How do galaxies accrete their mass? Quiescent and star-forming massive galaxies at high redshift

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In recent years, several surveys have shown that massive galaxies have undergone a major evolution during the epoch corresponding to the redshift range 1.5-3, assembling a significant fraction of their stellar mass at that epoch. To understand the origin of this rapid rise, a closer scrutiny on the nature and physical properties of massive galaxies at high redshift is needed. I will present our recent results based on the analysis of the 24 μm MIPS data of the GOODS-S field, that allow to trace star formation (or the lack of it) in high redshift galaxies without biases due to dust extinction. I will show the results of our analysis focusing in particular on the fraction of quiescent galaxies as a function of redshift and the evolution of the specific star formation rate as a function of redshift and stellar mass. The scenario emerging from these data will be compared with recent predictions of theoretical models to discuss the validity of their physical ingredients. The main results of this work are: a) the fraction of quiescent galaxies decreases with redshift, and a non-negligible fraction (∼15%) is already in place at z ∼ 3; b) massive star-forming galaxies are vigorously forming stars (∼300 M⊙ yr⁻¹) at z ∼ 2, and during this epoch they assemble a substantial part of their final stellar mass; c) the specific star formation rate shows a bimodal distribution up to z ∼ 2; d) theoretical predictions, although qualitatively in agreement, are unable to quantitatively reproduce these observations.

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I. INTRODUCTION

According to several independent lines of evidence, the population of massive galaxies has undergone major evolution during the very short epoch corresponding to the redshift range 1.5 – 3. Many previous works measured a rapid evolution in the stellar mass density within this redshift range (e.g., [1], [2], [3] and references therein) and demonstrated that a substantial fraction (30-50%) of the stellar mass formed during this epoch.

The nature of the physical processes responsible for this rapid rise remains unclear. A large number of massive (≈ 10¹¹ M⊙) actively star-forming galaxies is clearly in place at z ∼ 2 [4, 5]. These galaxies have been demonstrated to experience an extremely active phase in the same redshift range (e.g., [6]).

At the same time, galaxies with very low levels of star formation rate (SFR) at z ∼ 1.5 – 2 have been detected by imaging surveys based on color criteria (e.g., [4]) or SED fitting [5], and by spectroscopic observations of red galaxy samples (e.g., [6], [7]). These results have motivated the inclusion in theoretical models of efficient methods for providing a rapid assembly of massive galaxies at high z (such as starburst during interactions) as well as quenching of the SFR, most notably via AGN feedback (e.g., [10], [11]).

In the first part of this work we will focus on quiescent galaxies, while star-forming ones will be the object of the second part. Once presented the data sample in section II, in section III we attempt to compile a statistically well defined, mass-selected sample of galaxies with very low levels of star formation at high redshift (0.4 – 4), with the aim of comparing their abundance with theoretical model predictions. Such a comparison can shed light upon the nature of the star formation suppression. In section IV we investigate the star formation properties of our mass-selected sample between z ∼ 0.3 and z ∼ 2.5 in order to understand whether the rapid growth of the stellar mass density is due to star formation episodes inside the galaxies or to merging events. Once again, we will compare our observations with theoretical expectations. Conclusions will follow in section V.

Throughout this work, unless stated otherwise, we assume a Salpeter initial mass function (IMF) and adopt the Λ-CDM concordance cosmological model (H₀ = 70 km/s/Mpc, Ω₉ = 0.3 and Ωₐ = 0.7).
II. THE DATA SAMPLE

For this study, we used data from an updated version of the multicolour GOODS-MUSIC sample [12, 13]. The catalog covers an area of about 143 arcmin$^2$ located in the Chandra Deep Field South and consists of 15208 sources. After culling Galactic stars, it contains 14999 objects selected in either the $z$ band or the $K_s$ band or at 4.5 $\mu$m ($m_{45}$ hereafter). The 15-bands multiwavelength coverage ranges from 0.35 to 24 $\mu$m, as a result of the combination of images from different instruments (2.2ESO, VLT-VIMOS, ACS-HST, VLT-ISAAC, Spitzer-IRAC, Spitzer-MIPS). The whole catalog has been cross-correlated with spectroscopic catalogs available to date, and a spectroscopic redshift has been assigned to logs of images from different instruments (2.2ESO, VLT-VIMOS, ACS-HST, VLT-ISAAC, Spitzer-IRAC, Spitzer-MIPS). The whole catalog has been cross-correlated with spectroscopic catalogs available to date, and a spectroscopic redshift has been assigned to $\sim$12 % of all sources. For all other objects, we have computed well-calibrated photometric redshifts ($|\Delta z/(1+z)| < 0.06$). Physical properties of each object, such as total stellar mass, SFR, age and dust obscuration, have been obtained through a standard SED fitting technique to the overall photometric data from 0.3 to rest-frame 5.5 $\mu$m using the synthetic templates of Bruzual and Charlot [14].

Our work is mainly based on the analysis of the 24 $\mu$m MIPS data, which is described in details in [12]. Notable contaminants affecting galaxy mid-IR emission are represented by highly obscured AGNs, where the IR emission is generated by matter accretion onto a central black hole rather than dust heating by young stars. In order to avoid biases in our IR-based SFR estimates as well in the selection of quiescent galaxies, we removed highly obscured AGN candidates from our sample by following the approach described by [13].

III. QUIESCENT GALAXIES

A. Selection criterium

It is difficult to isolate passively evolving galaxies from the wider population of intrinsically red galaxies at high redshift, which include also a (probably larger) contribution of star-forming galaxies reddened by a large amount of dust. The two classes are indeed indistinguishable when selected by means of traditional single colour criteria, since a dusty stellar population may have similar UV-optical characteristics as an old population. The problem can be overcome by considering the mid-IR emission of these optically red galaxies, which appears to be clearly different for the two populations. Star-forming galaxies are bright because the UV light released by their young stars is absorbed by dust and re-emitted at mid-IR wavelengths. By contrast, passively evolving galaxies are faint, as the starlight from evolved populations peaks in the near-IR. We separated the quiescent and the star-forming population by means of their $F(24\mu m)/F(K_s)$ flux ratio, which we demonstrated to have a clear bimodal distribution [16].

However, we were not simply interested in quiescent galaxies, but rather we aimed to explore the very quiescent tail of the red galaxy population, which can be used to investigate the mechanisms which shut down the star formation. We therefore combined the mid-IR information with the SED fitting analysis, and we selected a sample of “red and dead” galaxies by requiring that $SFR/M < 10^{-11} yr^{-1}$, which ensures negligible levels of star formation in these galaxies (see [16]).

In the following, we adopt a mass-selected sample, obtained by applying a mass threshold at $M \geq 7 \times 10^{10} M_\odot$ to the photometric catalog based on a combined selection $K_s < 23.5$ or $m_{45} < 23.2$. This photometric sample is complete at this mass limit to $z \simeq 4$, also for dust-absorbed star-forming galaxies [2].

B. The fraction of “red and dead” galaxies and comparison with theoretical predictions

The fraction of “red and dead” is shown in Figure 1 as a function of redshift from $z = 0.4$ to $z = 4$. A detailed analysis of the highest redshift ($z > 2.5$) candidates, where the selection is affected by large uncertainties, is presented in [16]. Error bars were computed by summing (in quadrature) Poissonian and cosmic variance errors. The latter were computed by measuring the relative variance within 200 samples bootstrapped from the Millennium Simulation [18], using an area as large as GOODS-South and applying the same selection criteria.

Our analysis confirms the cosmological decrease in the number density of massive early-type galaxies at high redshifts: “red and dead” galaxies make up more than 50% of the population of massive galaxies at $z <$ 1, and become progressively less common at higher $z$. However, we note that a sizeable fraction of galaxies with
extremely low levels of SFR is already in place at $z > 1.5$ and up to the highest redshifts sampled here ($z \simeq 3.5$) with a fraction of about 15% at $z > 2$. This implies that the star formation episodes in these galaxies must be quenched either by efficient feedback mechanism and/or by the stochastic nature of the hierarchical merging process.

It is interesting to determine whether theoretical models agree with these observational results. In Figure 1, we plot the predictions of several models, applying the same selection criteria that we applied on the data. We consider purely semi-analytical models (Menci et al. 1999, M06, and MORGANA 2007, F07), a semi-analytical rendition of the Millennium N-body dark matter simulation (Kitzbichler and White 2009, K07), and purely hydrodynamical simulations (Nagamine et al. 2010, N06). The latter are presented for three different timescales $\tau$ of the star formation rate (ranging from $2 \times 10^7$ yrs to $2 \times 10^8$ yrs), and represented with a shaded area.

All these models agree in predicting a gradual decline with redshift in the fraction of galaxies with very low SFR. However, the predicted fraction of “red and dead” galaxies varies significantly at all redshifts. For this reason, it turns out to be a particularly sensitive quantity, which provides a powerful way of highlighting the differences between the models. Some models (M06, F07) underpredict the fraction of “red and dead” galaxies at all redshifts, and in particular predict virtually no object at $z > 2$, in contrast to what observed. The Millennium-based model agrees with the observed quantities, while the hydro model appears to overpredict them.

IV. STAR-FORMING GALAXIES

A. The estimate of the SFR

Since the most intense star formation episodes are expected to occur in dusty regions, and based on the assumption that most of the photons originating in newly formed stars are absorbed and re-emitted by dust, the mid-IR emission is in principle the most sensitive tracer of the star formation rate. Moreover, it has the great advantage of being unaffected by dust obscuration and independent on still uncertain dust corrections.

In addition to mid-IR emission, a small fraction of unabsorbed photons will be detected at UV wavelengths. A widely used SFR indicator is therefore based on a combination of IR and UV luminosity, which supply complementary knowledge of the star formation process. For 24 $\mu$m detected sources, we estimated the instantaneous SFR using the same calibration as [3]:

$$\text{SFR}_{IR+UV}/M_{\odot}yr^{-1} = 1.8 \times 10^{-10} \times L_{bol}/L_{\odot}$$

(1)

$$L_{bol} = (2.2 \times L_{UV} + L_{IR})$$

(2)

The total IR luminosity $L_{IR}$ was computed by fitting 24 $\mu$m emission to Dale and Helou 2002 (DH) synthetic templates. The rest-frame UV luminosity, uncorrected for extinction, was derived from the SED fitting technique, $L_{UV} = 1.5 \times L_{2700\AA}$, although often negligible, it accounts for the contribution from young unobscured stars.

Following [3], we then applied a lowering correction to the estimate obtained from Equation 1. They found that 24 $\mu$m fluxes, fitted with the same DH library, overestimate the SFR for bright IR galaxies, with respect to the case where longer wavelengths (70 and 160 $\mu$m MIPS bands) are considered as well, and they corrected the trend using an empirical second-order polynomial.

We derived the SFR using the prescriptions above for all objects with $F_{24\mu m} \geq 20 \mu Jy$ (which we estimated to be the flux limit of our 24 $\mu$m catalog), while we adopted the estimate derived from the SED fitting analysis for all fainter galaxies undetected at 24 $\mu$m.
B. The evolution of the specific star formation rate and the mass assembly process

With respect to other surveys, our sample has the distinctive advantage of being selected by a multiwavelength approach. In this section, we consider a subsample created by performing the following magnitude cuts: \( z < 26 \) or \( K_s < 23.5 \) or \( m_{45} < 23.2 \). The \( K_s \) and \( m_{45} \) cuts ensure a proper sampling of highly absorbed star-forming galaxies, and hence likely a complete census of all galaxies with high SFR. On the other hand, the deep \( z \)-selected sample contains the lower mass, fainter and bluer galaxies of both low levels of dust extinction and low star formation rate.

In Figure 2, we plot the relation between the stellar mass and the specific star formation rate (defined as the SFR per unit mass, SSFR hereafter) for all galaxies divided into redshift bins, from \( z = 0.3 \) to \( z = 2.5 \). To be able to compare our findings with the Millennium Simulation predictions, we converted our masses and SFR to the Chabrier IMF used by the Millennium Simulation.

First of all, we notice a strong bimodality in the SSFR distribution at all redshifts. Two distinct populations, together with some sources lying between the two, are detectable, one made of young, active and blue galaxies (the so-called blue cloud) and the other one consisting of old, “red and dead”, early-type galaxies (red sequence). The loci of these two populations are consistent with the selection in [21] between early- and late-type galaxies.

A trend for the specific star formation rate to increase with redshift at a given stellar mass is evident: galaxies tend to form their stars more actively at higher redshifts, or, in other words, the bulk of active sources shifts to higher values of SSFR with increasing redshift. Moreover, at a given redshift, low mass galaxies are more actively star-forming than their higher mass counterparts. Our findings are in good agreement with [3] and [22].

A significant fraction of the sample, increasing with redshift, is witnessing an active phase (see also section III B). It is natural to compare the SSFR (which has units of the inverse of a timescale) of these galaxies with the inverse of the age of the Universe at the corresponding redshift (\( t_U(z) \)). We define galaxies with \( M/SFR < t_U(z) \) as “active” in the following, since they are experiencing a major episode of star formation, potentially building up a substantial fraction of their stellar mass (see [12]). Galaxies selected following this criterium are forming stars more actively than in their recent past.

At \( 1.5 < z < 2.5 \), the fraction of massive (with \( M > 7 \cdot 10^{10} M_\odot \)) active galaxies in the total sample is 66\%, and their mean SFR is \( 309 M_\odot yr^{-1} \). To compute the total stellar mass produced within this redshift interval, it is necessary to know the duration of the active phase. For this purpose, we used a duty cycle argument and supposed that the active fraction of galaxies is indicative of the time interval spent in the active phase. We adopted the assumption that the active fraction is stable within the redshift bin considered. The time spanned in the 1.5–2.5 redshift interval corresponds to 1.5 Gyr. By multiplying the fraction of active galaxies by the time available, we derived an average duration of the active phase of 0.99 Gyr. The average amount of stellar mass assembled within each galaxy during these bursts is measured to be the product of the average SFR and the average duration of the active phase, and equals to \( \sim 3.1 \times 10^{11} M_\odot \), representing a significant fraction of the final stellar mass of the galaxies considered. Although quite simplified, this analysis implies that most of the stellar mass of massive galaxies is assembled during a long-lasting active phase at \( 1.5 < z < 2.5 \). It is important to remark that this process of intense star formation occurs directly within already massive galaxies, and, given its intensity, prevails throughout growth episodes due to merging events of already formed progenitors.

C. Comparison with theoretical predictions

To provide a further physical insight in this process, we compared our results with the predictions of three recent theoretical models of galaxy formation and evolution. Our sample is affected by mass incompleteness, so only galaxies above the completeness limit in each redshift bin were considered in the comparison. We note that this limit depends on the redshift bin [2], and it is equal to \( 5 \cdot 10^9 \), \( 8 \cdot 10^9 \), \( 2 \cdot 10^{10} \) and \( 7 \cdot 10^{10} M_\odot \), respectively (calibrating masses to a Salpeter IMF).

In Figure 2 we show the predictions of the K07 [18] model based on the Millennium Simula-
We find that the model predicts an overall trend that is consistent with our findings. The SSFR decreases with stellar mass (at given redshift) and increases with redshift (at given stellar mass). In addition, it forecasts the existence of quiescent galaxies even at \( z > 1.5 \), as already found in section III B. However, the average observed SSFR is systematically under-predicted (at least above our mass limit) by a factor \( \sim 3-5 \) by the Millennium Simulation. A similar trend for the Millennium Simulation at \( z \sim 2 \) was already shown by [6].

We also compared our findings with M06 and MORGANA models. They show very similar trends with respect to the Millennium Simulation, with only slightly different normalizations, up to a factor 10 discrepancy (see [12]) with respect to observations.

A more comprehensive comparison between theoretical predictions and observations was presented in [23].

V. CONCLUSIONS

We have studied the mass accretion process in galaxies around \( z \sim 2 \) by investigating the properties of both the quiescent and the star-forming population and by comparing observations with theoretical expectations.

In the first part we considered the fraction of very quiescent, “red and dead” galaxies, as a function of redshift, to the total sample of massive galaxies. Since these galaxies are reproduced by the models by shutting down the star formation (SF), the fraction of “red and dead” galaxies provides information about the mechanism responsible for the SF quenching. A non-negligible fraction (\sim 15\%) of galaxies with very low SF activity is already in place at the highest redshift sampled in this work. This motivates the inclusion in the models of very efficient SF mechanisms as well as their rapid suppression.

In the second part we studied the evolution of the specific star formation rate as a function of redshift and stellar mass. The SSFR shows a well-defined bimodal distribution, with a clear separation between actively star-forming and passively evolving galaxies. Massive star-
forming galaxies at $z \simeq 2$ are vigorously forming stars, typically at a rate of $\sim 300 \, M_\odot \, yr^{-1}$.
A simple duty cycle argument suggests that they assembled a significant fraction of their final stellar mass during this phase, implying that star formation episodes in already massive galaxies are the main responsible for the rapid growth of the stellar mass density at $z \sim 2$.

We used our results for the quiescent and the star-forming galaxy populations to investigate the predictions of a set of theoretical models of galaxy formation in a Λ-CDM scenario. All the models taken into account qualitatively reproduce the global observed trend. However, quantitatively, they predict an average specific star formation rate that is systematically lower than observed, at least in the mass regimes considered. On the other side, for what concerns the “red and dead” fraction, they vary to a large extent in their predictions and are unable to provide a global match to the data, making this observable very sensitive and powerful to constrain the SF quenching mechanism.

Although some hypothesis have been suggested by [12], the origins of the discrepancies between observations and theoretical predictions are difficult to ascertain, because of the complex interplay between all the physical processes involved in these models, the different technical implementations. The failure of most models to reproduce simultaneously the fraction of “red and dead” massive galaxies in the early Universe and the star formation activity probably implies that the balance between the amount of cool gas and the star formation efficiency on the one side, and the different feedback mechanisms on the other, is still poorly understood.

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