The specific star formation rate of high redshift galaxies: the case for two modes of star formation

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ABSTRACT
We study the specific star formation rate (SSFR) and its evolution at \( z > 4 \), in models of galaxy formation, where the star formation is driven by cold accretion flows. We show that constant star formation and feedback efficiencies cannot reproduce the observed trend of SSFR with stellar mass and its observed lack of evolution at \( z > 4 \). Model galaxies with \( \log(M_\star) < 9.5 \ M_\odot \) show systematically lower specific star formation rates by orders of magnitudes, while massive galaxies with \( M_\star \gtrsim 5 \times 10^{10} \ M_\odot \) have up to an order of magnitude larger SSFRs, compared to recent observations by Stark et al. (2009). To recover these observations we apply an empirical star formation efficiency in galaxies that scales with the host halo velocity dispersion as \( \propto \sigma^{-3} \) during galaxy mergers. We find that this modification needs to be of stochastic nature to reproduce the observations, i.e. only applied during mergers and not during accretion driven star formation phases. Our choice of star formation efficiency during mergers allows us to capture both, the boost in star formation at low masses and the quenching at high masses, and at the same time produce a constant SSFR-stellar mass relation at \( z \sim 4 \) under the assumption that most of the observed galaxies are in a merger triggered star formation phase. Our results suggest that observed high-z low mass galaxies with high SSFRs are likely to be frequently interacting systems, which experienced bursts in their star formation rate and efficiency (mode 1), in contrast to low redshift \( z < 3 \) galaxies which are cold accretion-regulated star forming systems with lower star formation efficiencies (mode 2).

Key words: galaxies: formation – galaxies: high-redshift – galaxies: interactions – galaxies: starburst

1 INTRODUCTION
The cosmic star formation rate in the universe is shaped by the physical conditions that govern the growth of galaxies. An initial, probably short-lived, \( t \sim 10^6 \) yr, episode of population III-dominated star formation at \( z \sim 15 \) (e.g. Maio et al. 2010) is followed by a steady increase in cosmic population II/I star formation activity that reaches a peak around \( z \sim 2 \) (Hopkins & Beacom 2006), coinciding with a peak in the merger activity of galaxies (e.g. Khochfar & Burkert 2001; Conselice et al. 2008; Khochfar & Silk 2009a). The steady decline at lower redshifts is quite strong, however, allowing for \( \sim 50\% \) of the present-day stellar mass to have been formed between \( z = 0 \) and 1 (Pérez-González et al. 2008). Within the hierarchical ΛCDM framework, the initial increase in the cosmic star formation is closely linked to the growth of the hosting dark matter haloes. The short cooling time-scale of halo gas favours efficient fuelling of star formation in galaxies, in particular at high redshifts and in dark matter haloes with \( M_{\text{vir}} \lesssim 10^{12} \ M_\odot \) (e.g. Binnov 1977, Silk 1977, Rees & Ostriker 1977, Birnboim & Dekel 2003). More massive haloes at \( z > 2 \) however, reveal efficient feeding of their central galaxies as well. Cold streams of gas that enter the virial radius along cosmic filaments penetrate through the diffuse hot halo gas and reach the potential minimum of the halo (Keres et al. 2005, Devirk et al. 2008, Dekel et al. 2009). Massive galaxies at \( z \sim 2 \) show gas-to-stellar mass ratios of order unity suggesting that cold flows could indeed be a very efficient means of providing gas to galaxies (Daddi et al. 2010a, Tacconi et al. 2010).

At \( z < 2 \), cold streams in massive haloes cease to exist and feedback effects control the cosmic star formation (e.g. Schaye et al. 2010, see however Bouche et al. 2010).
Different feedback sources are also held responsible for shaping the mass function (e.g. Dekel & Silk 1986; Benson et al. 2003; Croton et al. 2006; Khochfar et al. 2007; Oppenheimer et al. 2010) or the colours of galaxies (e.g. Kang et al. 2005; Cattaneo et al. 2006; Dekel & Birnboim 2006; Khochfar & Ostriker 2008).

The importance of cold accretion for the star formation rate of galaxies has recently been the subject of various semi-analytic studies, which show that the evolution of the specific star formation rate (SSFR) of galaxies can be reproduced at $z \lesssim 4$ (Khochfar & Silk 2009b; Bouche et al. 2009; Dutton et al. 2010; Kang et al. 2010). However, these models fail to reproduce the observed SSFR of galaxies at $z > 4$ (Bouche et al. 2009), where in particular the SSFR is approximately constant (Stark et al. 2009; González et al. 2011). One option is that a second mode of star formation enters at high redshift, perhaps driven by mergers (Genzel et al. 2010; Daddi et al. 2010), in contrast to the canonical cold gaseous disk instability model that elegantly reproduces the Schmidt-Kennicutt star formation relation at $z \lesssim 2$.

In this Letter, we address the question whether it is possible to reconcile observations of specific star formation rates at $z > 4$ with simple models of accretion-driven star formation at high-z. We focus on the question how star formation needs to be modulated to accomplish this task and derive empirical scaling relations for the star formation efficiency in galaxies at high $z$.

2 MODEL

The basic modelling approach we follow is similar to Neistein & Weinmann (2010) and Bouche et al. (2009). In this approach the evolution of a galaxy within a dark matter halo is followed by calculating the accretion rate of cold gas, the associated star formation rate and the effect from supernovae feedback for a grid of dark matter haloes with varying masses starting at a fiducial redshift. We approximate the accretion rate of cold gas onto central galaxies by $\dot{M}_{\text{acc}} = f_b M_{DM}$, with $f_b = 0.165$ as the universal baryon fraction and $M_{DM}$ the dark matter halo mass (Dekel et al. 2009). To simplify matters even more, we approximate the dark matter growth rate by an analytic fit $M_{DM}(z) \approx 6.6 f_b^{-1} M_{12}^{15} (1 + z)^2 \sigma_8^5$ yr$^{-1}$ (Neistein et al. 2004). Here $M_{12}$ is the dark matter halo mass in units of $10^{12} M_\odot$. Once the gas accretion rate as a function of time is known, one can calculate the gas mass in the central galaxy of a given dark matter halo. We assume that the gas settles onto a rotationally-supported disc hosted by an isothermal halo using the model of Mo et al. (1998), and convert the gas into stars using a global Schmidt-Kennicutt law $\dot{M}_* = \alpha_* \dot{M}_{\text{gas}}/t_{dyn}$ (Kennicutt 1998). The fiducial value for the star formation efficiency is set to $\alpha_* = 0.02$ (Kennicutt 1998) and the dynamical time of the disc, $t_{dyn} = 0.1 R_{vir}/V_c$ (Kauffmann et al. 1999). Here $R_{vir}$ is the halo virial radius and $V_c$ its circular velocity. Besides models with constant $\alpha_*$ we also investigate models with more general efficiencies that depend on the halo velocity dispersion. The feedback effects from supernovae onto the cold gas reservoir are included using the approach in Kauffmann et al. (1999) with $\dot{M}_{SN} = c E_{SN} m_{\text{IMF}} \dot{M}/V_c^2$. The energy per supernova is $E_{SN} = 10^{51}$ ergs, $m_{\text{IMF}} = 1/150$ $M_\odot$ is the number of type-II supernovae per solar mass stars formed assuming a Chabrier IMF, $M_*$ the star formation rate and $c$ is the feedback efficiency for which we assume a fiducial value of $c = 0.2$. The gas reheated by supernovae feedback contributes to the hot halo and we assume that it does not cool down by $z = 4$. Numerical simulations suggest that most gas in galaxies indeed never reheats before joining it (Keres et al. 2009). In the following we show our results for solving the differential equations for the evolution of the stellar mass $M_*$, the cold gas mass $M_{\text{gas}} = M_{\text{acc}} - M_*$, and star formation rate $\dot{M}_*$, by explicitly following the dark matter growth $M_{DM}$ as a function of time using the fitting formulae for the average growth rate given above.

3 RESULTS

In Fig. 1 we show the predicted SSFRs for galaxies for the fiducial model and compare them to the observational data by Stark et al. (2009).

Our results show the same trend as the non-accretion floor model of Bouche et al. (2009). Applying an accretion floor of $M_{DM} = 10^{11} M_\odot$, below which no cold accretion occurs, gives good agreement with observed data at $z < 3$, but suppresses the formation of enough low mass galaxies at $z > 5$. For this reason we do not apply an accretion floor, and allow gas accretion in halos of all mass. The trend in SSFR is in stark contrast to the observed data. Most strikingly, low mass galaxies of $M_* \lesssim 5 \times 10^9 M_\odot$ show orders of magnitude too low star formation rates, while massive galaxies with $M_* \gtrsim 5 \times 10^{10} M_\odot$ show an order of magnitude too high star formation rates. Independently of these failures, the time-scales of the inverse SSFRs at $z = 4$ are smaller than the age of the universe, indicating efficient early formation. Fig. 1 also highlights that the model SSFR-$M_*$ relation is significantly evolving from $z = 4$ to $z = 6$, indicated by open and filled circles, respectively. In contrast the observations shown in the same figure indicate almost no evolution.

Before we continue comparing model results to observations it is worth pointing out potential observational biases. The main source of uncertainty are the observed star formation rates. In Fig. 1 we show SSFRs that are not corrected for dust extinction (Stark et al. 2004). Including dust extinction results in higher star formation rates, shifting the SSFR-$M_*$ relation to larger values in SSFR, thus worsening the discrepancy between models and observations in particular at the low mass end, if these galaxies were to host significant amounts of dust. Another important source of uncertainty is the completeness of the observed samples. The Stark et al. (2009) sample is complete above $\log(SFR) = (0.25, 0.41, 0.54)$ for $z = (4, 5, 6)$. Stark et al. (2009) argue that at low stellar masses their sample is not
circles show the model SSFR at $z$ range from $10^{-6}$ to $10^{3}$.

Within the CDM framework, galaxy mergers are a natural mass. Each individual line shows the growth history of one central galaxy within a dark matter halo under the assumption of the fiducial model. The initial halo masses at $z = 10^{-6}$ and $z = 6$ are $10^{9}$ and $10^{12}$, respectively. The red triangles and blue squares show the observed data from Stark et al. (2009) at these redshifts, uncorrected for dust extinction and assuming an exponential decaying star formation rate with $\tau = 100$ Myr. Typical errors are 0.3 dex. Light blue triangles show the $z = 7$ data from Schaerer & de Barros (2010). Dashed lines show lines of constant star formation rate for 500, 100, 10, 3.5 and 1.8 $M_\odot$/yr. Latter two correspond to the reported completeness limit in Stark et al. (2009) at $z = 6$ and 4, respectively. The Schaerer & de Barros (2010) sample is a combination of three different samples and we refer the reader to their paper on a discussion on the observational limits and incompleteness of their sample selection. The solid horizontal line marks the inverse age of the universe at $z = 4$.

We tested the behaviour of the SSFR for various star formation and feedback efficiencies. In general, increasing $\alpha_*$ leads to an increase in the stellar mass of galaxies within halos, and a lower SSFR. The latter is directly related to the scaling of the accretion rate with halo mass $M_{\text{acc}} \propto \sigma_{\text{vir}}^{15} M_{\odot}/h$ and the lower reservoir of remaining gas in galaxies. The same trend is found for reducing the feedback efficiency $\epsilon$. SSFRs drop as galaxies form more easily and now live in less massive halos. Our results suggest that a constant boost in star formation efficiency is not going to improve the low SSFR for galaxies with $M_* \lesssim 10^9$ $M_\odot$. What is needed is a boost in $\alpha_*$ that is not constant, but of a stochastic nature. Within the CDM framework, galaxy mergers are a natural candidate to provide such a behaviour. To recover the strong observed mass-dependence of the SSFR, we propose a relation in which the star formation efficiency during mergers is a power-law of the halo velocity dispersion. We adopt the following relation during mergers:

$$\alpha_* = \alpha_0 \left(\frac{\sigma}{\sigma_0}\right)^\gamma$$  

with $\alpha_0 = 0.02$ as the fiducial value observed locally and $\sigma_0$ a characteristic velocity dispersion. The values of $\gamma$ and $\sigma_0$ are treated as free parameters to obtain the observed scaling in the relation between the SSFR and the stellar mass at $z > 4$. Our best-fit values matching the $z = 4$ Stark et al. (2009) data are $\sigma_0 = 85$ km/s and $\gamma = 3$. A similar scaling has been recently suggested in Silk & Norman (2008) based on a porosity model for the inter-stellar medium. Within their model black hole feedback triggered by mergers plays a prominent role. The authors argue that black holes in low mass galaxies are not massive enough to shut down star formation during their initial growth phase, but instead can possibly help boost it (Antonuccio-Deolug & Silk 2008; Silk & Norman 2009), whereas massive black holes are able to prohibit star formation via AGN-feedback (e.g. Silk & Rees 1998; King 2003).
We furthermore neglect the stellar mass contribution of the merging partner to the remnant. Our model is clearly a simplification, and we tested the influence of our assumptions on the results by letting mergers occur randomly during the evolution of galaxies, and changing the duration of the merger episode as well as adding stellar mass from a merger partner. It turns out that the exact frequency of mergers is not important, as long as there is enough time for gas accretion to happen after the merger. Given the high accretion rates at \( z > 4 \), merger-triggered star formation can be frequent in our model, as long as the merger duration is not too long (<100 Myr). Adding mass from merger partners only shifts the relation slightly, which can be compensated for by adjusting \( \sigma_0 \). Outside merger episodes, we apply the fiducial star formation efficiency, i.e. \( \alpha_* = \alpha_0 \) and follow the evolution of our model galaxies. The evolution of the SSFR is presented in Fig. 2. We find good agreement between the modelled SSFR-\( M_* \) relation and the data of Stark et al. (2009). In addition we find that the our SSFR-\( M_* \) relation does not change much with redshift, if we assume interacting galaxies are dominating the sample. As we pointed out above, the observed sample might be missing a population of low star forming galaxies. Such galaxies would be non-merging galaxies within our model, which show low SSFRs closer to the fiducial model shown in Fig. 1 To highlight the non-evolution of the SSFR we compare in Fig. 3 our model predictions for individual galaxy masses with the observations in the literature. We find good agreement with the data of Stark et al. (2009) and Gonzalez et al. (2010) if we consider model galaxies between \( 10^9 \) and \( 5 \times 10^9 \) M\(_\odot\). However, the data of Schaerer & de Barros (2010) and Yabe et al. (2009) show larger values in SSFR. Most of the discrepancy between these and the former data sets is due to different star formation rate estimates that the authors assume, reflecting e.g. their different choice of dust extinction corrections and star formation histories. Interestingly, the latter surveys also predict no or only a week evolution from \( z = 4 \) to \( z = 7 \). Within our model we can achieve higher SSFRs to be in agreement with this data by adjusting our free parameter \( \sigma_0 \). Our results suggest, that if indeed the sample of Stark et al. (2009) is complete in terms of SSFR sensitivity, most if not all low mass high star forming galaxies have to be merger induced.

### 4 DISCUSSION AND CONCLUSION

In this Letter, we present a study of the SSFR in \( \Lambda \)CDM models in which galactic star formation is driven by cold gas accretion onto a central galaxy, that parallels the growth of the hosting dark matter halo. Such models have been shown to reproduce the observed star formation rates of galaxies successfully at \( z \gtrsim 3 \) (e.g. Bouche et al. 2009), but fail at high redshifts (see however Lacey et al. 2010). The rise in SSFR at \( z \gtrsim 2 \) is due to the increased gas fraction. However, a new ingredient is required at higher \( z \). The two observational constraints of a high SSFR for low mass galaxies and non-evolution of the SSFR-stellar mass relation at \( z > 4 \) cannot be met by a simple constant increase in the star formation efficiency \( \alpha_* \) at \( z > 4 \). However, an occasional boost in \( \alpha_* \) triggered by mergers in between periods of low star formation efficiency can provide high SSFR. Galaxy mergers are known to trigger starbursts even in minor merger interactions (\( M_1/M_2 < 10 \), \( M_1 \gtrsim M_2 \)) (e.g. Peirani et al. 2010).

Observationally, merger-induced star formation at low redshifts \( z < 2 \) is not the main driver of star formation (Jogee et al. 2009). This is consistent with the growth of dark matter haloes in simulations, which takes place through significant accretion events and not major mergers (e.g. Genel et al. 2010). Our results indicate that the situation at \( z > 4 \) is rather different. Merging time-scale estimates using dynamical friction predict to first order a dependence on the mass ratios of the merging partners only, once expressed in units of the Hubble time (Springel et al. 2001; Bovlan-Kolchin et al. 2008; Jiang et al. 2008). An equal mass merger thus will take place approximately a factor of a few lower at \( z = 2 \) than at \( z = 6 \). This behaviour supports frequent interactions at \( z > 4 \) that can trigger star formation while at lower redshifts star formation takes mainly place during quiescent periods in between mergers.

While mergers certainly can boost star formation, AGN-regulated starbursts in mergers could provide a natural explanation for the non-evolution of the SSFR-stellar mass relation at \( z > 4 \). If the effects of AGN-feedback are related to the dark matter potential (Booth & Schaye 2010) a
scaling of the star formation efficiency with the halo velocity dispersion can effectively produce a mildly or non-evolving relation. We show that this is indeed the case for the empirical scaling that we adopt in this paper with $\alpha \propto \sigma^{-3}$ during mergers. A more physical model might appeal to AGN growth and feedback which are much less efficient in low mass galaxies, thereby inhibiting quenching, while in massive galaxies, the central black holes are already fully grown and are responsible for quenching the SFR.

Enhanced merging at high redshift provides the SSFR boost that also lends itself to generating enhanced $\alpha/Fe$ in the resulting massive galaxies. We predict that there should be rare low mass $\alpha/Fe$ "refugees", perhaps companions of massive ETGs, that have avoided the final merging fate and gas blow-out, but nonetheless carry chemical traces of their enhanced SSFR history.

The role of AGN remains to be elucidated. Quenching of star formation is commonly attributed to AGN. This may be the case for massive galaxies at high redshift. However AGN may also play a role in boosting star formation in the low mass systems where the SSFR is enhanced. A future test of the role of AGN will be to examine the residuals of a sample with measured AGN accretion rates and star formation rates in order to see whether for example the Eddington ratio correlates (boosting) or anti-correlates (quenching) with SSFR.

Our results suggest that the majority of galaxies with $M_* \lesssim 10^9 \, M_\odot$ at $z > 4$ are interacting systems. This prediction can be tested with future upcoming observational missions, and should provide a strong test on the early build-up of galaxies. In a follow-up paper, we will investigate the individual contribution from merger triggered star-bursts and AGN with respect to accretion-driven star formation in the context of a full semi-analytic model.

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High-redshift Galaxies