Delayed star formation in high-redshift stream-fed galaxies

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ABSTRACT

We propose that star formation (SF) is delayed relative to the inflow rate in rapidly accreting galaxies at very high redshift ($z > 2$) because of the energy conveyed by the accreting gas. Accreting gas streams provide fuel for SF, but they stir the disc and increase turbulence above the usual levels compatible with gravitational instability, reducing the SF efficiency in the available gas. After the specific inflow rate has sufficiently decreased – typically at $z < 3$ – galaxies settle in a self-regulated regime with efficient SF. An analytic model shows that this interaction between infalling gas and young galaxies can significantly delay SF and maintain high gas fractions (>40 per cent) down to $z \approx 2$, in contrast to other galaxy formation models. Idealized hydrodynamic simulations of infalling gas streams on to primordial galaxies confirm the efficient energetic coupling at $z > 2$ and suggest that this effect is largely under-resolved in existing cosmological simulations.

Key words: galaxies: evolution – galaxies: formation.

1 INTRODUCTION

Star-forming galaxies at redshift $z \approx 1$–2 have high gas fractions $\gtrsim 50$ per cent, probed by both their molecular gas and dust properties (Daddi et al. 2010; Magdis et al. 2012; Tacconi et al. 2013, but note criticism from Narayanan, Bothwell & Davé 2012). Many galaxy evolution models underpredict gas fractions at high redshifts (Dutton, van den Bosch & Dekel 2010; Davé, Finlator & Oppenheimer 2012), and cosmological simulations find gas fractions as low as 10 per cent at $z \approx 1$–2 for stellar masses in the $10^{10}$–$10^{11} \ M_\odot$ range (e.g. Ceverino, Dekel & Bournaud 2010; Kereš et al. 2012, but higher in some cases, e.g. Genel et al. 2012b). This likely results from a too rapid consumption of gas reservoirs at $z > 2$, where observations suggest that the efficiency of star formation (SF) is more moderate (in proportions that remain contentious; Daddi et al. 2007; González et al. 2010; Elbaz et al. 2011; Bouwens et al. 2012; Reddy et al. 2012; Stark et al. 2013). The need to delay SF in the $z > 2$ progenitors of star-forming galaxies, summarized by Bouché et al. (2010) and Weinmann et al. (2012), may (Henriques et al. 2013) or may not be solved by stellar feedback – recently simulated galaxies with stronger feedback still become star dominated within their effective radii by $z \approx 3$, with excessive specific star formation rates (SFR) at earlier epochs (Ceverino et al. 2013). Feedback from active galactic nuclei tends to exacerbate the problem by lowering gas fractions (Dubois et al. 2012a) if it has a substantial effect at all (cf. Gabor & Bournaud 2013a). Low metallicity could play a role by hindering cooling (Krumholz & Dekel 2012). Here, we examine another possibility to maintain high gas fractions: infalling gas streams could themselves delay SF.

Cosmological simulations indicate that galaxies are predominantly fed by relatively diffuse gas flowing along dark matter filaments, rather than mergers (e.g. Kereš et al. 2005; Ocvirk, Pichon & Teyssier 2008; Brooks et al. 2009). If the kinetic energy from the infalling gas couples with the galactic disc, this may increase the turbulent velocity dispersion at early times (Elmegreen & Burkert 2010; Genel, Dekel & Cacciato 2012a), until grown-up galaxies at lower redshift manage to self-regulate their gas turbulence. We propose that this boosted velocity dispersion will tend to increase the physical size of the galaxy gas distribution, lowering the gas density and SF efficiency. As we will show, the overall SF efficiency can be reduced by factors of about 3 at $z \geq 3$, making it possible to maintain high gas fractions of 40–50 per cent down to $z \approx 2$–3. We study this process with an analytic model (Section 2) that combines the ‘bath-tub’ approach for galaxy evolution (Bouché et al. 2010; Davé et al. 2012; Lilly et al. 2013) with analytic descriptions of SF in turbulent gas (Elmegreen 2002; Krumholz & Tan 2007) and accounts for the external energy supply. We also simulate the hydrodynamic interaction of galaxies with infalling gas streams (Section 3) and confirm that rapid gas infall feeds only reduced and delayed SF in $z \approx 3$–6 conditions.

2 ANALYTIC MODEL

We develop an analytic model for galaxy evolution that combines three main physical elements: an estimate of self-regulated versus infall-driven gas turbulence, a SFR linked to the gas density and velocity dispersion and a standard ‘bath-tub’-like mass budget.

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(i) Self-regulated versus infall-driven gas turbulence: we use an approach similar to Elmegreen & Burkert (2010) to determine the gas velocity dispersion. Internal processes in galaxies that generate turbulence (e.g. gravitational instabilities, radial flows and SF feedback) all saturate about the limit for gravitational instability, which corresponds to a Toomre parameter $Q = 0.7$ for thick discs (Dekel, Sari & Ceverino 2009). These processes, regardless of their respective individual contribution, stir the gas disc at a minimal level $\sigma_{\mathrm{min}} = \Omega_\ast \Sigma_{\mathrm{gas}}/\sqrt{2} \nu_{\mathrm{circ}}/r$ below which the gas velocity dispersion cannot drop (in a steady state). $\Sigma_{\mathrm{gas}}$ is the gas surface density and $\Omega_\ast = \nu_{\mathrm{rot}}/r$ is the orbital frequency of the disc.

The next question is whether external gas infall alone can stir the disc above this internally determined level. Because internal processes saturate at $\sigma_{\mathrm{min}}$, a contribution from external sources lower than $\sigma_{\mathrm{min}}$ will not add turbulence – it will only decrease the relative contribution of internal sources in the $\sigma_{\mathrm{min}}$. External infall at a mass rate $\dot{M}_{\text{infall}}$ injects kinetic energy at a rate $E_{\text{turb,infall}} = A_{\text{infall}} \cdot 0.5 \dot{M}_{\text{infall}} v_{\text{infall}}^2$, where $v_{\text{infall}} = \sqrt{2} \mathcal{M}_\ast / (10 \, M_\odot \, H(z))^{1/2}$, $M_\ast$ is the halo mass and $H(z)$ is the redshift-dependent Hubble parameter (Croton et al. 2006). $A_{\text{infall}}$ specifies the coupling efficiency of infall energy to the turbulent energy of the disc. For simplicity, we assume that $A_{\text{infall}} = (\text{disk surface area})/(\text{stream cross-sectional area})$, with a maximum value of 1. We address the disc radius and thus the disc area below. We assume the typical cosmic stream radius to be $r_{\text{stream}} = 0.1$ times the virial radius of the characteristic Press–Schechter halo (cf. Dekel & Birnboim 2006). This typically gives $A_{\text{infall}} = 1$ at $z \gtrsim 2$ for the galaxies we study here, which is supported by simulations in Section 3. The other key behaviour of this coupling is that it becomes weak around $z = 2$, as required to prevent low-$z$ discs from being too thick (Genel et al. 2012a). We discuss the coupling further at the end of Section 3.1.

While infall adds turbulent energy, dissipation of that energy occurs over $\tau_{\text{diss}} \approx 3$ disc dynamical times (cf. Mac Low et al. 1998; Gammie 2001), such that $E_{\text{turb,diss}} = E_{\text{turb}}/\tau_{\text{diss}} = E_{\text{turb}} \nu_{\text{circ}}/\langle f_{\text{diss}} R_{\text{gal}} \rangle$, where $\nu_{\text{rot}}$ is the galaxy rotation velocity and $R_{\text{gal}}$ is the radius. With the equations we track the turbulent energy in the gas, $E_{\text{turb}}$, and the velocity dispersion achievable from infall $\sigma_{\text{infall}} = \sqrt{2/3} E_{\text{turb}}/M_{\text{gas}}$. Because of the previously mentioned saturation effects, we assume that the gas settles at a velocity dispersion equal to max ($\sigma_{\min}, \sigma_{\text{infall}}$).

(ii) The SFR is determined based not just on the gas density, but also on its velocity dispersion. We assume the gas takes on a log-normal density probability distribution function (PDF) typical of supersonic turbulence (e.g. Padoan, Jones & Nordlund 1997), independent of the main source of turbulence. The peak of the log-normal is determined from the average gas density of the galaxy (see below) and the width of the PDF is (ln (1 + 0.75 $(\sigma/c_\text{t})^2$))$^{1/2}$, where the sound speed $c_\text{t}$ is assumed to be $\approx 10 \, \text{km} \, \text{s}^{-1}$ for the star-forming gas (Padoan et al. 1997). We assume that gas at number densities above 100 $\text{cm}^{-3}$ forms stars at a volumetric rate of $\rho_{\ast} = \epsilon_\ast \rho/\tau_{\text{ff}} = \epsilon_\ast (32 \, G \rho^2 / (\pi c_\text{t})^2)^{1/2}$, where $\tau_{\text{ff}}$ is the free-fall time and $\epsilon_\ast = 0.01$ is the local SF efficiency per free-fall time (cf. Krumholz, Dekel & McKee 2012). Numerical integration over the density PDF and galaxy volume gives the total SFR of the galaxy.

Determining the average gas density requires an estimate of the galaxy geometry. The disc radius depends on the galaxy’s angular momentum, which is highly uncertain for high-$z$ galaxies. For simplicity and consistency with previous work, we follow Krumholz & Dekel (2012) to obtain the standard, undisturbed disc scale radius of $R_{\text{scale}} = 0.5 \lambda R_\odot$, where $\lambda$ is the halo spin parameter and $R_\odot$ is the halo virial radius. We use $\lambda = 0.07$ as a typical value (Dutton et al. 2011). This radius is increased when infalling gas increases the velocity dispersion and scatters gas to larger radii. We can estimate this effect by taking $v_{\text{circ,rot}}^2 \approx v_{\text{infall}}^2 - 3 \sigma^2$ for the rotational specific energy, then assuming angular momentum is approximately conserved with $R_{\text{scale}} v_{\text{circ}} \approx R_{\text{disturbed}} v_{\text{rotation}}$. Here, $v_{\text{circ}}$ is the circular velocity and $v_{\text{rotation}}$ is the actual rotational velocity. The disc scale radius becomes $R_{\text{disturbed}} \approx R_{\text{scale}} (1 - \sigma^2 / v_{\text{circ}}^2)$. For simplicity, we multiply this scale radius by 1.7 to obtain the total disc radius, as appropriate for exponential discs. The scaleheight of the gas disc is given by $H_c = \sigma_c / \langle \nu_{\text{circ}} \Sigma_{\text{gas}} \rangle$, where $\Sigma_{\text{gas}}$ is the total mass surface density of stars and gas in the disc. Thus, when inflowing gas streams increase $\sigma$, both the radius and scaleheight increase. The average gas density decreases because the rapidly infalling gas does not immediately settle into a thin, self-gravitating disc.

(iii) ‘Bathtub’-like mass budget: cosmological inflow acts as a gas source, while SF and galactic winds act as sinks. We take the cosmological mass inflow rate of gas into a dark matter halo of mass $M_h$ at redshift $z$ to be $\dot{M}_{\text{inflow}} = 6.6 f_h (M_h/10^{12})^{1.15} (1 + z)^{1.25}$ (Dekel et al. 2009). We assume that the cosmological fraction of baryons $f_b = 0.15$ per cent accompanies the dark matter into the halo, and for simplicity we assume that all the baryons enter as gas via cold streams (rather than mergers). Although recent simulations raise doubt that cold streams can penetrate the halo (Nelson et al. 2013), they are likely the dominant mode of galaxy fuelling in low-mass haloes at high $z$. SF (as described above) removes gas from the galaxy’s reservoir, and we assume that young stars drive galactic winds that eject gas from the galaxy at a rate equal to the SFR.

Using these equations to track the turbulent energy, SF and gas reservoir, we evolve a model galaxy over cosmic time with a simple numerical integration scheme. To make the discussion concrete, we focus on a Milky Way progenitor galaxy with an initial halo mass of $5 \times 10^{10} \, M_\odot$ at $z = 6$ and a final ($z = 0$) halo mass of $1.7 \times 10^{12} \, M_\odot$. The galaxy has an initial baryonic mass of $2.5 \times 10^9 \, M_\odot$, an initial gas fraction of 75 per cent and an initial velocity dispersion of 50 km s$^{-1}$, but the galaxy rapidly evolves towards an equilibrium independent of these choices.

2.1 Results of the infall model

Fig. 1 compares the results of our fiducial coupled-infall model with a control model, in which inflow is decoupled from the disc. In the decoupled model, the galaxy has the same mass inflow rate, but we neglect any energy coupling between inflows and the disc. At $z > 2$ in our infall model (solid blue lines), inflows are strongly coupled to the galactic disc. They deposit turbulent energy into the disc, causing a boost in the velocity dispersion (bottom panel). The boosted velocity dispersion slightly lowers the average gas density of the galaxy, thus lowering the global SF efficiency and SFR. Because the SF efficiency is suppressed, gas is allowed to accumulate in the galaxy, leading to a sustained high gas fraction (higher by a factor of $\sim 2$). The specific SFR remains almost unchanged compared to the control model because both the SFR and stellar mass are suppressed by infall.

At $z = 2$, the coupling between the infalling cold streams and galaxy disc becomes less efficient (with an abruptness owing to our simple assumptions about $A_{\text{infall}}$). This occurs when the typical filament size equals the size of the galaxy disc. When the coupling weakens, the turbulent energy in the disc decays, causing the velocity dispersion to decline (bottom panel near $z = 2$). This leads to...
Figure 1. In our simple cosmological inflow model (solid blue lines), accreting gas suppresses SF, allowing a substantial gas reservoir to remain in place to $z < 2$. We compare this fiducial model with an otherwise identical model where inflowing cold streams have no effect on the galaxy (other than to provide fuel for SF; dashed red lines). Top: the SFR is suppressed by $\sim 25$ per cent due to infalling gas at high redshifts. We also show net gas inflows to the galaxy for comparison (dotted line). Second panel: global galaxy SF efficiency, SFR/$M_{\text{gas}}$, is reduced by a factor of $\sim 3$ due to inflows. Third panel: gas fraction. By suppressing the SFR, infalling cold streams allow the gas fraction to remain high. Bottom: velocity dispersion. For the coupled-inflows model, we also show $\sigma_{\text{min}}$ (long-dashed line). Infalling cold streams increase the velocity dispersion by up to $\sim 50$ per cent compared to $\sigma_{\text{min}}$ and a factor of 3 above the control simulation (which has a lower gas fraction).

In summary, the main effect of infalling gas is to increase the velocity dispersion, ‘puff up’ the galaxy disc, lower the SFR and SF efficiency, and increase the gas fraction. These effects persist as long as the coupling between infalling gas and the galaxy disc is strong (as we have assumed). When the coupling becomes weak (at $z \approx 2$ in our model), the galaxy converges towards the solution where infalling gas is decoupled from the disc.

### 3 Simulations

To test our model, we simulate the accretion of cold gas flows by young galaxies with the adaptive mesh refinement (AMR) code RAMSES (Teyssier 2002). A key difference with existing idealized and cosmological simulations is that we ensure relatively high resolution in low-density gas, at the expense of the maximal resolution in the densest regions. We start with a coarse grid of resolution 1.0 kpc and refine each cell into eight smaller cells when its gas mass exceeds 200 $M_{\odot}$ and/or it contains more than 240 particles (of stars and/or dark matter). The maximal resolution of 32 pc is ensured as soon as the gas number density exceeds 0.2 cm$^{-3}$ (with 64 pc resolution at 0.025 cm$^{-3}$). We allow cooling down to $10^{5}$ K and enforce a pressure floor to keep the Jeans length resolved by at least four cells.

Old stars, new stars and dark matter are modelled with particles of $2 \times 10^{4}$, 800 and $8 \times 10^{9}$ $M_{\odot}$, respectively. SF occurs in gas denser than 1 cm$^{-3}$, with an efficiency of 0.01 per local gravitational free-fall time (cf. Zuckerman & Evans 1974). The low density threshold ensures that variations in the SFR are not caused by artefacts near the highest resolvable densities, although in practice most of the SFR is obtained from gas at and above 100 cm$^{-3}$. We include stellar feedback – photoionization and radiation pressure, using the Renaud et al. (2013) model with a trapping parameter $\kappa = 5$ – and supernovae feedback: 10 Myr after its birth, a star particle dumps thermal energy in the nearest gas cell, at a rate of $10^{51}$ erg for each 10$M_{\odot}$ of progenitor mass. We account for non-thermal processes in supernova remnants by decreasing the gas cooling rate in the affected cells, as proposed by Teyssier et al. (2013). This can also be seen as a way to prevent overcooling of the thermal phases in supernovae remnants (cf. Stinson et al. 2006).

We use two galaxy models, roughly representative of progenitors of Milky Way-mass galaxies at redshifts $z \approx 5$ and $z \approx 1–2$. They start with a stellar mass of $1.3 \times 10^{7}$ $M_{\odot}$ for $z \approx 5$ (respectively, $8.0 \times 10^{10}$ $M_{\odot}$ for $z \approx 1–2$) and a gas fraction of 75 per cent (respectively, 50 per cent). The disc scalelength is 1.8 kpc (respectively, 4 kpc), and a bulge of radius 240 pc (respectively, 500 pc) contains 15 per cent of the stellar mass. Dark matter haloes with Navarro, Frenk & White (1996) profiles are used with concentration parameters set to 7.0. A hot ($>10^{6}$ K) atmosphere is included with a homogeneous density (a few $\times 10^{-3}$ cm$^{-3}$) such that the mass comprised in the dark halo virial radius is 37 percent of the disc mass.

Each galaxy is modelled with and without accreting cosmological streams. The inflow rate is 15 $M_{\odot}$ yr$^{-1}$ for the $z \approx 5$ case and 80 $M_{\odot}$ yr$^{-1}$ for the $z \approx 1–2$ case – for the lower mass, higher redshift progenitor, this corresponds to a 12 times higher specific inflow rate at $z \approx 5$, as expected from theory (cf. Section 2). The inflow gas is introduced in three streams. The streams originate at a distance from the galaxy centre equal to 1.2 times the virial radius of the dark matter halo. They have a circular cross-section with an azimuthal profile as follows: a central density set by the required inflow rate, an exponential decay with a scalelength equal to the galaxy disc radius and a truncation at 2.5 times this scale-length. In the disc frame, the streams are set to cross the virial radius at latitudes of $(+35^\circ, -45^\circ$ and $+65^\circ$, respectively, and longitudes of $(90^\circ, +90^\circ$ and $+180^\circ$, respectively. They contain, respectively, 45, 35 and 20 per cent of the mass inflow rate, have impact parameters of 1.5, 2.0 and 1.5 disc scalelengths with prograde
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3.1 Simulation results

We simulate each galaxy for \( \approx 2 \) rotation periods (300 + Myr). Fig. 2 shows edge-on gas maps of the two low-mass \( z \sim 5 \) galaxies at \( t = 107 \) Myr. The cold inflows puff up the disc, leaving the galaxy with fewer regions at the highest densities. Inflows increase the effective scaleheight from 325 to 612 pc and the half-mass radius from 2.12 to 2.86 kpc. We measure mass-weighted gas velocity dispersions and SFR within 5 kpc of the galaxy centre, along with radial profiles of gas surface density and an estimate of the Toomre \( Q \) parameter (assuming the gas and stellar velocity dispersions are equal). The velocity dispersion in the inflows simulation is higher by a factor of \( \sim 2 \), leading to a thicker disc and an SF efficiency lower by a factor of \( \sim 2-3 \). The figure also shows the (volume) density PDFs of the two simulations, illustrating that cold inflows can reduce the amount of gas at high, star-forming densities above \( 100 \) cm\(^{-3} \). The lower-right panels show that the central gas surface density, \( \Sigma_{\text{gas}} \), is actually decreased due to inflows. Rather than merely adding gas to the galaxy, the inflows contribute energy that stabilizes the disc at all radii, as indicated by the boosted Toomre \( Q \) parameter.

Thus, abundant, filamentary cold gas inflows can disturb small galaxies at \( z \sim 5 \), boosting the velocity dispersion and effectively lowering the SFR. For more massive galaxies at lower redshifts, the cold streams do not affect the gas disc as strongly as demonstrated by our \( z \sim 2 \) simulations. In these simulations, the velocity dispersion is barely changed (53 km s\(^{-1} \) with inflows versus 47 km s\(^{-1} \) without) and the SF efficiency remains within \( \sim 20 \) per cent, as shown in Fig. 3. This agrees qualitatively with the ‘high-redshift’ simulations of Hopkins, Kereš & Murray (2013), which are broadly representative of massive \( z \sim 2 \) galaxies. We speculate that the \( \sim 10 \times \) higher specific inflow rate \( (M_{\text{inflow}}/M_{\text{gas}}) \) in our low-mass \( z \sim 5 \) galaxies leads to a stronger coupling between infalling gas and the disc. Cosmological simulations – even zoom-ins – generally lack the resolution in the low-density circumgalactic gas to model this effect accurately (although they do show a messy, rapidly varying connection region between filaments and the galaxy, e.g. Danovich et al. 2012; Dubois et al. 2012).

These simulations imply that energy from infalling streams can, at least under some circumstances, couple strongly to the galactic disc. In our analytic model (Section 2), we posit that the coupling
(A_{\text{infall}}) is strong at z > 2 and then weakens as the streams become larger than the galaxy. Our simulations, though limited in the scope of parameter space, suggest instead a dependence of the coupling on halo mass or specific accretion rate. This dependence also leads to reduced SF efficiency at high z followed by a transition to normal efficiency at lower z. Another possibility is that cold streams are disrupted before they fully penetrate the halo (Nelson et al. 2013) – while such disruption precludes interaction with the disc, it could effectively delay SF by prolonging the time spent in the circumgalactic reservoir. In our simulations, the streams penetrate an idealized hot atmosphere without disruption, but cosmological simulations with high resolution in a more realistic circumgalactic gas distribution may be needed to confirm this result. Although some physical details remain in question, our model and simulations support a scenario where infalling cold streams delay SF in low-mass galaxies at high z, but have little effect on their more massive descendants at z ≲ 2.

4 CONCLUSION

Our simple model of cold gas inflows into high-redshift galaxies shows that if the coupling between inflows and the gas disc is strong, then inflows can lower the SF efficiencies by factors of 3 and keep gas fractions above 40 per cent until z < 2. While previous models suggest that the coupling between inflows and the disk is fairly weak (e.g. Klessen & Hennebelle 2010; Hopkins et al. 2013), our simulations with inflows show that this coupling can be strong if enough gas is inflowing. When the coupling is strong, cold flows do not settle into a self-regulated disc, but rather stir up the disc and suppress SF. Our work implies that in the high-z Universe where galaxies are small and inflow rates are large, the energetic injection of cold inflows has an important impact on galaxy evolution.

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