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THE ASSEMBLY OF EARLY-TYPE GALAXIES: COMBINING CLUSTERING AND LUMINOSITY FUNCTION MEASUREMENTS

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RESUMEN

Presentamos un estudio de la evolución de galaxias de tipo temprano (ETGs por sus siglas en inglés) que combina mediciones de acumulamiento y funciones de luminosidad. El acumulamiento nos permite inferir la masa de materia oscura de los halos anfitriones de las galaxias. Usamos predicciones del modelo ΛCDM para seguir estos halos hacia tiempos posteriores. Esta técnica demuestra que las ETGs de un dado corrimiento al rojo, evolucionan hacia galaxias más brillantes en un marco de referencia en reposo, evolucionadas pasivamente a este corrimiento al rojo menor. Nótese que esto indica que una selección por masa estelar a distintos corrimientos al rojo, no provee necesariamente muestras en una relación progenitor/descendiente. La comparación entre las ETGs de alto corrimiento al rojo y sus probables descendientes en $z = 0$ apunta a una mayor densidad de número de progenitores en un factor 3 a 11, lo que implica que se necesitan fusiones de galaxias para disminuír su densidad numérica hasta el presente. Dado que el producto de los cocientes de densidad de luminosidad entre progenitores y descendientes son cercanos al valor unitario, nuestros resultados muestran que no se necesitan eventos de alta formación estelar en ETGs desde $z = 1$, lo que indica que las fusiones son "secas", o sea, sin gas.

ABSTRACT

We present a study of the evolution of early-type galaxies (ETGs) that combines luminosity funciton and clustering measurements. The latter allows us to infer the typical dark-matter halo mass of the hosts of the galaxies. Using ΛCDM predictions, it is then possible to follow these haloes to a later time. This technique shows that ETGs at a given redshift evolve into brighter galaxies in the rest-frame passively evolved optical at lower redshifts. Notice that this indicates that a stellar-mass selection at different redshifts does not necessarily provide samples of galaxies in a progenitor-descendant relationship. The comparison between high redshift ETGs and their likely descendants at $z = 0$ points to a higher number density for the progenitors by a factor $3 - 11$, implying the need for mergers to decrease their number density by today. Because the progenitor-to-descendant ratios of luminosity density are consistent with the unit value, our results show no need for strong star-formation episodes in ETGs since $z = 1$, which indicates that the needed mergers are dry, i.e. gas free.

Key Words: galaxies: evolution — galaxies: formation — galaxies: statistics — cosmology: observations

1. INTRODUCTION

The study of the population of early type galaxies (ETGs) at different redshifts has been used extensively to test our knowledge of the galaxy formation process, in particular, the assembly of the stellar content of massive galaxies. Analyses of the evolution of the stellar mass and luminosity functions have found that high stellar mass ($M > 10^{11}$ h^{-1} $M_{\odot}$), passive galaxies do not show evolution in their comoving space density since $z \sim 1$ (Cimatti et al. 2002, 2004; McCarthy et al. 2004; Glazebrook et al. 2004; Daddi et al. 2005; Saracco et al. 2005; Bundy et al. 2006; Pérez-González et al. 2008; Marchesini et al. 2009). This result has been interpreted as evidence that the stellar content of such galaxies is already in place at high redshifts, ruling out the involvement of mergers (even dry, i.e., gas-free) since $z \sim 1$.

Recent statistical measurements of $z \sim 1$ to 3 galaxies, such as the stellar mass function (Perez-Gonzalez et al. 2008; Marchesini et al. 2009; but see Benson & Devereux 2010), the galaxy luminosity function (Marchesini & van Dokkum 2007), and SCUBA (Holland et al. 1999) number counts of $z \simeq 3$ galaxies detected in sub-millimetre bands, show little evolution in this galaxy population since these even higher redshifts. However, these results may still be subject to observational biases. For instance, Marchesini et al. (2010) showed that allowing for the existence of a previously unrecognized

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population of massive, old, and very dusty galaxies at $z \sim 2.6$ would result in an evolution of the number density of ETGs since $z = 3$ and would also provide good agreement between the observed abundance of massive galaxies at $z = 3.5$ and that predicted by semi-analytic models (e.g. Lagos, Cora, & Padilla 2008; Baugh et al. 2005).

The way in which the selection of a given population and its descentants proceeds, is usually via a fixed stellar mass selection (e.g. Robaina et al. 2010). Only in the case of ETGs, this can also be done using passively evolved luminosities, since these should scale linearly (and independent of the redshift) with the stellar mass in systems of old stars with no recent star formation activity (e.g. Cimatti et al. 2006). However, events such as mergers would produce a change in the stellar masses or passively evolved luminosities of the galaxies, which opens the possibility that this selection may not be appropriate for this purpose.

The approach we present here is intended to improve the selection of statistical descendants of a sample of high redshift ETGs. In order to do this we will use clustering information of the progenitor galaxies (the sample at high redshift from Padilla et al. 2010, hereafter P10), that will give us the mass of the host dark-matter halo masses which in a numerical simulation can be followed down to any given redshift. Then we will compare the number densities of the samples of progenitor and descendant galaxies (the lower redshift galaxies selected to have the clustering of the host haloes at this later cosmic time) obtained from luminosity function measurements (from Christlein et al. 2009, hereafter C09). We will interpret differences in these number densities in terms of mergers and their characteristics.

This article presents the measured correlation and luminosity functions used in our method in § 2, and shows the results and presents our conclusions in § 3.

2. LUMINOSITY FUNCTIONS AND CLUSTERING INFORMATION

We will analyse the evolution of MUSYC (MUltiwavelength Survey by Yale-Chile) ETGs using their measured LFs by C09. MUSYC comprises over 1.2 square degrees of sky imaged to 5σ AB depths of $U, B, V, R = 26$, $I = 25$, $z = 24$ and $J, K(AB) = 22.5$, with extensive follow-up spectroscopy. The source detection is done on the combined BVR image down to a magnitude of 27 (see Gawiser et al. 2006 for further details).

C09 proposed and applied a new technique, the photometric maximum likelihood (PML) method, to a subset of MUSYC comprising the Extended Chandra Deep Field South (ECDF-S), covering approximately 0.25 sq. degrees on the sky. The PML algorithm was used to measure the underlying luminosity function of galaxy populations characterised by different spectral types. The latter are parameterised with a set of SED templates from Coleman, Wu, & Weedman (1980, hereafter CWW) or fixed superpositions of two CWW templates, extended into the UV regime using Bruzual & Charlot (1993) models. For the present analysis, we will only use the LF corresponding to the two earliest type templates in this set, which correspond to an elliptical galaxy and to a E+20%Sbc mix. P10 demonstrate that the sample of ETGs selected this way is comparable to a selection of the red-sequence at each redshift (as adopted in e.g. Bell et al. 2004, hereafter B04; CDR; Brown et al. 2008). They also indicate that these ETGs are compatible with a sample resulting from a $K < 22.5$ selection. For the present article we will also use the PML estimate of the ETG LF obtained from the Extended Hubble Deep Field Sourh (EHDF-S), increasing the area of this analysis to an area on the sky of approximately 0.5 sq. degrees.

We use the rest-frame r- and B-band PML LF estimates from MUSYC ETGs in ECDF-S and EHDF-S. For comparison we will also use the LFs measured using the classic maximum likelihood estimate that uses photo-z measurements; these estimates are also provided by C09. All the ETG LFs are passively evolved down to $z = 0$ by applying an empirical passive evolution recipe whereby the evolved luminosity can be found via

$$M_B(z = 0) = M_B(z) + 1.15z\,, \qquad (1)$$

as proposed by CDR, following results from van Dokkum & Stanford (2003), Treu et al. (2005), and diSerego Alighieri et al. (2005). P10 showed that this passive evolution recipe is well followed by a [Fe/H]=0.3 single stellar population (SSP) which at $z = 1$ is 3.5 Gyr old, and used this SSP to work out the equivalent recipe for the r-band, which is fit by

$$M_r(z = 0) = M_r(z) + 0.98z\,. \qquad (2)$$

We apply these evolution corrections to B- and r-band LF measurements from relatively high redshift samples and compare them to results at $z \simeq 0.165$ from the Sloan Digital Sky Survey (SDSS; York et al. 2000) for ETGs by B04 in the B-band (selected using the red-sequence), and in the r-band by Benson et al. (2007, hereafter Be07), who selected ETGs as sources with a dominant bulge component (an alter-

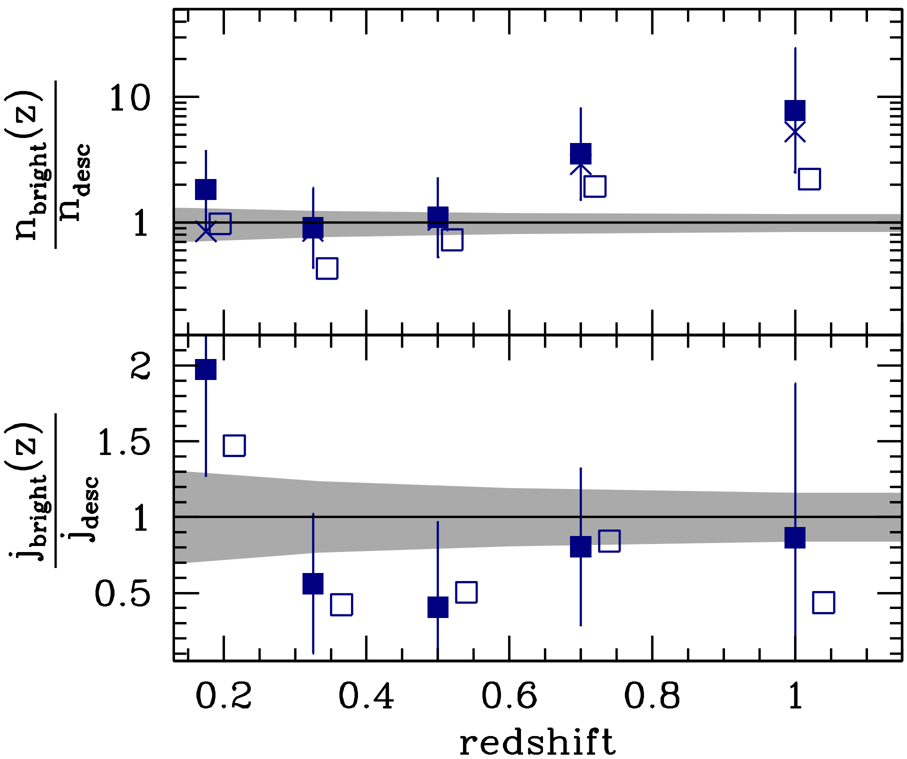

Fig. 1. Top panel: Ratio between the number density of ETGs at a given redshift and their expected $z = 0$ descendants, as inferred from the clustering analysis of P10. The filled squares show the results from using the PML r-band LF estimates; open squares show the results for the B-band. Errorbars are only shown for the r-band result to improve clarity. The crosses correspond to the results from the photo-z based maximum likelihood method to calculate the LF in the r-band. The solid line shows the unit ratio and the grey shaded area shows the estimated cosmic variance in a 0.25 sq. degree light-cone survey divided in slices of $\Delta z = 0.1$. Bottom panel: ratio between the luminosity density of progenitor ETGs and that of their $z = 0$ ETG descendants in the r- and B-bands (filled and open squares, respectively).

native ETG LF measurement from SDSS is provided by Ball et al. 2006).

These luminosity function measurements will allow us to measure the space density of galaxies selected according to limits in luminosity, at different redshifts. The limiting luminosities will be selected using clustering information.

We use the clustering results from P10, in particular those for the MUSYC sample of galaxies corresponding to the brightest absolute magnitude cut, $M_R(0) < -19.7$ corrected by passive evolution, for samples of ETGs in ECDF-S and EHDF-S. As was shown by these authors, ETGs show a higher clustering than the samples that included all galaxy types. When comparing to the clustering of $z = 0$ ETG SDSS galaxies of different luminosities and using the evolution of clustering of dark-matter haloes of different masses, P10 show that ETG samples of equal passively evolved luminosity (i.e. stellar mass selected) at different redshifts do not seem to be connected in a progenitor-to-descendant relationship. Luminous galaxies at $z \simeq 1.15$ evolve into objects with higher clustering than galaxies of similar rest-frame passively evolved luminosity at $z \simeq 0.35$. The present-day descendants of the bright volume-limited ECDF-S and EHDF-S $z = 1.15$ subsamples are roughly within $0.1 < L/L^* < 2.5$.

3. RESULTS AND CONCLUSIONS

We calculate the number density of $z = 0$ descendants using the B04 and Be07 SDSS ETG LFs for galaxies with median luminosities corresponding to the descendants of a given sample of MUSYC ETGs at redshift z. The number density of progenitors is calculated at redshift z, using a lower limit in $M_r(z = 0) = -19.7$, or equivalently, $M_B(z = 0) = -18.55$, consistent with the lower limits used in P10. The results are shown as squares in the top panel of Figure 1 (open symbols for the B-band, filled symbols for the r-band). The errorbars in this panel correspond to the uncertainties in the descendant luminosity, extracted from P10. As can be seen, the ratio is significantly higher than unity at $z > 0.6$ in both bands, indicating the need for mergers between ETGs in order to diminish their number density towards $z = 0$. Lower redshift samples show number densities similar to their expected descendants. As can be seen, the photo-z based maximum likelihood method (crosses, shown only for the r-band for clarity) provides results in agreement with those from the PML based LFs.

Taking advantage of the measured LFs for the high-redshift ETG samples, we calculate the ratios between the luminosity densities of the high-z ETGs and that of their $z = 0$ likely descendants, using the PML and B04/Be07 LF measurements for the MUSYC and SDSS ETGs, respectively. This is shown in the bottom panel of Figure 1 as squares (solid symbols correspond to results in the r-band, the open symbols to the B-band). As can be seen, regardless of the photometric band the data shows that as the redshift decreases the ratio of luminosity densities of progenitor and descentant ETGs is consistent with the unit value (bear in mind that our different high redshift ETG samples are *not* in the same evolutionary line).

The results from this analysis show that ETGs at $z = 1$ are likely to descend into $z = 0$ ETGs undergoing a decrease in space-density of a factor between 3 and 11 (the ranges cover the results from the B and r bands). But, due to the constant luminosity density, mergers would provide the required increase in luminosity without the need for important episodes of star-formation. Notice that the amount of mergers derived here (of two or more mergers since $z = 1$ for each $z = 0$ galaxy) is higher than that estimated from close pairs of stellar mass selected samples at different redshifts; Robaina et al. (2010) find that galaxies undergo $\sim$0.7 mergers between $z = 1.2$ and 0. We suggest that a more consistent measurement of merger rates using close pairs would require the use of samples in a more likely progenitor-descendant relationship than that provided by a stellar mass selection.

Upcoming surveys such as those planned for the Large Synoptic Survey Telescope (LSST Science Collaboration 2009), will allow much better statistics by increasing the solid angle with respect to the currently available deep photometric surveys such as MUSYC and COMBO17. With a higher signal it will be possible to apply this method and measure with high accuracy the importance of mergers in the evolution of the ETG population. Furthermore, with a careful treatment of sources and sinks in the samples of progenitors and descendants, it could also be possible to produce measurements of the expected merger rates and star formation history of combined samples of early and late type galaxies, and via comparisons with models of galaxy formation, help improve our understanding of the evolution of galaxies from high redshifts to the present day.

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