Highlights of Spanish Astrophysics VIII, Proceedings of the XI Scientific Meeting of the Spanish Astronomical Society held on September 8–12, 2014, in Teruel, Spain. A. J. Cenarro, F. Figueras, C. Hernández-Monteagudo, J. Trujillo Bueno, and L. Valdivielso (eds.)

The formation epochs of red-sequence galaxies

L. A. Díaz-García[1], A. J. Cenarro[1], and C. López-Sanjuan[1]

[1] Centro de Estudios de Física del Cosmos de Aragón (CEFCA), Plaza San Juan 1, Floor 2, E–44001, Teruel, Spain

Abstract

Making use of the novel code MUFFIT (a MUlti-Filter FITting code to retrieve the stellar content of galaxies via photometric data), we study the formation epochs of a sample of $\sim 18\,000$ red-sequence galaxies from the ALHAMBRA survey up to $z \sim 1$, only employing their multi-filter data. The luminosity-weighted ages derived from MUFFIT are consistent with galaxies being formed in the downsizing scenario, obtaining that more massive galaxies were formed in earlier epochs and in a more efficient way than their low-mass counterparts. In addition, to shed light on the potential mechanisms responsible for the growth in size of massive galaxies since high redshift to the present day, we present a preliminary study on whether there exist systematic differences in the main stellar population parameters between compact and extended galaxies at fixed stellar mass in the mass-size plane, using a sample of $\sim 1\,500$ ALHAMBRA red-sequence galaxies up to $z < 1.2$ with reliable sizes from Hubble fields. At fixed stellar mass, compact red-sequence galaxies at $z > 0.8$ are slightly older (by ~ 0.5 Gyr) than their extended counterparts.

1 Introduction

Multi-filter photometric surveys (e.g. COMBO-17 [16], ALHAMBRA [9], COSMOS [11], SHARDS [15], J-PAS [2], J-PLUS [4]), sample the spectral energy distribution (SED) of galaxies with sets of contiguous filters covering certain regions of the optical and NIR. The SEDs retrieved in this way are half-way between classical photometry and spectroscopy, being in practise a low-resolution spectrum (e.g. $R \sim 20$ for ALHAMBRA; $R \sim 50$ for J-PAS). Despite the lack of high spectral resolution, it is noteworthy that photometric surveys present some advantages respect to typical spectroscopy: i) the only selection criterion is driven by the photometric survey depth, and therefore the typical number of sources is also greater; ii) they do not suffer from systematic uncertainties in the flux calibration; iii) the observational depth is typically larger than usual spectroscopic surveys conducted at similar telescopes of the same aperture; and iv) they also provide spatially resolved photo-spectra (equivalent to an IFU technique). Consequently, multi-filter surveys are opening a new path to explore the stellar content of galaxies, as long as these studies are addressed by the adequate methods, broadening the stellar population diagnostics at earlier epochs of the universe, hence complementing the 'archaeology approach" of the local galaxies.

Present-day massive galaxies have doubled their sizes during the last $\sim 8\,\mathrm{Gyr}$, and they have grown in size a factor of four as compared with their ancestors at $z \sim 2$ (see [13]). Although it is not fully confirmed yet, the minor merger scenario remains as the most likely mechanism responsible of the increasing in size of massive galaxies [14]. A detailed study of the stellar content of these galaxies since $z \sim 1$, as well as its evolution during this $\sim 8\,\mathrm{Gyr}$ up to the present, will allow to clarify some aspects of the responsible mechanisms.

Our first goal comprises the study of the formation epochs of the ALHAMBRA red-sequence (RS) galaxies up to $z \sim 1$ (Sect. 4) using direct age estimations from multi-filter photometry. In Sect. 5, we carry out a preliminary study about the stellar content of massive galaxies as function of size, as an attempt to shed light in the mechanism that produces the growth in size. We adopt a ΛCDM cosmology with $\Omega_\mathrm{m} = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 71$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

2 Data

Throughout this work, we make use of the photometric data in the ALHAMBRA Gold catalogue[1] (complete up to $m_{F814W} \leq 23$, AB-magnitudes, [10]) with more than 95 000 galaxies to develop the present work. The ALHAMBRA survey [2] [9, 10] is composed by 20 contiguous, top-hat and medium-band filters (FWHM $\sim 300\,\mathrm{Å}$) in the optical range $3500 - 9700\,\mathrm{Å}$, that are supplemented with the standard NIR filters J, H, and K_s. In addition, the photo-z constraints provided in the same catalogue are also employed to constrain the plausible photo-z ranges for each galaxy.

Since ALHAMBRA partly overlaps with some *HST* fields (AEGIS [5], COSMOS, and GOODS-N [7]), we have been able to construct a sub-sample of galaxies with accurate sizes. The catalogue of [8] provides galaxy half-light radii, r_e, measured using the ACS/*HST* camera, for the bands $F814W$ (AEGIS, COSMOS), $F775W$ (AEGIS, GOODS-N), and $F606W$ (GOODS-N). The r_e used in this work are those derived from the $F814W$ band, for the ALHAMBRA galaxies in common with AEGIS and COSMOS, and from the $F775W$ band for those in common with GOODS-N.

3 Overview of the analysis techniques

To retrieve the main stellar population parameters, we just make use of MUFFIT (MUlti-Filter FITting code; extensively detailed in [6]), which is specifically designed to retrieve the stellar population parameters of galaxies from multi-filter photometric data, dealing with the

[1] `http://cosmo.iaa.es/content/alhambra-gold-catalog`
[2] `http://www.alhambrasurvey.com/`

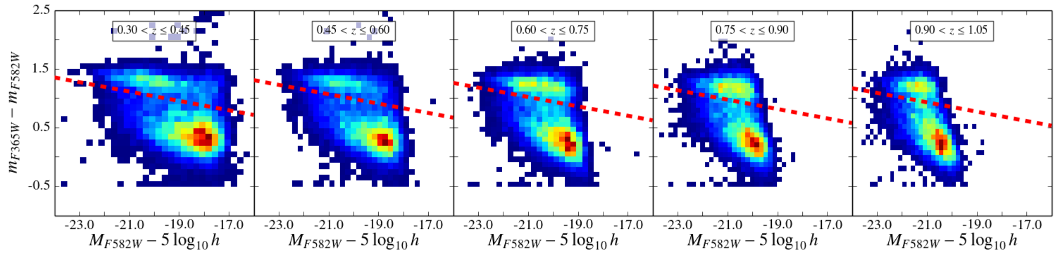

Figure 1: The CMD of the ALHAMBRA galaxies up to $m_{\rm F814W} \leq 23$, the dashed red line separates the RS and the blue cloud.

characteristic features of photometry in a reliable way. Using mixtures of two SSPs (younger and older than a certain age, specifically determined for each galaxy), MUFFIT carries out error-weighted χ^2-tests combined with Monte Carlo approaches to estimate the integrated stellar population parameters (age, metallicity, extinction, stellar mass, and redshift) of galaxies and their uncertainties. During the fitting process, MUFFIT properly identifies and subsequently removes the filters that may be affected by strong nebular emissions, improving the quality of the SED-fitting and the photo-z accuracy. MUFFIT is demonstrated to provide accurate ages, metallicities, extinctions, redshifts, k-corrections, and stellar masses, which have been successfully confronted with results from spectroscopic stellar population diagnostics, more precisely using the ALHAMBRA data. Hence, MUFFIT is the most adequate tool to carry out the study of the stellar content of the galaxies in the ALHAMBRA survey.

Throughout this paper, we use the Bruzual & Charlot SSP models [3].

4 The formation epochs of red-sequence galaxies

To select the sub-sample of ALHAMBRA RS galaxies, we run MUFFIT for the complete sample of ALHAMBRA galaxies up to $m_{\rm F814W} \leq 23$ (AB-magnitudes) and construct the colour-magnitude diagram (CMD; see Fig. 1) from the k-corrections retrieved for each galaxy. The RS is selected on the basis of the relation provided in [1] and the ALHAMBRA bands $F365W$ and $F582W$, rather than the U and V COMBO-17 bands. Formally, in the Vega system:

$$m_{F365W} - m_{F582W} = 1.15 - 0.3z - 0.08(M_{F582W} - 5\log h + 20). \quad (1)$$

We obtain $\sim$ 18 000 RS galaxies with $M_\star \geq 10^{10}\,{\rm M}_\odot$ at redshift $0 \leq z \leq 1$. After calculating the look-back time for these galaxies through the luminosity-weighted ages provided by MUFFIT, we explore the distribution of ages for different stellar mass ranges (see left panel of Fig. 2). We find that more massive galaxies ($M_\star[{\rm M}_\odot] > 11.5\,{\rm dex}$) are mainly composed by old stellar populations, which were formed in earlier epochs ($z \sim 2.5$) than the less massive ones ($M_\star[{\rm M}_\odot] < 10\,{\rm dex}$), which were formed at $z \sim 1$. In addition, the cumulative distribution functions (CDF) show than the more massive galaxies formed their stellar populations more rapidly and in a more efficient way (right panel of Fig. 2). This result is

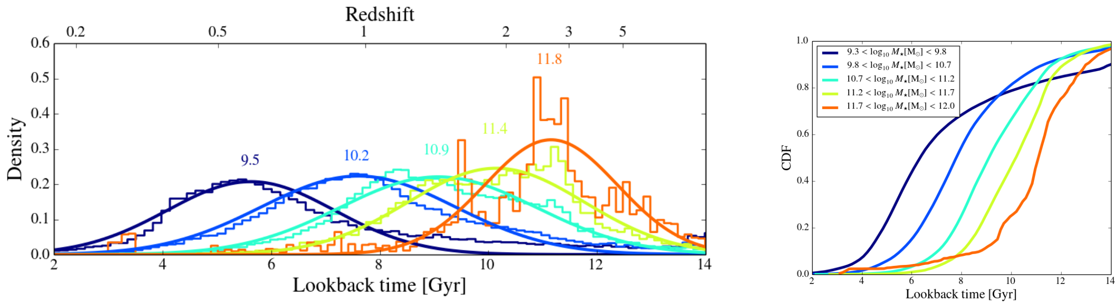

Figure 2: *Left*: the formation epochs for the RS galaxies in ALHAMBRA at different stellar mass ranges. *Right*: the CDF for the distributions of formation epochs for different stellar mass ranges.

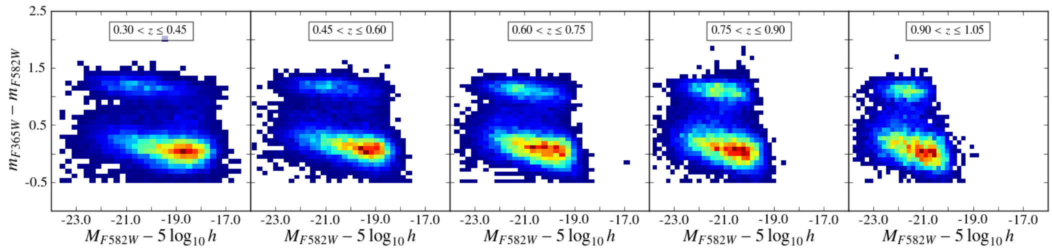

Figure 3: CMD of the full ALHAMBRA sample up to $m_{\rm F814W} \leq 23$, after correcting for dust reddening at different redshift ranges. The distinction between the red sequence and the blue cloud becomes clearer without the influence of dust (see Fig. 1 for comparisons).

fully consistent with the downsizing scenario and with previous spectroscopic studies related with formation epochs [12].

5 Stellar population of compact and extended red-sequence galaxies

For a sub-sample of ALHAMBRA galaxies with reliable sizes (in common with *HST* fields), and using the k-corrections and extinctions provided by MUFFIT, we build a sample of pure RS galaxies (PRS; i.e. free from RS galaxies reddened by a high dust content) via CMD after correcting of dust reddening (see Fig. 3). It is noteworthy that the bimodality in Fig. 3 becomes clearer than in Fig. 1, after uncovering the intrinsic colours of the populations. Our sample is finally composed by ~ 1500 PRS with $M_\star \geq 10^{10}\,{\rm M}_\odot$ at $0.2 \leq z \leq 1.2$, for which we have retrieved ages, metallicities, extinctions, stellar masses and redshifts. In Fig. 4 we present the above PRS galaxies in the stellar mass-size plane. Different ages are indicated according to the colour code given in the inner labels. We refer as compact/extended galaxies to those galaxies below/over the average stellar mass-size relation. The stellar mass-size relation (black straight-line in Fig. 4) has been computed taking into account both stellar

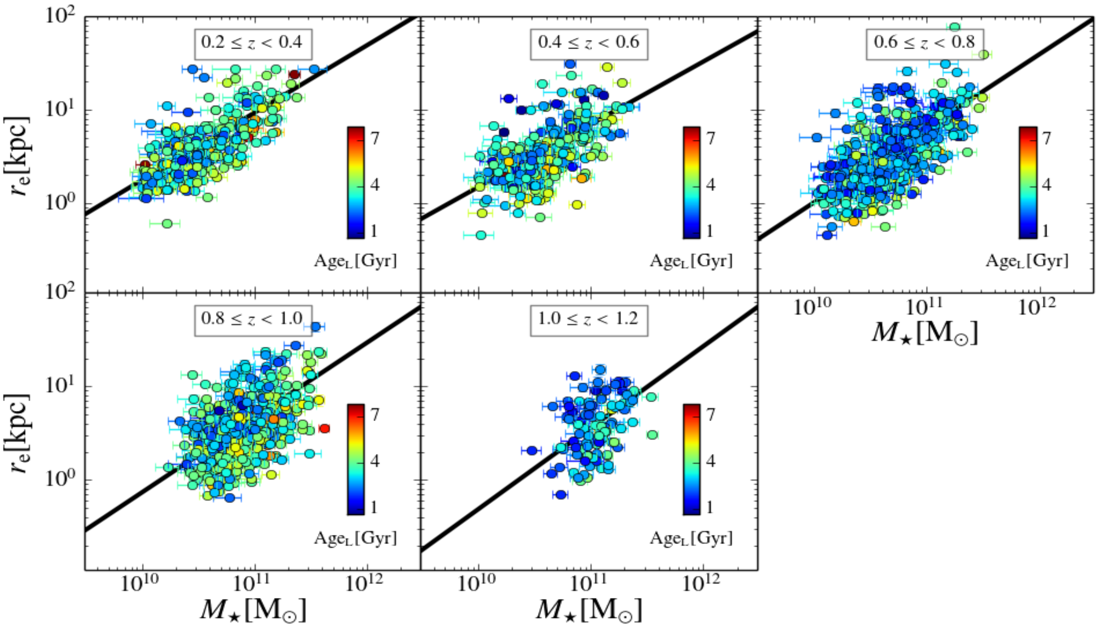

Figure 4: The stellar mass-size relation for the ALHAMBRA PRS galaxies at different redshifts. Each galaxy is colour-coded as a function of the luminosity-weighted age derived from *MUFFIT*.

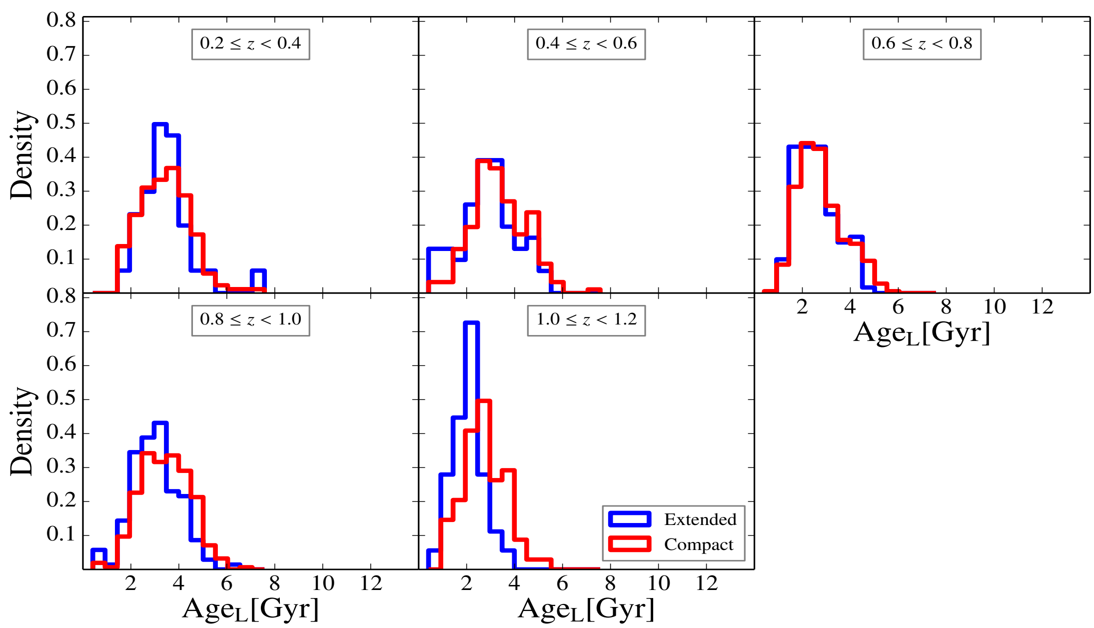

Figure 5: Distribution of ages for compact (red) and extended (blue) PRS galaxies at the same redshift bins than Fig. 4

masses and size uncertainties, an intrinsic dispersion in the proper relation, and that galaxies follow a Schechter function. The increasing in size is present, in qualitative agreement with [13], proving the reliability and accuracy of both stellar masses and photo-z.

The age differences between both samples are illustrated in Fig. 5 and studied through a Kolmogorov-Smirnov test (KS). At $z > 0.8$, we find compact PRS to be $\sim 0.5\,\mathrm{Gyr}$ older than extended PRS (99% confidence level in the KS test). If confirmed, this might be an imprint of the structure assembly process and growth in size that these galaxies suffered in the past, maybe, via merger. About metallicity and extinction, we do not find out statistically significant differences between the two samples.

Acknowledgments

LADG acknowledges support from the "Caja Rural de Teruel" to develop this research. AJC is a Ramón y Cajal Fellow of the Spanish Ministry of Science and Innovation. This work has been partly supported by the "Programa Nacional de Astronomía y Astrofísica" of the Spanish Ministry of Economy and Competitiveness under grant AYA2012–30789 and by the Aragón Government through the Research Group E103.

References

[1] Bell, E. F., Wolf, C., Meisenheimer, K., et al. 2004, ApJ, 608, 752

[2] Benítez, N., Dupke, R., Moles, M., et al. 2014, ArXiv e-prints

[3] Bruzual, G. & Charlot, S. 2003, MNRAS, 344, 1000

[4] Cenarro, A. J., Marín-Franch, A., Moles, M., et al. 2015, in prep.

[5] Davis, M., Guhathakurta, P., Konidaris, N. P., et al. 2007, 660, 1

[6] Díaz-García, L. A., Cenarro, A. J., López-Sanjuan, C., et al. 2015, A&A, in press, arXiv:1505.07555

[7] Giavalisco, M., Ferguson, H. C., Koekemoer, A. M., et al. 2004, ApJ, 600, 93

[8] Griffith, R. L., Cooper, M. C., Newman, J. A., et al. 2012, ApJS, 200, 9

[9] Moles, M., Benítez, N., Aguerri, J. A. L., et al. 2008, AJ, 136, 1325

[10] Molino, A., Bentez, N., Moles, M., et al. 2014, MNRAS, 441, 2891

[11] Scoville, N., Aussel, H., Brusa, M., et al. 2007, ApJ, 172, 1

[12] Thomas, D., Maraston, C., Bender, R., & Mendes de Oliveira, C. 2005, ApJ, 621, 673

[13] Trujillo, I., Conselice, C. J., Bundy, K., et al. 2007, MNRAS, 382, 109

[14] Trujillo, I., Ferreras, I., de La Rosa, I. G. 2011, MNRAS, 415, 3903

[15] Pérez-González, P. G., Cava, A., Barro, G., et al. 2013, ApJ, 762, 46

[16] Wolf, C., Meisenheimer, K., Rix, H.-W., et al. 2003, A&A, 401, 73