stellar masses using the expression derived for local E-S0s by Cimatti et al. (2006), considering the L-evolution of red galaxies derived by F07 and the redshift evolution of the $(B-K)$ colour expected for E-S0s (Shimasaku & Fukugita 1998; de Lapparent et al. 2003; Arnouts et al. 2007). AB magnitudes have been transformed to the Vega system in the $B$ and $K$ bands according to Blanton & Roweis (2007) transformations and considering galaxy colours derived for E-S0s by Fukugita, Shimasaku & Ichikawa (1995).

The good agreement between our results and those from independent studies for similar selection criteria supports the reliability of our methodology and completeness of our nominal red sample (compare the black filled circles with the rest of studies in all panels of Fig. 5). However, although our first data point in panels b and c in the figure is inside the cloud of points within errors, it does not follow the trend of the other authors. So, our data at this redshift are probably affected by volume and cosmic variance effects.

4 CLASSIFICATION OF RED GALAXY TYPES

The hierarchical picture of galaxy formation predicts that massive E-S0s are the result of the most-violent and -massive merging histories in the Universe (see references in section 1 in EM10). To test this scenario, we need to distinguish between galaxies undergoing a major merger and normal E-S0s (see Section 6). Normal relaxed galaxies and major mergers differ basically in their structural distortion level. Major mergers also exhibit different global morphology and star formation enhancement depending on the gas content of the progenitors and the evolutionary stage of the encounter.

A gas-rich major merger is expected to turn into a dust-reddened star-forming disc with noticeable structural distortions at intermediate and advanced stages of the encounter, basically since the coalescence of the two galaxies into a unique galaxy body (this stage is known as the merging-nuclei phase). In earlier phases of the merger, the two galaxies can develop noticeable tidal tails and asymmetric structures, but the two bodies can still be distinguished and are not expected to suffer from enough dust reddening to lie nearby or on top of the Red Sequence. During the latest phase of the encounter (post-merger), the star formation is quenched and the remnant gets a more relaxed spheroidal structure until it transforms into a typical E-S0 (see Cox et al. 2008; Lotz et al. 2008b, 2010a,b). Intermediate-to-late stages of gas-poor major mergers present a distorted spheroidal morphology and negligible levels of star formation, thus being quite red too (van Dokkum 2005). On the contrary, typical E-S0s present a spheroidal-dominated relaxed morphology, although they are also expected to be quite red due to their negligible star formation. Therefore, a gas-rich major merger is expected to be quite red from its merging-nuclei phase until its transformation into a typical E-S0, so we have traced major mergers once the two merging galaxies have merged into a unique remnant, because they are expected to be quite red in any case. Accounting for this, we have classified the galaxies in our red sample attending to their global morphology, structural distortion level and star formation enhancement to distinguish among normal galaxies and intermediate-to-advanced phases of major mergers.

4.1 Classification according to global morphology and distortion level

Despite the definition of very efficient quantitative morphological indices (Lotz et al. 2008a), visual inspection is still the most trustworthy method to classify galaxies morphologically (Schawinski et al. 2007; Jogee et al. 2009; Darg et al. 2010). The red galaxies in our sample have been thus classified visually by three co-authors. The comparison of the visual results with those obtained through quantitative classification methods has proven the reliability and robustness of the visual classification (see Section 4.2).

No pre-conceived or classical morphological types have been used for the visual classification, as the emergence of the classical Hubble types seems to occur at $z \sim 1.0$–1.5 (Oke et al. 1996; Papovich et al. 2005; Ravindranath et al. 2006). The visual types of red galaxies have been defined attending to the global characteristics exhibited by these galaxies in the sample. We find that red galaxies in our sample can be grouped morphologically attending to two aspects: (1) their structural distortion and (2) their disc- or spheroid-dominated morphology. Six major exclusive classes have been identified according to the previous two criteria (see Fig. 6).

(i) Compact galaxies (C). Galaxies exhibiting compact morphologies, according to the seeing of the $I$-band images. No spatial information is available for them. The number of these objects in the sample is negligible, so we will not consider them henceforth.

(ii) Regular spheroids (RSs). Galaxies with regular isophotes and dominated by a central spheroidal component. We remark that our RSs do not correspond to the spheroidal type defined by Kormendy & Bender (2012). This class basically groups E-S0 galaxies.

(iii) Regular discs (RDs). Galaxies with regular isophotes and dominated by a disc component. Dust-reddened, typical spiral Hubble types correspond to this class.

(iv) Irregular spheroids (ISs). Galaxies with irregular isophotes in the whole galaxy body but dominated by an spheroidal component.

(v) Irregular discs (IDs). Galaxies with irregular isophotes in the whole galaxy body and dominated by a disc.

(vi) Non-classified or unclassified objects (NC). Galaxies that cannot be classified into any one of the previous classes, because of their faintness or noise. The number of these objects is also negligible, so we will not consider them from now on.

We have used surface brightness isophotes and surface maps to identify structural or morphological features that are more noticeable in these maps than in normal images (see Fig. 7). We have also adopted the following additional classification rules. As commented above, we have traced exclusively advanced stages of major mergers, i.e. once both galaxies have merged into a unique body. Therefore, we have assigned a certain type to a red galaxy regardless of its environment, i.e. independently of whether it has close neighbours or not. We have considered as irregular galaxies only those systems that exhibit a noticeable distortion level in its whole body. This implies that a galaxy in an interacting pair is identified as an independent regular galaxy, because its central body does not exhibit noticeable distortions yet, despite of the existence of significant
Figure 6. False-colour postage stamps of some red galaxies in our sample, obtained using the $V$ and $I$ bands. One example representative of each type is shown for each wide-redshift bin used in this study ($0.3 < z < 0.7$, $0.7 < z < 1.1$ and $1.1 < z < 1.5$). North is up, east is left. The frames correspond to a 5 arcsec $\times$ 5 arcsec field of view, except for the irregular spheroid at $0.3 < z < 0.7$ (141 618.91 $+$ 521 352.3), where a 10 arcsec $\times$ 10 arcsec view is used to emphasize the interacting group to which this galaxy belongs (the galaxies at the north and at the southern-east of the central object are located at the same redshift as the central object). No compact or unclassified objects are found at $0.3 < z < 0.7$. 

Figure 7. $I$-band contour maps and surface plots of some red galaxies in Fig. 6. One galaxy representative of each type is shown (‘C’, ‘RS’, ‘RD’, ‘IS’, ‘ID’, ‘NC’). The axes in both the contour and surface maps are in CCD pixels.

Tidal features in its outskirts. We remark that we are excluding from the irregular class the early phases of mergers in which the interacting galaxies have not merged into one body yet. The reason is because the tests for the hierarchical scenario of E-S0 formation described in Section 6 are based in the tracing of these specific advanced stages of major mergers (and not of earlier phases).

Minor mergers imprint less significant distortions than major mergers (Eliche-Moral et al. 2006a, 2011; Lotz et al. 2008b), but they can also redden the galaxy enough to locate it at neighbouring regions of the Red Sequence temporarily (Lotz et al. 2010a,b). We have avoided the inclusion of minor mergers into the irregular class by considering exclusively morphological features typical of major mergers to classify a system as irregular, following Jogee et al. (2009), such as the existence of multiple nuclei of similar luminosity in the body, the existence of equal-length tidal tails or ‘train-wreck’ morphologies. So, our red galaxy sample contains some minor mergers, but they are included into the regular class.

Our classification criteria try to minimize the effects of the spatial resolution loss and cosmological dimming inherent to the rise of redshift, which soften the luminosity distribution of galaxies, losing the physical regions of fainter surface brightness. Therefore, we have defined our galaxy types attending to features that affect the whole galaxy body and that are poorly affected by these effects for the considered redshifts. Moreover, the classification has been done in the reddest visual band available with the best spatial resolution ($I$ band from Hubble Space Telescope/WFPC2). This band samples the rest-frame visual spectrum in the whole redshift range under study (from $I$ at low redshifts to $B$ at $z \sim 1.5$). Galaxies usually exhibit more distorted and clumpy morphologies in the rest-frame UV than in optical or NIR bands, but the morphology of a system is very similar in all rest-frame optical bands (Kuchinski et al. 2000; Jogee et al. 2009), so we expect our visual classifications to not be biased towards irregular types at any redshift in our study. Simulations of the cosmological effects in the apparent $I$-band morphology
of our systems have demonstrated the robustness of our visual classification against this effect (see Section 4.2.2). In general, the three independent classifiers agreed in \( \sim 90 \) per cent of the classifications at each redshift bin, a fact that strongly supports the robustness of the visual classification.

4.2 Tests to the robustness of the visual morphological classification

We have carried out two kind of quantitative tests to check the robustness of the visual classifications.

(i) Tests on the reliability of the visual distinction of spheroid-/disc-dominated and irregular/regular classes, based on the quantification of the light concentrations and the deviations of the isophotes from perfect ellipses in the whole galaxy body.

(ii) Tests on the cosmological effects on the visual morphology in the observed \( I \) band (resolution loss, cosmological dimming and change of the observed rest-frame band with redshift).

4.2.1 Reliability of the visual classifications

In order to check our visual classification, we have computed concentration and asymmetry indices as defined by Conselice (2003), which are quantitative indices closely related to our visual classes by definition (irregular galaxies should exhibit high asymmetries, while spheroid-dominated galaxies must have high concentrations). We find that galaxies visually classified as RSs show high-concentration indices in general (\( \sim 90 \) per cent). The irregulars (ISs and IDs) present a wide spread of concentration values, consistently with their merger-related nature.

Nevertheless, we also find that the galaxies classified visually as irregulars do not exhibit any correlations with the asymmetry index, contrary to expectations. This is probably because the asymmetry index estimates are extremely affected by background substructures, thus requiring high signal-to-noise data to be reliable (\( S/N > 100 \); see Conselice, Bershady & Jiang 2000; Conselice 2003; Conselice, Yang & Bluck 2009). But the galaxies in our red sample have \( S/N \sim 40–50 \) at most (as \( I \)-band magnitude errors are \( \sim 0.02–0.03 \) mag typically), making our asymmetry estimates quite uncertain. Moreover, asymmetry indices are sensitive to environmental influences in the galaxy outskirts. This means that some galaxies identified as regulars according to our criteria (because they do not exhibit noticeable distortions in their whole body) may have a high asymmetry index because of tidal features in the outer parts. This obviously smudges the correlation between visual irregularity and computed asymmetries.

We have adapted the method by Zepf & Whitmore (1993) to quantify the irregularity level of galaxy morphology. These authors developed a procedure to classify an elliptical galaxy as regular or irregular, attending to the distortion level of their isophotes with respect to perfect ellipses. They fitted ellipses to the isophotes of each elliptic to obtain the radial profiles of the coefficients \( a_1, b_1, a_2 \) and \( b_2 \) of their Fourier expansion series. The peak value of each Fourier coefficient was identified along the radial profile. These authors considered the following criteria to distinguish among regular and irregular galaxies.

(i) If all the peaks of the coefficients were small, this meant that the isophotes exhibited small deviations from perfect ellipses. Therefore, these galaxies could be considered as regulars.

(ii) If one of them was not small, then they differentiated between two possible cases.

(a) If the maximum value of the peaks of all coefficients did not correspond to \( b_1 \), then the isophotes deviated noticeably from ellipses, meaning that the galaxy was irregular.

(b) If the peak of \( b_1 \) was the maximum among all the peaks, its classification depended on its trend with the radial position in the galaxy. If the profile of this coefficient changed from one type to another within 1.5 effective radii of the galaxy, then the galaxy was irregular. If not, it just implied that the galaxy was boxy or discy (depending on the sign of \( b_1 \)), but the galaxy morphology could be considered as regular.

We can adopt this method for our galaxies, as we are considering irregularities that must affect the galaxy as a whole. We have limited the analysis in each red galaxy to the isophotes with a mean signal higher than 1.5 times the standard deviation of the sky signal per pixel. We have used the \textsc{iraf} task \texttt{ellipse} for fitting ellipses to the isophotes and for getting the third- and fourth-order coefficients of their Fourier expansion series. We have identified the peaks of each coefficient in the galaxy radial profile.

The task \texttt{ellipse} uses a normalization to the surface brightness of the isophote that directly measures the deviations of the isophote from perfect ellipticity. According to de Peletier et al. (1990), these deviations can be considered negligible if they are \( < 5 \) per cent, a value that can be translated directly into a value of 0.05 in these coefficients. Therefore, we have adopted this limit as the critical value to distinguish between small and high values. We have defined the irregularity index \( C_{\text{irr, isoph}} \) as the peak value of maximum absolute value among the peaks of the four Fourier coefficients. Therefore, according to Zepf & Whitmore (1993), any galaxy that has \( |C_{\text{irr, isoph}}| < 0.05 \) is regular. If not, it is irregular, except if \( C_{\text{irr, isoph}} \) corresponds to the \( b_1 \) coefficient and this coefficient does not change between \( |b_1| > 0.5 \) and \( |b_1| < 0.5 \) values or vice versa along its radial profile.

We compare the results of the visual and quantitative classifications concerning the irregularity level of our red galaxies in Fig. 8 for each wide-redshift bin. The percentage of agreement between the visual and quantitative classifications into the regular type is \( \sim 77 \) per cent (decreasing from 83 to 70 per cent from low to high redshifts). This percentage is slightly lower in the irregular type: \( \sim 66 \) per cent (rising from 58 to 74 per cent from low to high redshifts). The misclassifications between both methods are \( \sim 25 \) per cent for visually identified regular galaxies (rising the confusion percentage from 17 to 30 per cent from low to high \( z \)), and \( \sim 34 \) per cent for visual irregulars (dropping from 42 at low \( z \) to 26 per cent at high \( z \)). In general, both procedures coincide with \( \sim 78 \) per cent of the galaxy classifications at \( 0.3 < z < 0.7 \), with \( \sim 68 \) per cent of the classifications at \( 0.7 < z < 1.1 \) and with \( \sim 73 \) per cent at \( 1.1 < z < 1.5 \).

It is important to remark that only isophotal data above 1.5 times the sky standard deviation have been considered to quantify the irregularity of the galaxy in the quantitative method, i.e. it analyses isophotes of \( S/N > 1.5 \) at all redshifts. This implies that the quantitative method is not biased towards more irregular types at high redshifts, as it is limited to the isophotes with enough \( S/N \) at all redshifts. Obviously, \( C_{\text{irr, isoph}} \) is derived from an intrinsic physical region in the galaxies smaller at high redshift than at low redshift, just because of cosmological effects. But, as commented above, we consider as irregular galaxies only the stages of advanced major mergers, which imply a noticeable distortion level in its whole body. The effects of cosmological dimming and resolution loss on the classification are analysed in Section 4.2.2.

In conclusion, this test proves the robustness of the visual classifications into regular and irregular types at all redshifts.
4.2.2 Robustness of the observed morphology against cosmological effects

In order to find out how the loss of spatial resolution, the cosmological dimming and the change of rest-frame band with redshift are affecting our classification, we have simulated images of galaxies at different redshifts in the observed $I$ band. We have used COSMOPACK (Balcells et al. 2003), an IRAF package that transforms images of real galaxies to depict their appearance at a given redshift as observed with a given telescope, camera and filter. The transformation includes $K$-corrections, change of observing band, repixelation to the scale of the observing system, convolution by the seeing and noise from sky, detector and dark current.

Starting from the $I$-band image of a galaxy representative of one type at the lowest wide-redshift bin (0.3 $< z < 0.7$), we have simulated the observed $I$-band image of the same object at the middle of the other two redshift bins ($z = 0.9$ and 1.3), in order to check if its morphological classification changes as the object is placed at higher redshifts. We have assumed a typical SFH, metallicity and formation redshift for the galaxy to assign a characteristic SED at its original redshift. Once we obtain the simulated image at $z = 0.9$ and 1.3, we have classified them visually following the same procedure as with the original image.

The surface maps at different redshifts show that the distinction between the spheroid-/disc-dominated morphology is quite robust in the whole redshift interval under consideration. In general, we can distinguish the winged surfaces of discs in the surface maps at all redshifts (see Figs 6–7). This means that the visual classification into spheroid-/disc-dominated systems is quite robust against cosmological effects for the redshifts and magnitudes studied here.

Concerning the irregularity, the contour plots support the expected trend of external isophotes to appear more irregular as we move towards higher redshifts. But this effect should not affect strongly our results, as we derive our visual classification into regular/irregular classes taking into account the morphology of the isophotes over the whole galaxy body, discarding the most external ones. This qualitative test indicates that cosmological effects are not expected to affect noticeably the classification into regular/irregular types either.

4.3 Classification according to star formation activity

A typical problem of studies based on red galaxy samples is to disentangle dust-reddened star-forming galaxies from quiescent ones (Pozzetti & Mannucci 2000; Daddi et al. 2004; F07; Patton et al. 2011), because both galaxy populations are indistinguishable using only broad-band photometry at wavelengths $\lesssim 10\,\mu m$ (Stern et al. 2006). In particular, the rest-frame $U - B$ colour cannot differentiate between both red galaxy types adequately at $z > 0.8$ (F07). Therefore, different selection techniques based on colour indices, mid-infrared (MIR) data or SED fitting have been developed to isolate both populations in red galaxy samples (Lin et al. 1999; Wolf et al. 2003; Zucca et al. 2006; Williams et al. 2009).

The MIR emission and the SFR of a galaxy are known to be tightly correlated (Kennicutt 1998; Pérez-González et al. 2005). The higher sensitivities and spatial resolutions achieved by infrared (IR) instruments in the past few years have allowed the development of SFR indicators based on the emission of a galaxy in a single MIR band (Calzetti et al. 2005, 2007; Pérez-González et al. 2006). In particular, the 24 $\mu m$ band of the multiband imaging photometer in the Spitzer space telescope (MIPS) is found to be a good tracer of the IR emission coming from the dust heated by star-forming stellar populations (Alonso-Herrero et al. 2006).

In this study, we have identified galaxies with noticeable star formation compared to the average SFR exhibited by the galaxies with similar masses at the same redshift, because this is evidence of the fact that mechanisms different from passive evolution are triggering it (such as tidal interactions, mergers, gas infall or stripping). The SFR of a galaxy changes noticeably with redshift due to the natural evolution of their stellar populations. The specific SFR has decayed with cosmic time as $\sim (1 + z)^n$ since $z = 3$, with $n = 4.3$ for all galaxies and $n = 3.5$ for star-forming sources (Karim...
Evolution among different red galaxy types

The results in Table 2 show that the contamination by any type of AGNs to our HSFs is negligible (below 13 per cent at all redshifts), the contribution of pure AGNs being even smaller (<7 per cent at all redshifts). Therefore, we can conclude that AGN contamination does not affect our results concerning the classification into HSF galaxies significantly.

Table 2. Percentages of AGN contamination in the subsample of HSF red galaxies by morphological types.

| HSF type | 0.3 < z < 0.7 | 0.7 < z < 1.1 | 1.1 < z < 1.5 |
|----------|--------------|--------------|--------------|
|          | Pure | Total | Pure | Total | Pure | Total |
| RS       | 0    | 0    | 22   | 22    | 0    | 0     |
| RD       | 0    | 0    | 0    | 0     | 0    | 0     |
| IS       | 0    | 0    | 13   | 38    | 0    | 13    |
| ID       | 0    | 0    | 0    | 0     | 0    | 0     |
| All      | 0    | 0    | 7    | 13    | 0    | 4     |

Columns labelled as ‘Pure’ represent the contribution of pure AGNs (type 1 and 2) to each HSF galaxy type (i.e. without starburst connection).

Columns labelled as ‘Total’ provide the total contribution of AGNs to each type, including pure AGNs (type 1 and 2) and mixed types (starburst-dominated AGNs, starburst-contaminated AGNs and normal galaxies hosting AGNs).
5 ERRORS AND UNCERTAINTIES

The errors in the estimates of the number density of each red galaxy type are derived considering the following sources of errors: statistical and classification errors, photometric redshift errors and cosmic variance uncertainties.

Statistical counting errors have been estimated for the number densities derived by each classifier for each galaxy type and at each redshift (Gehrels 1986). The final number density of each morphological type at each redshift bin is estimated as the mean of the number densities resulting from the three independent classifiers. We have estimated the error of this mean as the quadratic propagation of the statistical error of each classifier (consult Jogee et al. 2009).

Concerning the redshift errors, we have used the redshift estimates from the Rainbow Extragalactic Database (Barro et al. 2011b). As commented in Section 2, uncertainties in the redshifts are $\Delta z/(1 + z) \lesssim 0.03$ for the whole redshift interval under consideration, for both bright and faint red sources.

We have included estimates of the uncertainties introduced in the number densities of each red galaxy type by the redshift errors. These estimates have been derived using Monte Carlo simulations. We have made 100 simulated catalogues of the (mass-limited) red galaxy sample, adopting a photometric redshift value for each source between $[z_{\text{phot}} - \Delta(z_{\text{phot}}), z_{\text{phot}} + \Delta(z_{\text{phot}})]$ at random, being $z_{\text{phot}}$ the nominal photometric redshift of the source and $\Delta(z_{\text{phot}})$ the typical dispersion of the photometric redshifts compared to the spectroscopic ones. This dispersion is estimated as: $\Delta(z_{\text{phot}}) = \langle \Delta(z)/(1 + z) \rangle \cdot (1 + z_{\text{phot}})$, where $\langle \Delta(z)/(1 + z) \rangle$ is the average value obtained for this normalized dispersion at the redshift bin of the galaxy (see Fig. 2). Then, we have obtained the number densities corresponding to each simulated catalogue for each galaxy type and at each redshift bin, accounting for the different redshifts of each catalogue. The dispersion of the 100 values obtained for the number density at each redshift bin and galaxy type represents an estimate of the error associated with the photometric redshift uncertainties.

Statistics of massive red galaxies can be dramatically affected by cosmic variance due to their high clustering (Somerville et al. 2004). We have estimated cosmic variance using the model by Moster et al. (2011), which provides estimates of cosmic variance for a given galaxy population using predictions from cold dark matter theory and the galaxy bias. They have developed a simple recipe to compute cosmic variance for a survey as a function of the angular dimensions of the field and its geometry, the mean redshift and the width of the considered redshift interval, and the stellar mass of the galaxy population. We have considered the geometry and angular dimensions of our field, as well as the different redshift bins analysed in each case to estimate the cosmic variance. Moster et al.’s software provides these estimates in two mass ranges overlapping with ours: $10.5 < \log(M_{\star}/M_\odot) < 11$ and $11 < \log(M_{\star}/M_\odot) < 11.5$. Therefore, we have considered the mean cosmic variance of both mass ranges as a representative value of the cosmic variance of our mass-limited sample at each redshift bin. Cosmic variance depends on the redshift. At $0.3 < z < 1.5$ and for our mass range, cosmic variance decreases from $0.3 < z < 0.5$ to $0.7 < z < 0.9$ approximately, and then starts rising again towards higher redshifts. This behaviour is observed for all used redshift bins ($\Delta z = 0.1, 0.2$ and 0.4). For $\Delta z = 0.1$, the root cosmic variance acquires minimum and maximum values equal to 34 and 40 per cent, respectively. For $\Delta z = 0.2$, it changes between 24 and 28 per cent, and between 17 and 19 per cent for $\Delta z = 0.4$. All our results include these uncertainties quadratically added to the other error sources (statistical and classification errors, and redshift uncertainties).

The predictions of the cosmic variance obtained with the model by Moster et al. (2011) are in good agreement with the rough estimates that can be derived from panel a of Fig. 5. At $0.7 < z < 1.1$, the dispersion of the different studies is $\sim 30$ per cent, most of which can be attributed to cosmic variance. This value is quite similar to the estimate obtained with Moster et al. model at these redshifts for $\Delta z = 0.2$ ($\sim 27$ per cent). At lower and higher redshifts, the dispersion among different authors may arise also in completeness problems and higher observational errors, so a direct comparison cannot be done.

The redshift errors have been added quadratically to the statistical and classification errors and to the uncertainties associated with cosmic variance to obtain the final error of the number density at each $z$ interval and for each galaxy type. In general, for regular red galaxies, the statistical and classification errors contribute to $\sim 30$ per cent of the total error of their number density for both low and high redshifts, the redshift errors represent $\sim 10$ per cent of the total error and the cosmic variance contributes to $\sim 60$ per cent of the total error at all redshifts. For irregular galaxies, the contribution of the statistical and morphological classification errors represents $\sim 35$ per cent at all redshifts, the redshift errors are $\sim 25$ per cent (being $\sim 30$ per cent at low $z$ and decreasing down to $\sim 23$ per cent at high $z$) and the cosmic variance contributes to $\sim 37$ per cent (being $\sim 35$ per cent at low $z$ and rising to $\sim 40$ per cent at high $z$).

6 OBSERVATIONAL TESTS TO THE HIERARCHICAL ORIGIN OF MASSIVE E-S0S

As commented in Section 1, no observational evidence on the existence of an evolutionary link between major mergers and the rise of the present-day massive E-S0s exists till date. In order to test the major-merger origin of massive E-S0s observationally, we must be capable of providing evidence supporting or rejecting the existence of such a link. However, the transitory stages and end products of these evolutionary tracks coexist at each redshift, making this task difficult. Here we define three tests to observational data based on the predictions of hierarchical models to check if data are coherent with the existence of this link, which can be done thanks to the classification performed in this study.

6.1 Equivalence between our galaxy types and the different evolutionary stages of red galaxies

The morphological and structural properties of a galaxy can be combined with information about its star formation enhancement to establish correspondences between its galaxy type in our classification and the evolutionary stage of the galaxy. Once a galaxy is identified as a major merger on the basis of its noticeable structural distortion, both its star formation level and its global morphology may be pointing either to the gas-content of its progenitors or to the merger phase (Cox et al. 2008; Lotz et al. 2008b, 2010a,b).

Galaxies involved in a gas-rich major merger are expected to be disc dominated during the merging-nuclei phase. During the initial moments of this phase, these mergers experience strong starbursts that last less than $\sim 0.5$ Gyr. Therefore, depending on the evolutionary stage of these mergers, they might appear either as HSF or LSF. Post-merger stages of these events will still exhibit noticeable distortion, but its morphology is expected to be spheroidal dominated. Depending on the efficiency of the star formation quenching in the merger, late phases of gas-rich major mergers may be HSF.
or LSF. Additionally, gas-poor mergers are expected to be irregular, spheroidal dominated and mostly LSF since their merging-nuclei phase. Normal discs and E-S0s exhibit an RD- or RS-dominated morphology, respectively. Most E-S0s are quiescent, meaning that they must be LSF.

Our classification thus allows us to distinguish among these evolutionary stages of red galaxies just attending to their types, except between gas-poor mergers and post-merger stages of wet mergers. In Table 3, we list the correspondence between a galaxy evolutionary stage and its characteristics in our classification.

### 6.2 Hierarchical evolutionary paths among red galaxy types

Here, we describe three tests based on the expectations of hierarchical models of galaxy formation to check whether data are coherent with the existence of an evolutionary link between major mergers and the E-S0s appearing on the Red Sequence since $z \sim 1.5$ or not.

F07 proposed a hierarchical mixed evolutionary scenario for explaining the observed mass migration from the massive end of the Blue Galaxy Cloud to that of the Red Sequence since $z \sim 2$, in which 'quenched galaxies enter the Red Sequence via gas-rich mergers', and can be 'followed by a limited number of gas-poor, stellar mergers along the sequence'. The semi-analytical model by EM10 proved the feasibility of the F07 scenario for explaining the buildup of E-S0s that end up with $M_* > 10^{11} \, M_\odot$ at $z = 0$, just accounting for the effects of the major mergers strictly reported by observations since $z \sim 1.2$ (López-Sanjuan et al. 2009). This model reproduces the observed evolution of the massive end of the galaxy luminosity function by colour and morphological types. The evolutionary track described by F07 appears naturally in the model, as it considers the relative contribution of gas-poor and gas-rich mergers at each redshift reported by Lin et al. (2008) and their different effects on galaxy evolution.

The advantage of this model is that its predictions are in excellent agreement with cosmological hierarchical models (despite being based on observational major merger fractions), reproducing observational data at the same time (see EM10; Eliche-Moral et al. 2010b). Based on these predictions, we have defined some tests that observational data must fulfil if most massive E-S0s are really derived from major mergers occurred at relatively late epochs in the cosmic history. These predictions are as follows:

(i) Most present-day E-S0s with $M_* > 10^{11} \, M_\odot$ are the result of at least one gas-rich major merger that places them on the Red Sequence since $z \sim 1.2$.

(ii) In addition, $\sim 75$ per cent of the remnants resulting from these gas-rich events have been involved in a subsequent gas-poor major merger, occurred quite immediately. The remaining $\sim 25$ per cent have thus continued their evolution towards an E-S0 passing through a quiet post-merger phase.

(iii) The bulk of these major mergers are at intermediate-to-late stages during the $\sim 2$ Gyr period elapsed at $0.7 < z < 1.2$, which means that the gas-rich ones must have started at $1 < z < 1.5$, accounting for the typical time-scales of these events. The gas-poor ones are later, but must take place earlier than $z \sim 0.7$ in any case, as the resulting massive E-S0s have been in place since that epoch.

Therefore, according to the EM10 model, the appearance of the bulk of massive E-S0s takes place at $0.7 < z < 1.2$, and nearly all have evolved according to the following path:

Note that this evolutionary track implies the existence of a nearly 1:1:1 numerical relation at $0.7 < z < 1.2$ between gas-rich major mergers at merging-nuclei stages, gas-poor events and post-mergers stages of gas-rich ones, and the massive E-S0s assembled at those epochs. Accounting for the correspondence of these evolutionary stages and the red galaxy types defined in this study (see Table 3), the evolutionary path schematized in equation (1) can be re-written as follows:

Therefore, the previous 1:1:1 relation between the different stages of these galaxies in their evolution towards the Red Sequence can be translated into an equivalent 1:1:1 relation between the following red galaxy types, according to Table 3:

\[
\text{ID (HSF/LSF)} \downarrow \quad \text{IS (HSF/LSF)} \quad \text{IS (mostly LSF)} \downarrow \quad \text{RS (mostly LSF)}
\]
If most-massive E-S0s have really evolved according to the hierarchical scenario proposed by the EM10 model, then the data must fulfill this evolutionary path among massive red galaxy types at $0.7 < z < 1.2$. This imposes the following three observational tests or constraints to observations:

1. The accumulated number density of IDs (gas-rich major mergers) on our red sample since $z \sim 1.2$ down to a lower redshift $z$ must reproduce the net numerical increment of RSs (E-S0s) observed between the two redshifts.

2. An analogous relation must be fulfilled by the accumulated number density of ISs (gas-poor major mergers and post-merger stages of gas-rich events).

3. The bulk of RSs (E-S0s) with stellar masses $M_* > 10^{11} M_{\odot}$ at $z = 0$ must have been definitely built up during the ~2.2 Gyr time period elapsed at $0.7 < z < 1.2$.

Our data are complete for galaxy masses $M_* > 5 \times 10^{10} M_{\odot}$ at each redshift. This means that we can ensure that we are in a position to trace back in time the potential progenitors of the present-day E-S0s with $M_* > 10^{11} M_{\odot}$ at $z \sim 0$ that could have merged to create them during the last ~9 Gyr (see Section 2).

Therefore, we have estimated the cumulative distribution of IDs and ISs, and we have compared them with the redshift evolution of the number density of RS’s since $z \sim 1.5$. In the case that major mergers have not driven the assembly of the massive E-S0s as proposed by the EM10 model, the previous three tests must fail. On the contrary, if these three distributions agree pretty well, these tests will support strongly the existence of an evolutionary link between major mergers and the appearance of massive E-S0s, as expected by hierarchical scenarios of galaxy formation. The results of these tests are presented in Section 7.3.

We must remark that the EM10 model exclusively quantifies the effects of major mergers on galaxy evolution at $z < 1.2$. Hence, it does not discard the contribution of different evolutionary processes to the definitive assembly of massive E-S0s, although it predicts that it must have been low, as most of their number density evolution can be explained just accounting for the effects of the major mergers. This seems to be confirmed by observations, as other evolutionary mechanisms (such as minor mergers, ram pressure stripping or bars) seem to have been significant for the formation of the Red Sequence only for low and intermediate masses, but not for high masses (Kormendy & Kennicutt 2004; Desai et al. 2007; Dominguez-Palmero & Balcells 2008; Bundy et al. 2009; Simard et al. 2009; Cameron et al. 2010; Kaviraj et al. 2011). Moreover, the model does not exclude disc rebuilding after the major merger either. On the contrary, it is probably required for giving rise to an S0 instead of an elliptical, as indicated by observations (Hammer et al. 2005, 2009a; b; Yang et al. 2009).

Moreover, the EM10 model assumes that intermediate-to-late stages of major mergers are red and will produce an E-S0, on the basis of many observational and computational studies (see references in EM10 and Cimatti et al. 2002; Schawinski et al. 2007, 2010; Chilingarian et al. 2010). These assumptions are crucial for the model, as they are necessary to reproduce the redshift evolution of the luminosity functions selected by colour and morphological type. Therefore, testing if our data is coherent with the existence of an evolutionary link between the advanced stages of major mergers in our red sample and the definitive buildup of massive E-S0s, we are also indirectly testing these assumptions of the EM10 model.

6.3 Observational considerations for the tests

According to Bell et al. (2006), the average number density of major mergers at a given redshift centred at $z$, $n_{m}(z)$, is related to the number density of the major mergers detected at certain intermediate phase of the encounter in that redshift bin, $n_{m}\text{phase}(z)$, as follows:

$$n_{m}(z) = \langle n_{m}\text{phase}(z) \rangle t(z_1, z_2) / \tau_{\text{det}},$$

with $t(z_1, z_2)$ being the time elapsed in the redshift bin and $\tau_{\text{det}}$ representing the detectability time of the intermediate merger stage under consideration. We have used this equation in our tests.

We find that the number densities of IDs and ISs remain quite constant with redshift (see Section 7). As IDs and ISs correspond to intermediate merger stages, this means that the major merger rate must evolve smoothly with redshift, in good agreement with observational estimates of merger rates (Lin et al. 2008; Brammer et al. 2011; Lotz et al. 2011). This also indicates that the net flux of irregular galaxies appearing on the Red Sequence or at nearby locations on the Green Valley (i.e. the number of red irregulars created and destroyed per unit time in the red sample) must have been nearly constant at $0.3 < z < 1.5$ for our mass range. Together with the evolutionary track stated in equation (3), this implies that the accumulated number of IDs observed in a redshift bin must be equal to the accumulated number of ISs in the same bin, and also to the number of RSs assembled at the end of the redshift bin. As we also find that the number of RSs is negligible at $z = 1.5$ (see Section 7); it is also justified to start accumulating IDs and ISs since this redshift down to $z \sim 0.3$.

In order to estimate $n_{m}(z)$, we have adopted the merger timescales derived by Lotz et al. (2010a). These authors report typical detectability time-scales through CAS indices (Conselice 2003) of simulated major mergers, as a function of the baryonic gas fraction and the mass ratio of the encounter. For gas fractions representative of gas-rich mergers up to $z \sim 1$ ($\sim 30$–50 per cent; see Hammer et al. 2009a) and mass ratios typical of major mergers (1:1 to 1:4), they find an average detectability time-scale $\tau_{\text{det}, \text{gas-rich}} \sim 1.0 \pm 0.3$ Gyr of merging-nuclei phases. For gas fractions representative of gas-poor major mergers ($\lesssim 30$ per cent), we estimated from these authors and from van Dokkum (2005) an average time-scale of $\tau_{\text{det}, \text{gas-poor}} \sim 0.5 \pm 0.2$ Gyr of their merging-nuclei phase. The timescales for post-merger stages are similar to those of merging-nuclei phases for both gas-rich and gas-poor mergers (Schweizer & Seitzer 2007; Lotz et al. 2010a). The errors in these time-scales account for small changes of these representative values with redshift, according to Lin et al. (2010).

7 RESULTS

In Table 4, we show the number densities of red galaxies with $M_* > 5 \times 10^{10} M_{\odot}$ per redshift bins at $0.3 < z < 1.5$ obtained from our data, according to the classification resulting from the morphological/distortion level of the galaxy (Section 4.1) and from its star formation level (Section 4.3). Therefore, the galaxies are classified as regulars or irregulars (according to their structural distortion level), as spheroid-/disc-dominated (according to their global morphology), and as HSF/LSF (according to their star formation enhancement). Errors in the results listed in this table and in all the figures of this section account for the statistical and classification errors, the redshift errors and the cosmic variance uncertainties, as described in Section 5.
Table 4. Comoving number densities of the different red galaxy types in units of $\times 10^{-4}$ Mpc$^{-3}$.

| Redshift | Number$^a$ | N(RS)$^b$ | N(RD) | N(IS) | N(ID) | N(Total) |
|----------|------------|-----------|--------|-------|-------|----------|
| (1)      | (2)        | (3)       | (4)    | (5)   | (6)   | (7)      |
| 0.3 < z < 0.5 | 18 | 5.2$^{+2.1}_{-1.8}$ | 1.2$^{+1.0}_{-0.6}$ | 0.6$^{+0.9}_{-0.9}$ | 2.3$^{+1.3}_{-0.9}$ | 0.0 | 0.8$^{+1.5}_{-1.5}$ | 0.0 | 1.9$^{+1.2}_{-0.8}$ | 11.0$^{+3.4}_{-2.7}$ |
| 0.5 < z < 0.7 | 48 | 10.2$^{+2.9}_{-2.8}$ | 1.7$^{+0.8}_{-0.6}$ | 1.7$^{+0.8}_{-0.5}$ | 0.8$^{+0.7}_{-0.5}$ | 0.2$^{+0.8}_{-0.8}$ | 1.0$^{+0.6}_{-0.4}$ | 0.1$^{+0.1}_{-0.4}$ | 16.6$^{+3.4}_{-4.2}$ |
| 0.7 < z < 0.9 | 61 | 6.3$^{+1.8}_{-1.7}$ | 1.6$^{+0.9}_{-0.8}$ | 1.6$^{+0.5}_{-0.3}$ | 0.9$^{+0.6}_{-0.4}$ | 1.6$^{+1.1}_{-0.9}$ | 0.3$^{+0.3}_{-0.3}$ | 2.8$^{+0.9}_{-0.8}$ | 15.0$^{+2.7}_{-2.9}$ |
| 0.9 < z < 1.1 | 54 | 3.4$^{+1.0}_{-0.9}$ | 0.3$^{+0.3}_{-0.2}$ | 0.3$^{+0.3}_{-0.2}$ | 2.2$^{+0.8}_{-0.7}$ | 0.9$^{+0.5}_{-0.4}$ | 0.9$^{+0.4}_{-0.3}$ | 2.5$^{+0.8}_{-0.7}$ | 10.6$^{+3.0}_{-1.8}$ |
| 1.1 < z < 1.3 | 31 | 1.0$^{+0.4}_{-0.3}$ | 0.2$^{+0.2}_{-0.2}$ | 0.2$^{+0.3}_{-0.2}$ | 0.2$^{+0.3}_{-0.2}$ | 0.8$^{+0.4}_{-0.3}$ | 1.1$^{+0.5}_{-0.4}$ | 5.3$^{+1.2}_{-1.0}$ |
| 1.3 < z < 1.5 | 24 | 0.3$^{+0.2}_{-0.1}$ | 0.0 | 0.0 | 1.0$^{+0.5}_{-0.5}$ | 0.7$^{+0.6}_{-0.5}$ | 0.4$^{+0.3}_{-0.2}$ | 1.5$^{+0.6}_{-0.5}$ | 3.7$^{+1.1}_{-0.9}$ |

$^a$Net number of galaxies in the final sample in a sky area of ~155 arcmin$^2$.

$^b$Galaxy types according to morphology: regular spheroid-dominated (RS), regular disc-dominated (RD), irregular spheroid-dominated (IS), irregular disc-dominated (ID).

$^c$Galaxy types according to star formation activity: high star forming (HSF), low star forming (LSF).

Red Galaxies

![Figure 10](https://academic.oup.com/mnras/article-abstract/428/2/999/998802)

7.1 Morphological evolution of red galaxies since z ~ 1.5

Fig. 10 shows the redshift evolution of the fraction and the comoving number density of massive red galaxies by galaxy types considering their global morphology and structural distortion level. The fractions and number densities of red regular galaxies rise with cosmic time, with the fraction of spheroids being higher than that of discs at the same redshift. Therefore, we are tracing the progressive settlement of regular galaxies on the massive end of the Red Sequence at 0.3 < z < 1.5, made primarily of spheroids but also containing some RDs (mainly at z < 0.7). We also find significant populations of irregular galaxies at all redshifts up to z ~ 1.5, with number densities $>10^{-4}$ Mpc$^{-3}$. Although the fractions of red ISs and discs decrease with cosmic time, their densities remain quite constant at 0.3 < z < 1.5. This fact clearly points to the transitory nature of red irregular galaxies at any redshift, as indicated by previous studies (Lotz et al. 2008a).

Fig. 11 shows the redshift evolution of the number density and fractions of red regular galaxies (RS + RD) and irregulars (IS + ID) at 0.3 < z < 1.5, for the three wide-redshift bins under consideration. The fraction of regular galaxies increases by a factor of ~6 since z ~ 1.3 down to z ~ 0.5, whereas the fraction of irregulars decreases by the same amount (top panel in the figure). Moreover, the number density of regulars has risen by a factor of ~12 during this time period (bottom panel in the figure), while that of the irregulars keeps constant until z ~ 0.9, decreasing by a factor of ~3 at z ≤ 0.6 (in excellent agreement with the results by Ilbert et al. 2010).
Figure 11. Redshift evolution of the number density and fraction of all regular and irregular (i.e. major mergers) red galaxies with $M_\ast > 5 \times 10^{10} \, M_\odot$ at $0.3 < z < 1.5$, in the three wide-redshift bins under consideration ($0.3 < z < 0.7$, $0.7 < z < 1.1$ and $1.1 < z < 1.5$). Top panel: redshift evolution of the fraction of red massive regular and irregular galaxies with respect to the total red galaxy population. Bottom panel: redshift evolution of the number density of regular and irregular massive red galaxies in the same redshift bins.

At $z \sim 1.3$, irregular galaxies (i.e. major mergers) represent nearly 80 per cent of the red galaxy population. Their fraction decreases down to $\sim 50$ per cent at $z \sim 0.9$ and reaches $\lesssim 15$ per cent at $z \sim 0.5$. Considering that $\sim 70$ per cent of these irregular galaxies are dust reddened due to intense star formation (see Section 7.2), these results are in good agreement with previous estimates of the fraction of dust-reddened star-forming galaxies on the Red Sequence (Cimatti et al. 2002; Gilbank et al. 2003; Yan & Thompson 2003; Bell et al. 2004a; Moustakas et al. 2004; Weiner et al. 2005; Cirasuolo et al. 2007; Franzetti et al. 2007; Zhu et al. 2011).

We have derived the redshift evolution of the number density of regular and irregular massive red galaxies in narrower redshift bins to delimit more accurately the epoch at which the bulk of the red regular galaxies appears into the cosmic scenario (see Fig. 12). The large uncertainties of our results in these narrow-redshift bins prevent us of deriving quantitative conclusions based on this figure. However, we can conclude from it that the number density of red irregulars (i.e. major mergers) has remained nearly constant at $0.7 \lesssim z \lesssim 1.5$ within errors. This indicates that these systems must have been forming and disappearing at similar rates during this time period. Therefore, the decrease of the fraction of irregular systems with cosmic time is exclusively relative, i.e. it is just due to the rise of the population of regular galaxies, but not to a net drop in their number density down to $z \sim 0.6$. The figure also shows that the redshift evolution of the number densities of regulars and irregulars on the Red Sequence cross at $z = 0.9$ for $M_\ast > 5 \times 10^{10} \, M_\odot$.

As commented in Section 1, the rise of the number density of red regular types with cosmic time and the constancy of that of irregular ones has been interpreted as a sign pointing to the conversion of irregulars into regulars with time. We provide observational evidence supporting the existence of this evolutionary link in Section 7.3.

7.2 Star formation activity according to red galaxy types since $z \sim 1.5$

In Fig. 13, we show the redshift evolution of the number density of massive red galaxies for each morphological type defined in this study, attending to its star formation activity. We remark that HSFs are galaxies that show enhanced SFRs compared to the average SFR of the galaxy population at each redshift (Section 4.3). All types, except RSs, host a significant number of HSF galaxies, with percentages varying depending on type and redshift. Red RSs are the galaxy types hosting the lowest fractions of HSF systems at all redshifts since $z \sim 1.5$, as expected. Curiously, red RDs exhibit a noticeable increase of the HSF systems fraction at $z < 0.7$ (panel b).

Irregular types harbour enhanced SFRs typically (both spheroidal and disc systems), coherently with their merger-related nature (panels c and d in the figure). The percentage of HSF objects in these galaxies increases significantly from redshift $z \sim 1.3$ to $z \sim 0.9$.

Figure 12. Redshift evolution of the number density of red regulars and irregulars with $M_\ast > 5 \times 10^{10} \, M_\odot$ at $0.3 < z < 1.5$, using narrow-redshift bins of $\Delta z = 0.1$. The large uncertainties of our results in these narrow-redshift bins prevent us of deriving quantitative conclusions based on this figure. However, we can conclude from it that the number density of red irregulars (i.e. major mergers) has remained nearly constant at $0.7 \lesssim z \lesssim 1.5$ within errors. This indicates that these systems must have been forming and disappearing at similar rates during this time period. Therefore, the decrease of the fraction of irregular systems with cosmic time is exclusively relative, i.e. it is just due to the rise of the population of regular galaxies, but not to a net drop in their number density down to $z \sim 0.6$. The figure also shows that the redshift evolution of the number densities of regulars and irregulars on the Red Sequence cross at $z = 0.9$ for $M_\ast > 5 \times 10^{10} \, M_\odot$.

As commented in Section 1, the rise of the number density of red regular types with cosmic time and the constancy of that of irregular ones has been interpreted as a sign pointing to the conversion of irregulars into regulars with time. We provide observational evidence supporting the existence of this evolutionary link in Section 7.3.
Evolution among different red galaxy types

Figure 13. Redshift evolution of the comoving number density of red galaxies with $M_*>5 \times 10^{10} M_{\odot}$, according to their morphological, structural and star formation activity properties. Solid lines: number densities for LSF galaxies of each type. Dashed lines: number densities of HSF galaxies of each morphological type. Panel a: regular spheroids (RSs). Panel b: regular discs (RDs). Panel c: irregular spheroids (ISs). Panel d: irregular discs (IDs).

Figure 14. Observational tests to the data of red galaxies for testing the hierarchical buildup of massive E-S0s, on the basis of the expectations of the EM10 model. Panel a: test 1. Cumulative redshift distribution of red IDs (intermediate-to-late stages of gas-rich major mergers) since $z=1.5$ down to $z=0.3$, compared to the buildup of massive RSs (E-S0s) during the same time period. Panel b: test 2. Cumulative redshift distribution of red ISs (intermediate-to-late stages of gas-poor major mergers and late stages of gas-rich ones) since $z=1.5$ down to $z=0.3$, compared to the buildup of massive RSs (E-S0s) during the same time period. Panel c: test 3. Comparison of the redshift evolution of the number density of RSs (E-S0s) for two different mass ranges ($M_*>5 \times 10^{10}$ and $10^{11} M_{\odot}$) and the predictions of the EM10 model for E-S0s that end up with $M_*>10^{11} M_{\odot}$ at $z=0$. Vertical solid line: epoch at which the E-S0s with $M_*>10^{11} M_{\odot}$ derived by Madgwick et al. (2003) from 2dF Galaxy Redshift Survey. The filled areas around the cumulative data points in panels a and b correspond to the uncertainties in the merger detectability time-scales, while in panel c indicate the model uncertainties. The lowest redshift bin probably suffers from incompleteness.

types has not changed at $0.3<z<1.5$ within errors, the fraction of HSF objects in IDs being much higher than in ISs at all redshifts ($\sim80$ for IDs and $\sim50$ per cent for ISs). This is normal if we consider that the former ones correspond to intermediate stages of gas-rich mergers, while the later ones group gas-poor major mergers and post-merger phases of the gas-rich ones.

Fig. 13 implies that, at $0.7<z<1.5$, the enhanced star formation in red galaxies is mostly hosted by major mergers; mostly by gas-rich merger remnants at intermediate phases (IDs, which represents $\sim30$ per cent of all red galaxies at these redshifts, see Fig. 10) and by $\sim50$ per cent of spheroidal remnants (ISs, which represent $\sim30$ per cent). At $z<0.7$, enhanced SFRs can be found still in most red major mergers (which represent $\sim25$ per cent of the whole red population, see Fig. 10) and in nearly all red RDs ($\sim15$ per cent of it). RSs are the types that host the lowest levels of SFR enhancement at all redshifts, hosting $\sim20$ per cent at most at $z<0.7$ (despite being $\sim60$ per cent of the whole red population at $z<0.7$).

Considering that our detectability time-scale for gas-rich mergers is $\tau \sim 1$ Gyr (Section 6.3), the merger rate derived from our data for IDs at $0.3<z<0.7$ is $\sim2.5 \times 10^{-4}$ Gyr$^{-1}$ Mpc$^{-3}$ (considering their number density from Fig. 13), which is an estimate that is in good agreement with the one reported by Chou, Bridge & Abraham (2011) for gas-rich mergers using a different methodology (see their fig. 6). This strongly supports the identification of our IDs with intermediate stages of gas-rich major mergers.

7.3 Tests to the definitive buildup of massive E-S0s through major mergers

This section presents the results of the three observational tests commented in Section 7.3 to test the hierarchical formation scenario of massive E-S0s.

7.3.1 Test 1: cumulative redshift distributions of red IDs since $z=1.5$

The first panel of Fig. 14 shows the result of the first test proposed in Section 6.2. We plot the cumulative number density distributions of red IDs (intermediate stages of gas-rich major mergers, see Table 3) since $z=1.5$ down to redshift $z$ as obtained from equation (4), and compare it with the redshift evolution of the number
density of red RSs (E-S0s, see the same table). The detectability time-scale considered for the IDs is that commented in Section 6.3. The filled area around the cumulative data points accounts for the uncertainties in this time-scale. The number densities at the lowest redshift bin are probably affected by volume and selection effects as suggested by this figure and as indicated in Section 3.3, so we will override this redshift bin in all our results and comments henceforth.

The cumulative distribution of IDs reproduces pretty well both the redshift evolution of all RSs (E-S0s) and that of exclusively the LSF RSs (quiescent E-S0s) at 0.6 < z < 1.5 within errors (most E-S0s at these redshifts are LSFs, see Fig. 13). This is compatible with the fact that a majority of red gas-rich major mergers at intermediate stages of their evolution at these redshifts evolve into the E-S0s that start to populate the Red Sequence at later cosmic times. Therefore, panel a in Fig. 14 supports the existence of the following evolutionary link among these two massive red galaxy types at 0.6 < z < 1.5:

\[ \text{ID} \rightarrow \text{RS}. \] (5)

Panel a of Fig. 14 provides observational support to many aspects concerning the build-up of massive red galaxies expected by hierarchical models of galaxy formation.

(i) At 0.6 < z < 1.5 all IDs populating the massive end of the Red Sequence and nearby locations have evolved into the RSs that appear on it some time later.

(ii) This implies that the bulk of red massive E-S0s at z ~ 0.6 derive from disc galaxies that have migrated from the Blue Cloud to the Red Sequence during the time period enclosed at 0.6 < z < 1.2.

(iii) It also supports that the dominant mechanism after this evolution has been major merging, as data are compatible with the fact that most-massive E-S0s that have appeared on the Red Sequence since z ~ 1.2 seem to have undergone a previous phase of gas-rich major merger (i.e. a previous evolutionary stage as a red ID).

We remark that the major mergers detected at their phases as IDs by z ~ 1.2 in this study must have started ~0.5–0.7 Gyr before, i.e. they were at their approaching (pre-merger) phases by z ~ 1.5. Therefore, the first generation of E-S0s that should result from these mergers according to the hierarchical scenario has appeared after z ~ 1.2. Accounting for this and for the fact that the EM10 model traces the evolution of massive E-S0s back in time up to z = 1.2, a comparison between our data and this model is feasible only up to this redshift.

In conclusion, panel a of Fig. 14 indicates that the data fulfill the first observational constraint imposed by the EM10 model (Section 6.2), supporting the evolutionary track indicated in equation (1) (see also equations 2 and 3).

7.3.2 Test 2: cumulative redshift distributions of red irregular spheroids since z ~ 1.5

Panel b of Fig. 14 now compares the accumulated redshift distribution of all ISs (gas-poor mergers plus post-merger stages of gas-rich ones, see Table 3) with the redshift evolution of the number density of massive E-S0s (RSs) since z ~ 1.5. The detectability time-scales considered for the ISs are those commented in Section 6.3. The filled area around the cumulative data points accounts for the uncertainties in this time-scale. Again, the accumulated distribution of ISs reproduces quite nearly the buildup of massive E-S0s at 0.6 < z < 1.5 within errors. Therefore, this figure supports the existence of an additional evolutionary link at 0.6 < z < 1.5 among the following red galaxy types:

\[ \text{IS} \rightarrow \text{RS}. \] (6)

This panel of Fig. 14 also shows that data are compatible with the fact that most massive red E-S0s at z ~ 0.6 have also experienced a previous transitory phase as a red IS at 0.6 < z < 1.5. The evolutionary links shown in equations (5) and (6) can be summarized into the following evolutionary track:

\[ \text{ID} \rightarrow \text{IS} \rightarrow \text{RS}. \] (7)

which is the evolutionary path between red galaxy types expected by the hierarchical scenario of the EM10 model for the build-up of massive E-S0s (see equation 3). Therefore, panel b of Fig. 14 shows that the data also fulfill the second constraint imposed by the hierarchical evolutionary scenario proposed in the EM10 model (Section 6.2), supporting the evolutionary track indicated in equation (1).

7.3.3 Test 3: epoch of definitive assembly of massive E-S0s

In the last panel of Fig. 14, we compare the redshift evolution of the number density of E-S0s predicted by the EM10 model with the one obtained from our data for two different mass selections: for our nominal one (\( M_e > 5 \times 10^{11} M_\odot \)) and for an alternative one which is identical to our nominal one in all aspects, except in the mass range (\( M_e > 10^{11} M_\odot \)).

The EM10 model tracks back in time the evolution of the E-S0s that have \( M_e > 10^{11} M_\odot \) at z = 0 (Section 6.2). According to the model, these galaxies have been mostly assembled through major mergers at 0.7 < z < 1.2, their build-up being frozen since then. Therefore, the model starts to trace the progenitors of these E-S0s at z > 0.7, which have masses lower by a factor of ~2 compared to the E-S0s resulting from the merger. Consequently, the model predictions on the number density of E-S0s at z > 0.9 can be compared with our results for \( M_e \gtrsim 5 \times 10^{10} M_\odot \) (as both studies trace similar mass ranges globally). But at lower redshifts, the EM10 model traces E-S0s that already have \( M_e > 10^{11} M_\odot \), so it is comparable to the results with a mass selection \( M_e > 10^{11} M_\odot \).

As Fig. 14(c) shows, at z > 0.7, the model reproduces much better settlement of the RSs with \( M_e \gtrsim 5 \times 10^{10} M_\odot \), whereas at z < 0.7 it clearly follows the trend of RSs with \( M_e > 10^{11} M_\odot \), as expected from the arguments given above. However, our data seem to have completeness problems at z < 0.5, so we cannot assure that the number density of E-S0s with \( M_e > 10^{11} M_\odot \) has remained constant since z ~ 0.7.

Nevertheless, the number density of E-S0s with \( M_e > 10^{11} M_\odot \) at z ~ 0.6 estimated with our data is quite similar to the one estimated for these galaxies at z = 0 (Madau et al. 2003), as shown in panel c of Fig. 14. This means that the number density of these objects has remained nearly constant since z ~ 0.6, in good agreement with the predictions of the EM10 model.

Although better data at z < 0.6 are required to directly confirm this result, our data are coherent with the fact that E-S0s with \( M_e > 10^{11} M_\odot \) have been definitively assembled since z ~ 0.6, supporting that the bulk of the assembly of red massive E-S0s has occurred during the ~2.2 Gyr period elapsed at 0.7 < z < 1.2, as predicted by the EM10 model. Therefore, we can conclude that our data fulfill the third constraint imposed by the hierarchical evolutionary scenario proposed in the EM10 model (Section 6.2), supporting again the evolutionary track indicated in equation (1).

Summarizing, the three observational tests to the hierarchical evolutionary framework proposed by the EM10 model strongly
supports this scenario, pointing to major mergers as the main mechanism for the buildup of massive E-S0s.

8 DISCUSSION

In general, our results strongly support a late definitive formation redshift for massive E-S0 \((z \lesssim 1.5)\), in agreement with hierarchical scenarios of galaxy formation (see references in Section 1). Ilbert et al. (2010) already claimed for the freezing in the assembly of massive E-S0s at \(z \lesssim 0.7\), proposing that a sudden drop of the gas-rich major merger rate must take place at \(z \lesssim 0.8\) to explain it. This fact was proven to be observationally feasible by the EM10 model, just accounting for the major merger fractions reported by observations (Eliche-Moral et al. 2010b). This study supports it observationally.

Apart from the major mergers that seem to have been the main responsible mechanisms to place the massive E-S0s on the Red Sequence at \(0.6 < z < 1.5\), other evolutionary processes must have contributed to the evolution of massive E-S0s down to the present (and even coeval with them). But, as commented above, they must not have risen their masses noticeably or changed their morphology noticeably, as E-S0s with \(\log (M_*/\text{M}_\odot) > 11\) seem to have been in place since \(z \sim 0.6\) (see Section 7.3). This is supported by the fact that many of these processes are observed to be relevant only for the evolution of galaxies with lower masses (in particular, the fading of stellar populations; see Driver et al. 1998; Bekki, Couch & Shioya 2002; Aragón-Salamanca, Bedregal & Merrifield 2006).

We must also remark that our red galaxy sample does not trace the evolution of S0s observed in the clusters, which seems to have been relevant since \(z \sim 0.4–0.5\) due to the environmental star-formation quenching of the spirals that fall into the clusters (Desai et al. 2007; Poggianti et al. 2009b; Simard et al. 2009; Vulcani et al. 2011). Cluster S0s have typical masses lower than those selected here \((M_* \lesssim 5 \times 10^{10}\text{M}_\odot)\); see Dressler et al. 1999; Bedregal, Aragón-Salamanca & Merrifield 2006), and hence, our results do not apply to them in general. Moreover, some studies indicate that the fraction of S0s in groups is similar to that of clusters at \(z \sim 0.5\) (Wilman et al. 2009). Considering that most galaxies reside in groups (\(\sim 70\%\) per cent; see Berlind et al. 2006; Crook et al. 2007), this means that the majority of S0s in the Universe are located in groups (not in clusters). Nevertheless, note that this evolution in clusters does not contradict the EM10 model at all, because this model exclusively analyses the effects of the major mergers on galaxy evolution since \(z \sim 1.2\), independently of the relevance of other evolutionary processes.

To summarize, our study supports that major mergers have been the main drivers of the evolution of the massive end of the Red Sequence since \(z \sim 1.5\), although other processes can also have contributed to it significantly at intermediate-to-low masses (especially, since \(z \sim 0.6\)). Our tests support observationally a late definitive buildup of the massive E-S0s through major mergers (mostly at \(0.6 < z < 1.2\)), in agreement with the expectations of hierarchical models of galaxy formation.

9 CONCLUSIONS

We study the buildup of the Red Sequence by analysing the structure, morphology and star formation properties of a sample of red galaxies with stellar masses \(M_* \gtrsim 5 \times 10^{10}\text{M}_\odot\) at \(0.3 < z < 1.5\). The novelty of this study is two-fold: first, our red galaxy sample includes galaxies both on the Red Sequence and at nearby locations on the Green Valley to trace transitory evolutionary stages towards it, and secondly, we have simultaneously considered structural (regular/irregular), morphological (discs/spheroids) and star formation enhancement (HSE/LSF) to define galaxy classes that can be directly associated with intermediate-to-late stages of major mergers, as well as with normal E-S0s and red RDs. The redshift evolution of the fractions and number densities of each red galaxy type have been derived. Finally, these data are used to carry out a set of novel observational tests defined on the basis of the expectations of hierarchical models, to test the hierarchical origin of massive E-S0s.

Both the number densities and fractions of regular galaxies increase with cosmic time at \(0.3 < z < 1.5\), tracing the progressive buildup of massive normal early-type galaxies during the last \(\sim 9\) Gyr (mostly E-S0s, but also some red discs). The fractions of red RSs (E-S0s) plus red discs increase by a factor of \(\sim 6\) since \(z \sim 1.3\) down to \(z \sim 0.5\), whereas the fraction of irregulars (major mergers) decreases by the same factor. However, the number density of red irregulars (major mergers) is constant down to \(z \sim 0.7\), decreasing at lower redshifts. This means that the fraction of red irregulars decreases only relatively to that of regulars, pointing to their transitory nature, as already claimed in previous studies. We find that the number density distributions of RSs (E-S0s) and irregulars (major mergers) cross at \(z \sim 0.9\) for \(M_* \gtrsim 5 \times 10^{10}\text{M}_\odot\).

Enhanced SFRs compared to the average SFR of the global galaxy population at each redshift at \(0.3 < z < 1.5\) are hosted by most IDs in our red sample and by nearly half of the ISs (in agreement with the major merger-related nature of both types). At \(z \gtrsim 0.7\), enhanced star formation can also be found in nearly all red RDs. On the other hand, only \(\sim 25\%\) per cent of red RSs (E-S0s) harbour enhanced star formation at all redshifts.

The main result of this study is that we provide observational evidence pointing to the existence of a main evolutionary path among red galaxy types at \(0.6 < z < 1.5\), being:

\[ \text{ID} \rightarrow \text{IS} \rightarrow \text{RS}. \]

This track traces the conversion of blue discs into passive E-S0s through major mergers and dominates the buildup of the Red Sequence at \(z \gtrsim 0.6\), in excellent agreement with the expectations of the EM10 model. Our data are coherent with the prediction of this model about that the bulk of massive E-S0s with \(M_* \gtrsim 10^{11}\text{M}_\odot\) have been definitively assembled through major mergers during the \(\sim 2.2\) Gyr period elapsed \(0.6 < z < 1.2\), as also proposed by Ilbert et al. (2010).

Our results support observationally several expectations of hierarchical theories of galaxy formation concerning the buildup of massive red galaxies.

(i) Data are compatible with the fact that the massive red regular galaxies at low redshifts derive from the irregular ones populating the Red Sequence and its neighbourhood at earlier epochs up to \(z \sim 1.5\).

(ii) The progenitors of the bulk of present-day massive red regular galaxies seem to have been discs that have migrated to the Red Sequence mostly through major mergers at \(0.6 < z < 1.2\) (these mergers thus starting at \(z \lesssim 1.5\)).

(iii) The formation of E-S0s that end up with \(M_* \gtrsim 10^{11}\text{M}_\odot\) at \(z = 0\) through gas-rich major mergers seems to have frozen since \(z \sim 0.6\).

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