Galaxy Masses as Constraints of Formation Models
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The evolution of the ages and metallicities of massive galaxies since $z = 0.7$

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Abstract. We present results on the stellar population properties of massive galaxies at $z = 0.7$ based on deep, medium-resolution IMACS spectra for a sample of ~ 70 galaxies in the ECDFS with $M_* > 10^{10} M_\odot$. The age–mass and stellar metallicity–mass relations for the population as a whole have a similar shape as the local relations over the probed mass range, but offset to ages younger by ~ 4 Gyr and metallicities lower by $\sim$0.13 dex. Quiescent galaxies alone have stellar ages and metallicities consistent with passive evolution onto the local quiescent galaxies relations. The evolution in metallicity is driven by star-forming galaxies. However a significant fraction of massive star-forming galaxies have metallicities comparable to those of local quiescent galaxies. If quenched at $z < 0.7$ they can provide the necessary population to reproduce the scatter in age and metallicity of local quiescent galaxies.

1. Introduction

The population of massive galaxies has undergone a significant evolution since $z < 1$ as witnessed by the dramatic drop in the cosmic star formation rate (SFR) density (e.g. Cucciati *et al.* 2012) alongside a growth in the number density of quiescent galaxies (e.g. Moustakas *et al.* 2013; Muzzin *et al.* 2013). Tracing the ages and chemical abundances of the stellar populations in galaxies at different redshifts in relation to galaxy mass and star formation activity puts additional constraints on the mechanisms leading to the global suppression of star formation and the build-up of the quiescent galaxy population.

Studies of galaxy stellar populations at intermediate z are still limited as they require deep spectroscopy in the rest-frame optical where absorption features with distinct sensitivity to age and metallicity are located. Most of these works target red-sequence galaxies in clusters (e.g. Sánchez-Blázquez *et al.* 2009; Jørgensen & Chiboucas 2013) and find their properties to be consistent with passive evolution at high masses. So far only few works have presented the ages and metal abundances of massive quiescent galaxies in the field at $z \lesssim 0.7$ (Schiavon *et al.* 2006; Gallazzi *et al.* 2014; Choi *et al.* 2014).

Here we present results obtained on a sample of ~ 70 galaxies selected from the COMBO-17 catalog of the E-CDFS in the redshift range $0.65 < z < 0.75$ and with stellar mass $> 10^{10} M_\odot$. For this sample we obtained spectra with IMACS on the 6.5 m Magellan telescope at the Las Campanas Observatory covering the rest-frame range $3700 - 5500$Å with a spectral resolution of ~ 3.7Å rest-frame. As opposed to previous works we analyse both quiescent early-type galaxies and star-forming late-type galaxies. We quantify the relations between age, stellar metallicity and stellar mass for the population as a whole and for quiescent galaxies only and compare them with their analogs at

$z = 0$. By analysing individual galaxy spectra, we wish to understand whether individual galaxies that are already on the red-sequence at $z \sim 0.7$ undergo some evolution to $z = 0$ or whether the ensamble population evolves through addition of recently quenched galaxies, as suggested by number density evolution studies. In parallel, we analyse whether $z = 0.7$ star-forming galaxies have ages and stellar metallicities compatible with the population required for the observed red-sequence evolution.

2. Results

We estimate luminosity-weighted mean age, stellar metallicity and stellar mass following the bayesian approach developed in Gallazzi *et al.* (2005) to analyse SDSS galaxy spectra. We compare the strengths of the absorption features $D4000_n$, $H\beta$, $H\delta_A$+$H\gamma_A$, $[Mg_2Fe]$, $[MgFe]'$ to a library of synthetic spectra based on the Bruzual & Charlot (2003) models convolved with a Monte Carlo library of star formation histories and metallicities.

In Fig. 1a we plot the median and the 16th and 84th percentiles of the age distribution in bins of stellar mass for our sample at $z = 0.7$ (filled stars with error bars). The mean stellar age increases from ~ 2.3 Gyr at $3 \times 10^{10} M_\odot$ to ~ 4.5 Gyr over an order of magnitude in mass. This can be directly compared with the analog age–mass distribution for SDSS galaxies (shaded area; Gallazzi *et al.* 2005): the shape of the relation at $z = 0.7$ is consistent within the uncertainties with that at $z = 0$, while the characteristic age at $10^{11.5} M_\odot$ is ~ 4 Gyr younger than the local value. The observed relation at $z = 0.7$ is significantly shallower and has a zero-point at an older age than what expected by passively evolving back in time the observed $z = 0$ relation (dotted curve). Similarly, in Fig. 1b the stellar metallicity distribution in bins of stellar mass for $z = 0.7$ galaxies is compared to the relation for SDSS galaxies. The shape of the relation is similar at both redshifts, while the characteristic stellar metallicity at $z = 0.7$ is ~ 0.13 dex lower than at $z = 0$. Both observations indicate that simple passive evolution of the entire massive galaxy population at $z = 0.7$ would not correctly predict the local age–mass and metallicity–mass relations.

We further separate galaxies into quiescent and star-forming based on a cut in specific SFR. The age and stellar metallicity distributions as a function of stellar mass of the $z = 0.7$ quiescent and star-forming galaxies are compared in Fig. 2 to the corresponding ones at $z = 0.1$ based on SDSS data. The ages of $z = 0.7$ quiescent galaxies display a similar increase with mass as local galaxies, but offset by ~ 3 Gyr. The stellar metallicities of $z = 0.7$ quiescent galaxies have a similar distribution as their $z = 0$ analogs over the same mass range, suggesting no evolution in stellar metallicity for this class of galaxies. The lack of evolution in the stellar metallicity distribution suggests that passive evolution applies to those massive galaxies that were already quiescent at intermediate redshift. Indeed their passively evolved ages are consistent with the local quiescent population (empty circles in Fig. 2a). However, the predicted scatter at $z = 0$ is lower than observed. The similar stellar metallicity as local galaxies and the low fraction of post-starburst galaxies (as we show in Gallazzi *et al.* 2014) allow for only a small amount of 'frosting' to slow down the aging of quiescent galaxies.

Star-forming galaxies have a steeper age–mass relation than quiescent galaxies, offset by ~ 5 Gyr from its local analog (Fig. 2c). Their stellar metallicities are on average ~ 0.12 dex lower than their local analogs. The observed offset between $z = 0.7$ and $z = 0$ is similar to the average evolution in gas-phase oxygen abundance of star-forming galaxies (e.g. Moustakas *et al.* 2011). It is also similar, although slightly larger, than the evolution predicted by Peeples & Somerville (2013) (0.07 dex) over the same mass and redshift range based on estimates of the average galaxy star formation histories and the

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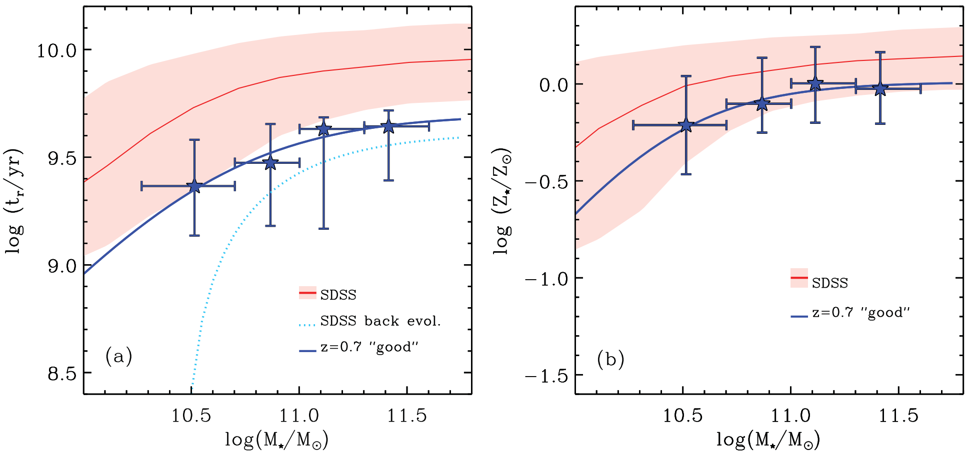

Figure 1. Luminosity-weighted mean age (panel *a*) and stellar metallicity (panel *b*) as a function of stellar mass for galaxies at $z = 0.7$. Filled stars show the median trends in bins of stellar mass, with error bars corresponding to the 16^{th} and 84^{th} percentiles. The solid curve shows the fitted relation. These relations are compared to the corresponding distributions for $z = 0.1$ SDSS galaxies. The dotted curve in panel *a* indicates the age–mass relation at $z = 0.7$ expected by passive backward evolution of the SDSS relation. Adapted from Fig. 7 of Gallazzi *et al.* (2014).

observed mass-gas metallicity-SFR relation. The observed evolution in the average stellar metallicity indicates chemical enrichment in at least some of the massive star-forming galaxies. We note though that a significant fraction of $z = 0.7$ star-forming galaxies have metallicities already comparable to those of local quiescent galaxies. These galaxies have stellar population properties compatible with those required to populate the younger part of the local quiescent galaxy population, increasing the scatter in age without altering the metallicity distribution.

3. Conclusions

Based on deep, medium-resolution IMACS spectroscopy of a sample of ~ 70 massive galaxies at $z = 0.7$, we characterize for the first time at these redshifts the stellar metallicity and age scaling relations for the population as a whole and for quiescent and star-forming galaxies separately We find that $z = 0.7$ quiescent galaxies have stellar metallicities and stellar ages consistent with local quiescent galaxies under passive evolution hypothesis, in qualitative agreement with results on cluster quiescent galaxies by Sánchez-Blázquez *et al.* (2009) and Jørgensen & Chiboucas (2013). However, we also show that the scatter in age of $z = 0.7$ quiescent galaxies is too low to reproduce the scatter of the local relation. Addition of recently-quenched star-forming galaxies could contribute to the build-up of the younger portion of the local red-sequence. This possibility was also suggested for field galaxies by Schiavon *et al.* (2006) and is not ruled out by Choi *et al.* (2014). About 40% of massive star-forming galaxies in our sample have indeed stellar ages and metallicities compatible with those required to increase the scatter in age without affecting the metallicity distribution to reproduce the local quiescent population. Upcoming large deep spectroscopic programs will allow to extend these studies to lower stellar masses and to better sample the star-forming galaxy population. Comparison of these studies with those based on cluster galaxies can shed light on the role of environment in setting the mass scale where galaxies evolve passively.

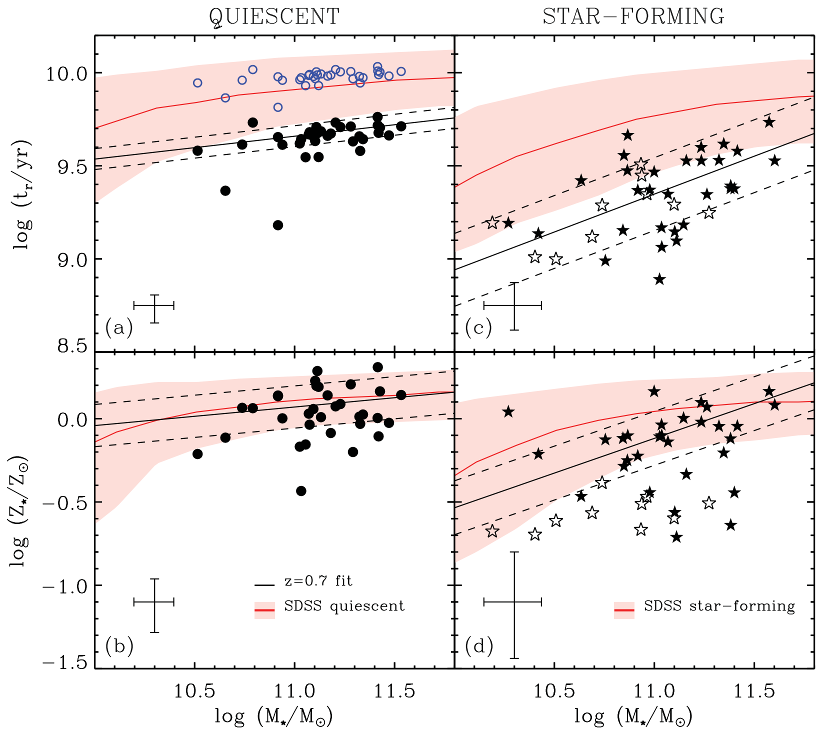

Figure 2. Luminosity-weighted mean age (panels *a* and *b*) and stellar metallicity (panels *c* and *d*) versus stellar mass for quiescent (*left*) and star-forming galaxies (*right*; empty stars indicate $z = 0.7$ galaxies with poor metallicity constraints). The shaded regions and solid curves show the relations for SDSS galaxies, while the solid and dashed lines show the linear relation and scatter fitted to $z = 0.7$ galaxies. The empty circles in panel *a* indicate the expected location on the local relation of $z = 0.7$ quiescent galaxies if they evolved passively until $z = 0.1$. The error bars in each panel represent the mean error on the parameters for each subsample of $z = 0.7$ galaxies. Adapted from Fig. 12 of Gallazzi *et al.* (2014).

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