Can galaxy outflows and re-accretion produce a downsizing in the specific star-formation rate of late-type galaxies?

C. Firmani,1,2⋆ V. Avila-Reese2⋆ and A. Rodríguez-Puebla2

1Osservatorio Astronomico di Brera, via E. Bianchi 46, I-23807 Merate, Italy
2Instituto de Astronomía, Universidad Nacional Autónoma de México, AP 70-264, 04510 México DF

Accepted 2010 January 15. Received 2010 January 15; in original form 2009 September 25

ABSTRACT

An increasing amount of recent observational evidence shows that the less massive galaxies are, the higher on average their specific star-formation rates (SSFR = SFR/M∗, where M∗ is the stellar mass). Such a trend, called the ‘SSFR downsizing’ (SSFR–DS) phenomenon, is seen for local and high-redshift (back to z ∼ 1–2) galaxy samples. We use observational data related only to disc galaxies and explore how the average SSFR changes with z for different masses. For all masses in the range ∼ 109.5–1010.5 M⊙, the SSFR increases with (1 + z) to a power that seems not to depend on M∗, and at all redshifts smaller galaxies always have higher SSFRs; galaxies less massive than M∗ ∼ 1010 M⊙ are now forming stars at a greater rate than in the past, assuming constant SFRs over a Hubble time to build stellar mass. We show that these features strongly disagree with the Λ Cold Dark Matter (ΛCDM) halo hierarchical mass accretion rates. Further, by means of self-consistent models of disc galaxy evolution inside growing ΛCDM haloes, the effects of disc-feedback-driven outflows and gas re-accretion on galaxy SSFR histories are explored. The parameters of the outflow and re-accretion schemes are tuned to reproduce the present-day Mh–M∗ relation (where Mh is the halo mass) inferred from the observationally based M∗ function of disc galaxies. In the case of outflows only, the SSFR of individual model galaxies increases with z roughly as (1 + z)2.2 for all masses (somewhat shallower than observations) with a normalization factor that depends on mass as M0.1, i.e more massive galaxies have slightly larger SSFRs, contrary to the observed strong SSFR–DS trend. For the re-accretion cases, the dependence on z remains approximately the same as without gas re-infall, but the correlation with mass increases even for the most reasonable values of the model parameters. The comparison of models and observations in the SSFR–M∗ plane at z ∼ 0 (where the data are more reliable) clearly shows the divergent trend in SSFR when the masses are lower (upsizing versus downsizing). We explain why our models show the reported trends, and conclude that the SSFR–DS phenomenon for low-mass galaxies poses a sharp challenge for ΛCDM-based disc galaxy evolution models.

Key words: galaxies: evolution – galaxies: haloes – galaxies: high-redshift – galaxies: spiral – galaxies: stellar content – cosmology: theory.

1 INTRODUCTION

Inferring the history of assembly of stellar populations in galaxies as a function of their morphological type and luminosity (mass) is a major topic of present-day extragalactic astronomy, as well as a key probe for cosmologically based models of galaxy formation and evolution.

Based on chemical and spectrophotometric studies of local galaxies, it has long been known that more massive/earlier-type galaxies hold on average older stellar populations and were formed over a shorter time-span than less massive/later-type galaxies (e.g. Faber, Worthey & Gonzalez 1992; Worthey, Faber & Gonzalez 1992; Carollo, Danziger & Buson 1993; Bell & de Jong 2000). With the advent of large and complete surveys of local galaxies and a significant improvement in population synthesis models, the average ages and even the entire star-formation rate (SFR) histories of all kinds of galaxies have been inferred (e.g. Kauffmann et al. 2003; Heavens et al. 2004; Jimenez et al. 2005; Gallazzi et al. 2005, 2008; Cid Fernandez et al. 2005; Panter et al. 2007). The general conclusion of works on the subject confirms and extends the previous results: more massive galaxies assembled their stars at earlier epochs

⋆E-mail: firmani@merate.mi.astro.it (CF); avila@astro.unam.mx (VA-R)
and on shorter time-scales, halting their star formation (SF) at later epochs. This phenomenon has been now dubbed as ‘archaeological downsizing’ (Thomas et al. 2005; Fontanot et al. 2009).

In the last decade, the observational capabilities have allowed the extension of galaxy population studies to high redshifts. With these ‘look-back studies’, the current properties of galaxies at their observed times, as well as their past histories, were inferred. In a pioneering work, Cowie et al. (1996) have found that the maximum rest-frame K-band luminosity of actively star-forming galaxies has declined with time in the redshift range $z = 1.7-0.2$, i.e. the SF efficiency shifts to lower mass galaxies with time. This phenomenon has been confirmed by subsequent works based on wider surveys with multiwavelength information (Feulner et al. 2005; Juneau et al. 2005; Bell et al. 2007; Noeske et al. 2007a,b; Zheng et al. 2007; Cowie & Barger 2008; Chen et al. 2009; Damen et al. 2009; Mobasher et al. 2009; see Fontanot et al. 2009 for more references). These works have allowed specific SF rates (SSFR = SFR/$M_\star$, $M_\star$ is the galaxy stellar mass) to be inferred for relatively complete samples of galaxies at different redshifts up to $z \sim 1-2$. The general result is that the measured SSFRs tend to be higher as $M_\star$ is smaller, a phenomenon called ‘SSFR downsizing’, this trend being observed at all the redshifts studied. Recent look-back studies of galaxy luminosity functions have also confirmed the local inferences of archaeological downsizing mentioned above: the high-mass end of the galaxy mass function seems to be mostly in place since $z \sim 2$, while the abundances of galaxies of smaller stellar masses grow gradually with time (Daddi et al. 2004, 2007; Bundy et al. 2004, 2006; Drory et al. 2005; Conselice et al. 2007; Marchesini et al. 2009; Pérez-González et al. 2008 and more references therein).

The emerging observational picture of downsizing in stellar-mass galaxy assembly has been confronted with the hierarchical clustering scenario of galaxy formation and evolution, based on the Λ Cold Dark Matter ($Λ$CDM) cosmological model. At this point, as shown in Neistein et al. (2006; see also Fontanot et al. 2009), it is important to realize that the downsizing effect to which observations refer generically actually has many manifestations related to different phenomena, involving different types of galaxies and different epochs in their histories. Herein we emphasize the two distinct downsizing phenomena mentioned above:

(i) the ‘archaeological downsizing’ related to the early ($z \gtrsim 2$) assembly of most stars in massive/early-type galaxies;

(ii) the ‘SSFR downsizing’ (hereafter SSFR–DS) related to later growth of the relative stellar mass as galaxies become less massive.

Archaeological downsizing has a partial explanation in the frame of the hierarchical clustering process of dark-matter haloes (Mouri & Taniguchi 2005; Neistein, van den Bosch & Dekel 2006; Guo & White 2008; Kereš et al. 2009), and astrophysical processes like feedback from active galactic nuclei (AGNs) have also been introduced to obtain better agreement with observations (e.g. Bower et al. 2006; Cattaneo et al. 2006; Croton et al. 2006; Monaco, Fontanot & Taffoni 2007; Hopkins et al. 2008; Somerville et al. 2008 and more references therein).

Regarding the SSFR–DS, which is the focus of this work, if confirmed it will become a pervasive problem for current models. This problem regards mainly the high SSFRs of low-mass ($M_\star \sim 10^{9-3} \times 10^{10} M_\odot$) star-forming disc galaxies. For these galaxies AGN feedback is not expected to be important, because either they do not have AGNs (e.g. Kauffmann et al. 2003; Salim et al. 2007) or the AGNs are too weak to produce significant feedback (e.g. Bower et al. 2006; Croton et al. 2006). By using semi-analytical models (SAMs), several authors have found systematically that the SF in modelled low-mass galaxies happens too early and is overquenched at later times, showing that these galaxies have SSFRs that are too low at low redshifts compared with observational inferences (see Somerville et al. 2008 and Fontanot et al. 2009 for recent results and more references). The problem is sharpened by the fact that, in the SAMs, the baryon mass fraction of low-mass galaxies has to be decreased systematically in order to reproduce the low-luminosity end of the luminosity function (e.g. Benson et al. 2003). This is accomplished by introducing appropriately tuned schemes of very strong stellar ejective feedback as a function of mass, which worsens the SSFR–DS problem (see Section 4). Late re-infall of the ejected gas (Bertone, De Lucia & Thomas 2007; Oppenheimer & Davé 2008) could offer a partial cure to this problem.

In this work we aim to ‘isolate’ the SSFR–DS problem for low-mass disc galaxies and explore in transparent way the effects of ejective stellar feedback and gas re-accretion on the SSFR histories of galaxies by means of evolutionary hydrodynamical models of disc galaxies formed inside growing CDM haloes. We will show that a solution to the SSFR–DS problem is not simple in the context of the hierarchical $Λ$CDM scenario.

In Section 2, the observational data to be used in this paper are presented and discussed. Preliminary theoretical predictions regarding the SSFR histories of galaxies as a function of mass are presented in Section 3. A brief review of our galaxy disc evolutionary models and the parametric schemes introduced for modelling ejective feedback and gas re-infall are given in Section 4. The model results and their comparison with observations are presented in Section 5. Finally, a summary of the results and a discussion are presented in Section 6.

The cosmological model used throughout this paper is the concordance one with $h = 0.7$, $Ω_Λ = 0.7$, $Ω_m = 0.3$, $Ω_b = 0.042$ and $σ_8 = 0.8$.

2 THE OBSERVATIONS

Our aim is to target the potential problem of SSFR–DS, and then compare observations with detailed theoretical predictions. We focus our study here only on normal (not dwarf) low-mass disc galaxies ($10^{9.5} \lesssim M_\star \lesssim 10^{10.5} M_\odot$). On the one hand, due to completeness issues dwarf galaxies are not taken into account in the $z \sim 0$ and high-redshift observational samples that are used here. On the other hand, since most dwarf galaxies are satellites in bigger systems, their physics is affected by several environmental processes (ram pressure, tidal stripping, interactions, etc.) that are not considered in our models.

In order to determine the SSFR–$M_\star$ relation at different redshifts, extensive multiwavelength photometric and spectroscopic samples are necessary. The stellar masses and SFRs of galaxies are commonly inferred by using techniques of fitting to stellar population synthesis (SPS) models; the SFRs of galaxies can also be inferred by using emission lines that trace SF when available. The uncertainties associated with these methods are large due to selection effects, sample incompleteness and the methods used to infer $M_\star$ and SFR (see Section 6.1 for a discussion). For our work, we require samples where late-type galaxies are separated from early-type ones. This is the case of the observational works by Salim et al. (2007; $z \sim 0$) and Bell et al. (2007; high redshifts).

Bell et al. (2007; see also Zheng et al. 2007; Damen et al. 2009) analyse the COMBO-17 photometric redshift survey combined with Spitzer 24-μm data ($0.2 < z \lesssim 1.0$). Stellar masses were estimated using 17 passbands in conjunction with a non-evolving template
library derived from the Pégase SPS model, and SFRs were determined from the combined UV and IR fluxes of galaxies. In Fig. 1, we reproduce the averaged data presented in their fig. 3 (SSFR versus $M_*$), where four redshift bins centred on $z \sim 0.9, 0.7, 0.5$ and 0.3 are given. We reproduce the data associated only with the blue cloud (late-type) galaxies and for four masses $[\log (M_*/M_\odot) = 9.5, 10.0, 10.5$ and 11.0 from top to bottom, respectively]$. Their data are separated according to two COMBO-17 fields observed by Spitzer: the extended Chandra Deep Field South (CDFS) and the field around the Abell 901/902 (A901) galaxy cluster (upper and lower curves in Fig. 1, respectively). Note that the SFRs from CDFS are systematically higher than those around the denser field and lower curves in Fig. 1, respectively. Note that the SSFRs from the field around the Abell 901/902 (A901) galaxy cluster (upper curves) are systematically higher than those around the denser field and lower curves in Fig. 1, respectively. Note that the SSFRs from the field around the Abell 901/902 (A901) galaxy cluster (upper curves) are systematically higher than those around the denser field and lower curves in Fig. 1, respectively. Notice that each of the pairs of curves inferred from observations for $z \geq 0.3$ in Fig. 1 refers to a given $M_*$, that is the same at each redshift, i.e. these curves do not refer to the evolution of individual galaxies (evolutionary tracks) but to galaxy populations at different epochs. We have carried out an exercise for recovering approximate galaxy evolutionary tracks from the observational data shown in the diagram of Fig. 1. We assume that a galaxy of mass $M_*$ at redshift $z$ increases its mass during the time interval $dt/dz$ by forming stars at a rate $\dot{M}_*= (1-R)\text{SSFR}(M_*,z)M_*(z)$, where SSFR is given by equation (1) and $R = 0.4$ takes into account the gas return due to stellar mass loss. In this way, we are able to calculate $\dot{M}_*/M_*$ at each $z$ for an ‘average’ galaxy evolutionary track that ends at $z \sim 0$ with a given $M_*$. The dot–dashed line shows the average evolutionary track for a present-day galaxy stellar mass curve of $10^{10.5} M_\odot$. The evolutionary tracks over the range of the data shown are roughly parallel and at $z \sim 0$ they intercept the SSFR axis at the level of the corresponding masses. As seen in Fig. 1, an evolutionary track inferred in this way is only slightly steeper than the observed constant-mass curves.

3 PRELIMINARY THEORETICAL PREDICTIONS

From a theoretical point of view, in order to estimate the level of SF activity of galaxies as a function of their masses and epochs, let us consider first the case of a constant SFR history. Then, $\dot{M}_*$ at the cosmic time $t_H(z)$ should be given by $\dot{M}_* \sim \text{SSFR} \times (1-R) \times [1/(1+z)] - 1 \text{Gyr}$; 1 Gyr is subtracted in order to take into account the (average) delay in the formation of haloes that host galaxies. If the measured SSFR at $z=0$ is smaller (larger) than $1/[t_H(z) - 1 \text{Gyr}](1-R)$, then the average SFR of the given galaxy has been higher (lower) in the past than at the current epoch. In Fig. 1 the curve $1/[t_H(z) - 1 \text{Gyr}](1-R)$ for the cosmology used here and for $R = 0.4$ is plotted (thin solid line). The constant-SFR case is only indicative of the situation: low-mass galaxies ($M_* \lesssim 10^{10} M_\odot$) show current SFRs higher than their past average SFR here. Now, within the context of the $\Lambda$CDM cosmogony, one may anticipate a potential disagreement with observations related to the SSFR–DS phenomenon. By using an extended Press–Schechter approach (Avila-Reese, Firmani & Hernández 1998; Firmani & Avila-Reese 2000, hereafter FA2000; see Section 4), we calculate for a given present-day $M_*$ its averaged mass aggregation history (MAH), $M_H(z)$, from tens of thousands of Monte Carlo extractions.

Figure 1. Evolution of the SSFR of late-type galaxies for different fixed values of $M_*$. The data at $z \sim 0$ (squared dots) are from Salim et al. (2007). The solid curves were inferred from Bell et al. (2007) for their two fields, CDFS and A901 (corresponding upper and lower curves, respectively; see text). From top to bottom, the data correspond to mass bins centred at $\log (M_*/M_\odot) = 9.5$ (cyan), 10.0 (blue), 10.5 (green) and 11.0 (red), respectively. The thin dot–long-dashed green line is our estimate from the data for the individual evolution of an average galaxy that ends at $z = 0$ with $M_*= 10^{10.5} M_\odot$ (see text). The solid black line shows the curve $1/[t_H(z) - 1 \text{Gyr}](1-R)$ corresponding to constant SFR with time. The dashed curves are ‘dark-matter halo’ SSFR histories calculated as $M_*/[M_\odot(1-R)]$ (see text); from top to bottom the corresponding masses are $M_*= 10^{12.8} M_\odot$ (red), $M_*= 10^{12.1} M_\odot$ (green), $M_*= 10^{11.7} M_\odot$ (blue) and $M_*= 10^{11.4} M_\odot$ (cyan). The corresponding stellar masses are roughly the same as those of the data. The cosmological specific infall rates drive SSFRs that are slightly higher for massive galaxies and significantly lower for low-mass galaxies than observational inferences.

The data in Fig. 1 corresponding to $z \sim 0$ were taken from Salim et al. (2007), who obtained $M_*$ and dust-corrected SFRs for $\approx 50,000$ galaxies by fitting the SDSS and GALEX photometry to a library of dust-attenuated SPS models. They were able to separate from their sample the ‘pure’ star-forming galaxies with no AGN, which form a well-defined linear sequence in the SSFR versus $M_*$ plot, fitted linearly by $\log \text{SSFR} = -0.35(\log M_* - 10) - 9.83$. In Fig. 1 the same four masses related to the data from Bell et al. (2007) are used for the Salim et al. (2007) results at $z \sim 0$.

From Fig. 1 we see that the SSFR of what can roughly be considered late-type galaxies declines from $z \sim 1$ to $z \sim 0$ almost with the same slope for all masses. However, the normalization strongly depends on $M_*$, the SSFRs at all redshifts being on average higher when $M_*$ is lower. This shows the SSFR–DS behaviour. A crude approximation to the range of the data displayed in Fig. 1 is

$$\text{SSFR} = 0.13 M_*^{0.33} (1+z)^2 \text{Gyr}^{-1}. \quad (1)$$

where $M_{*,10}$ is $M_*$ in units of $10^{10} M_\odot$. Recently, for all (late- and early-type) galaxies and back to $z \approx 2.8$, Damen et al. (2009) have reported a trend of SSFR with redshift that does not strongly depend on $M_*$, this trend being roughly proportional to $(1+z)^6$ (see also Feulner et al. 2005; Martin et al. 2007; Zheng et al. 2007; Pérez-González et al. 2008). There is some evidence that the SSFRs of massive galaxies start to increase significantly and overcome the SSFRs of less massive galaxies only at redshifts larger than 2 (Pérez-González et al. 2008).

3 PRELIMINARY THEORETICAL PREDICTIONS

From a theoretical point of view, in order to estimate the level of SF activity of galaxies as a function of their masses and epochs, let us consider first the case of a constant SFR history. Then, $\dot{M}_*$ at the cosmic time $t_H(z)$ should be given by $\dot{M}_* \sim \text{SSFR} \times (1-R) \times [1/(1+z)] - 1 \text{Gyr}$; 1 Gyr is subtracted in order to take into account the (average) delay in the formation of haloes that host galaxies. If the measured SSFR at $z = 0$ is smaller (larger) than $1/[t_H(z) - 1 \text{Gyr}](1-R)$, then the average SFR of the given galaxy has been higher (lower) in the past than at the current epoch. In Fig. 1 the curve $1/[t_H(z) - 1 \text{Gyr}](1-R)$ for the cosmology used here and for $R = 0.4$ is plotted (thin solid line). The constant-SFR case is only indicative of the situation: low-mass galaxies ($M_* \lesssim 10^{10} M_\odot$) show current SFRs higher than their past average SFR here. Now, within the context of the $\Lambda$CDM cosmogony, one may anticipate a potential disagreement with observations related to the SSFR–DS phenomenon. By using an extended Press–Schechter approach (Avila-Reese, Firmani & Hernández 1998; Firmani & Avila-Reese 2000, hereafter FA2000; see Section 4), we calculate for a given present-day $M_*$ its averaged mass aggregation history (MAH), $M_H(z)$, from tens of thousands of Monte Carlo extractions.
By assuming that the SSFR is driven by the halo-specific mass aggregation rate, \((M_b/M_h)\), and correcting by the gas return factor \((1 - R)\), we have calculated the ‘dark matter’-driven SSFR histories for different halo masses. In Fig. 1 the dashed lines show, from top to bottom, the SSFR histories for halo masses from \(M_h = 10^{12} M_\odot\) (red) to \(M_h = 10^{14.2} M_\odot\) (cyan), which correspond roughly to stellar masses from \(M_* = 10^{11} M_\odot\) to \(M_* = 10^{13.5} M_\odot\), respectively (see Section 4.1 and Fig. 2). A good interpolating formula to our results since \(z \sim 1\) is

\[
SSFR \approx \frac{1}{(1 - R)} \frac{M_h}{M_*} = 10^{-1.5} \frac{M_h}{M_*} (1 + z)^{2.5} \text{Gyr}^{-1},
\]

where \(M_{*,12}\) is \(M_*\) in units of \(10^{12} M_\odot\).

From this very preliminary calculation, we conclude that while the dark matter-driven SSFR histories of massive galaxies do not show a significant discrepancy with observations, for low-mass galaxies \((M_* \lesssim 10^{10.5} M_\odot)\) the discrepancy becomes significant and it increases as the mass becomes smaller. The predicted SSFRs of low-mass galaxies are lower than the observed ones beyond the uncertainty level. A first guess to solve such a conflict within the context of the hierarchical cosmology is to propose that the main stellar formation epoch of low-mass galaxies is delayed by some astrophysical processes to lower redshifts. Can gas outflows and later re-accretion work in this direction? In the following, we turn to self-consistent models of disc galaxy formation and evolution to explore this question.

4 THE MODEL

The formation and evolution of disc galaxies within growing dark matter haloes can be followed in a transparent and self-consistent way by using simplified hydrodynamic models of discs in centrifugal and vertical hydrostatic equilibrium, and with a SF mechanism triggered by a disc instability criterion and self-regulated by an energy balance process (the semi-numerical approach: FA2000; Avila-Reese & Firmani 2000; see van den Bosch 2000; Naab & Ostriker 2006; Stringer & Benson 2007; Dutton & van den Bosch 2009, hereafter DvdB09, for similar approaches).

The main physical ingredients of the models used here are as follows. A special extended Press–Schechter approach based on the conditional probability (Lacey & Cole 1993) is used to generate the halo mass accretion histories (MAHs) from the primordial Gaussian density fluctuation field. A generalized secondary infall model with elliptical orbits is applied to calculate the time-by-time virialization of the accreting mass shells (Avila-Reese et al. 1998). The orbit ellipticity parameter is fixed in such a way that the structure of the \(\Lambda\)CDM haloes agrees with results from cosmological N-body simulations (Avila-Reese et al. 1999; FA2000). A (baryon) fraction of the mass of each accreting shell is assumed to cool down in a dynamical time and form a disc layer.\(^1\) We denote by ‘primary’ cosmological gas accretion that related to these accreting mass shells with a universal baryon fraction \(f_{b,uni} = \Omega_B/\Omega_M = 0.163\) for the cosmology adopted here. The final galaxy baryon fraction, \(f_{b,gal} = M_{gal}/M_h\), is determined by further disc gas-ejecting and infalling processes.

\(^1\)For halo masses lower than \(\sim 5 \times 10^{11} M_\odot\), the radiative cooling time is always shorter than the Hubble time, \(\eta_H\). Therefore, this assumption works well for haloes of this mass and smaller. For larger masses, the cooling time becomes larger than \(\eta_H\). Then, the mass baryon fraction available to form the galaxy decreases systematically with mass.

Figure 2. (a) Semi-empirical and modelled stellar versus halo masses. The former are inferred by different authors by matching a given observed luminosity \((M_\star)\) function with the theoretical halo mass function for all galaxies and haloes (non-continuous curves), for only late-type galaxies and haloes that likely host late-type galaxies (continuous red curve for the average, and dotted curves encompassing the dotted horizontal lines for the 1σ uncertainty), and from direct weak gravitational lensing studies (cyan solid squares with vertical error bars). The corresponding literature sources are indicated inside the figure. For the model predictions (thick dot-dashed curves), the disc outflow cases for \(n = 1, 2\) and 5 (respectively in a clockwise sense) are shown. The models are forced to agree with the continuous red line at \(10^{10.2} M_\odot\) by tuning the free parameter \(c\) in equation (3); see Table 1 for values. The \(n = 2\) ‘energy-driven’ outflow case best reproduces the observational inferences. (b) Same as (a) but for models that include gas re-accretion. Only cases with \(n = 1\) and \(M_{reac} = \text{constant} (c = 0, \text{see equation 5})\) are plotted. For larger values of \(n\), the re-accretion produces slopes that are too shallow in the \(M_h-M_\star\) relation. The three cases plotted with thick solid, dashed and dot-dashed lines correspond to values for the \((\log m, a)\) parameters of \((10.0, 1.0), (10.5, 1.0)\) and \((10.0, 0.5)\), respectively (see Table 1).

The accreting mass shells at the time of their virialization, \(t_v\), are assumed to rotate rigidly with a specific angular momentum calculated as \(J_{rot} = \Delta M_h \lambda_h\), where \(\Delta\) represents a difference between two time-steps and \(J_{rot} = \lambda_h G M_h^{3/2}/|E_h|^{1/2}\), \(M_h\) and \(E_h\) are the halo total angular momentum, mass and energy respectively; \(\lambda_h\) is the halo spin parameter, assumed to be constant in time. As a result of the assembling of these mass shells, a present-day halo.
ends with an angular momentum distribution close to the (universal) distribution measured in \( N \)-body simulations (Bullock et al. 2001). The radial mass distribution of the layer is calculated by equating its specific angular momentum with that of its final circular orbit in centrifugal equilibrium (detailed angular momentum conservation). The superposition of these layers forms a gaseous disc, which tends to be steeper in the centre and flatter at the periphery than the exponential law. The gravitational interaction of disc and inner halo during their assembly is calculated using the adiabatic invariance formalism.

A further step is the calculation of the stellar surface density profile. The previously mentioned processes and the fact that SF is less efficient at the periphery than in the centre produce stellar discs with a nearly exponential surface density distribution, and size determined mainly by \( \lambda_h \). The disc SF at a given radius (assuming azimuthal symmetry) is triggered by the Toomre gas gravitational instability criterion and self-regulated by a balance between the energy input due to supernovae (SNe) and turbulent energy dissipation in the interstellar medium (ISM). Both ingredients determine the gas disc height and the SF rate. This physical prescription naturally yields a Schmidt–Kennicutt-like law. The SF efficiency depends on the gas surface density, determined mainly by \( \lambda_h \) and on the gas infall history, which in its primary phase is proportional to the halo MAH.

### 4.1 Feedback-driven outflows

In our previous work, we did not take into account disc mass outflows (galactic superwinds) due to SN and radiation pressure feedback. Therefore, the driving factor for disc growth was solely the gas infall rate, assumed proportional to the halo mass aggregation rate where the proportionality coefficient is the galaxy baryon mass fraction, \( f_{b, \text{gal}} \). This fraction was fixed to a constant value smaller than the universal baryon fraction, \( f_{b, \text{Univ}} \), by a factor \( \sim 4 \). With this simple assumption, nearly flat rotation curves at the present and at higher redshifts and good agreement with observed disc-scaling relations were obtained (e.g. FA00; Avila-Reese et al. 2008; Firmani & Avila-Reese 2009).

Here we introduce an algorithm for outflows from the disc similar to those used in the SAMs but applied locally to the evolving disc–halo system as a function of the radius (DvdB09). The outflow is assumed to move at the local escape velocity of the disc–halo system, \( V_{\text{esc}}(r) \). Therefore the efficiency of mass ejection depends on mass. For haloes less massive than \( \sim 10^{12} \, M_\odot \), the outflows were found to be able to reduce the initial universal baryon fraction by \( \sim 1 \) and greater as the mass decreases (cf. van den Bosch 2002; Benson et al. 2003; DvdB09). The mass ejected per unit of area and time from disc radius \( r \) is given by

\[
\Sigma_{\text{efg}}(r) = \Sigma_{\text{SFR}}(r) \epsilon \left( \frac{1000 \, \text{km s}^{-1}}{V_{\text{esc}}(r)} \right)^n,
\]

where \( \Sigma_{\text{SFR}} \) is the SFR surface density and \( \epsilon \) is a free parameter. In the literature, values for \( n \) from \( 1 \) to \( 5 \) were commonly used in order to reproduce the low-mass luminosity function. The values \( n = 2 \) and \( 1 \) are expected for ‘energy-driven’ and ‘momentum-driven’ outflows, respectively. For the former case, assuming that each SN produces an energy \( E_{\text{SN}} = 10^{51} \) erg, and that the the number of SNe per solar mass of stars formed is \( \eta_{\text{SN}} = 0.009 \, M_\odot^{-1} \), one obtains namely the value of \( \sim 1000 \, \text{km s}^{-1} \) reported in equation (3) and the parameter \( \epsilon \) can be interpreted as the fraction of SN kinetic energy transferred into the outflow. For the latter case \( (n = 1) \), by assuming that each SN produces a momentum \( p_{\text{SN}} = 3 \times 10^4 \, M_\odot \, \text{km s}^{-1} \) and using the same value of \( \eta_{\text{SN}} \) as above, the normalization velocity in equation (3) should be \( \sim 300 \, \text{km s}^{-1} \). By keeping \( 1000 \, \text{km s}^{-1} \) in equation (3), the outflow momentum is already 3.3 times the momentum produced by one SN; this should still be multiplied by our \( \epsilon \). However, we should point out that the ‘momentum-driven’ case is thought to show the effect of massive stars rather than SN contributions (e.g. Murray, Quataert & Thompson 2005; Oppenheimer & Davé 2008; Grimes et al. 2009); the total momentum (energy) injected by massive stars during their life is much higher than that injected by SNe.

Because the outflow rate is proportional to the SFR (equation 3), the outflows are more efficient in removing gas at earlier epochs, when the SFR is higher. The early accreted gas has lower angular momentum than the later accreted gas. Thus, as the result of disc gas ejection by outflows, the spin parameter \( \lambda \) of the final disc becomes larger than the spin in the case of no outflows, which, by assumption, is equal to the halo spin parameter (see also DvdB09).

The study of the galaxy-size outflow physics is a complicated hydrodynamic and radiation transfer problem, and it requires a very large dynamical range, from pc to mpc scales (e.g. Dalla Vecchia & Schaye 2008; Oppenheimer & Davé 2008 and more references therein). The model described above is certainly an oversimplification, which overestimates the feedback efficiency (see DvdB09 for a discussion). In most of the previous works it was assumed that the ejected gas is lost forever by the galaxy–halo system and the proportionality coefficient and exponent in equation (3) were varied in order to reproduce the low-luminosity side of the observed luminosity function as well as galaxy scaling laws like the Tully–Fisher relation (cf. Benson et al. 2003; DvdB09). Feedback-driven outflows also seem to be necessary to explain the steep mass–metallicity relation of galaxies at redshifts \( z \sim 1–2 \) and the observed metallicities of the intergalactic medium (IGM) at high redshifts (Aguirre et al. 2001; Oppenheimer & Davé 2006; Finlator & Davé 2008; DvdB09).

The full modelling of feedback-driven outflows is beyond the scope of this paper. Instead, we aim to explore in a semi-empirical way the effects of different kinds and levels of feedback on the SFR history of disc galaxies as a function of mass. The exploration is semi-empirical in the sense that we take care to agree with the present-day \( M_{\ast} \)–\( M_{\ast} \) relation inferred from matching the galaxy stellar (luminosity) and halo mass cumulative functions. In Fig. 2 we show this relation as inferred by different authors (Shankar et al. 2006; Baldry, Glazebrook & Driver 2008; Corroy & Wechsler 2009; Moster et al. 2009; Rodríguez-Puebla et al., in preparation). Different observed galaxy luminosity functions, different methods to pass from luminosity to \( M_{\ast} \) and different halo mass functions (analytical fits or haloes directly from \( N \)-body numerical simulations) as well as different corrections to account for halo groups and subhaloes were used by each of these authors. For completeness, we also reproduce in Fig. 2 the more direct (but as yet very uncertain) inferences based on weak lensing studies for late-type galaxies (squares with large vertical error bars: Mandelbaum et al. 2006).

The \( M_{\ast}–M_{\ast} \) relation has commonly been inferred using the whole galaxy population and all the haloes. In the case of Baldry et al. (2008: long-dashed blue line), the galaxy sample used refers to galaxies in the field, where disc galaxies dominate. Since our study refers to disc galaxies, the \( M_{\ast}–M_{\ast} \) relation should be inferred from a stellar mass function for only disc galaxies and from a halo mass function related to haloes that will host disc galaxies. This inference has been performed in Rodríguez-Puebla et al. (in preparation), who used the \( M_{\ast} \) function for SDSS late-type (blue) central galaxies as reported in Yang, Mo & van den Bosch (2009) and the halo \( M_{\ast} \) function corrected for haloes that did not suffer a
major merger (mass ratio larger than 0.2) since \( z = 0.85 \); Governato et al. (2009) have shown that after a major merger that takes place before \( z \approx 0.8 \), the galaxy can regenerate a significant disc until the present epoch. Rodríguez-Puebla et al. (in preparation) checked that the fractions of late-type galaxies and ‘quiet’ haloes were similar with respect to their corresponding distribution functions, around 55 per cent in both cases. The solid red line in Fig. 2 reproduces the results by Rodríguez-Puebla et al. (in preparation), including the 1σ uncertainty (dotted red lines that encompass the area of dotted horizontal lines); this uncertainty is mainly due to the uncertainties in the population synthesis models used to estimate \( M_* \).

We use the \( M_* - M_* \) relation by Rodríguez-Puebla et al. (in preparation) as indicative, intending that the feedback-driven mass ejection should help to reproduce roughly such a (semi-empirically derived) relation. It should be stressed that our conclusions below regarding SSFRs are unchanged if our models are calibrated to reproduce any of the other \( M_* - M_* \) relations shown in Fig. 2. We focus our study only on galaxies with \( M_* \lesssim 10^{10.5} \, M_\odot \), those for which the SSFR–DS phenomenon becomes strong (see Section 2).

In Fig. 2(a), the thick dot–dashed lines show our results for the cases \( n = 1, 2 \) and 5 in a clockwise sense, respectively. In each model the outflow efficiency \( \epsilon \) is fixed in order to obtain the best agreement with the \( M_* - M_* \) relation at \( M_* = 10^{10.5} \, M_\odot \). The higher \( n \) is, the shallower the \( M_* - M_* \) relation at low masses; for example, the slopes in the range \( 9.5 \lesssim \log M_* \lesssim 10.5 \) are 0.79, 0.62 and 0.36 for \( n = 1, 2 \) and 5, respectively (the corresponding slope for the Rodríguez-Puebla et al. inference is 0.65). We have also experimented with an outflow model with constant mass loading (i.e. \( n = 0 \)); as expected, the models follow a correlation steeper than the case \( n = 1 \). If outflows are not introduced (\( f_{\text{out}} = 0.04 = \text{constant is used} \)), then the correlation is only slightly shallower than the case \( M_* \propto M_* \) in Fig. 2 (slope \( \approx 0.94 \)); this is because in our models the lower the disc mass, the less efficient the process of gas transformation into stars.

As seen from Fig. 2, a reasonable agreement with the observational inferences below \( 10^{10.5} \, M_\odot \) is obtained for \( n = 2 \) (‘SN energy-driven’ outflows) with a high SN energy transference efficiency, \( \epsilon = 0.62 \). The values of \( \epsilon \) for different cases, as well as the values of \( M_* \) obtained at \( z = 0 \) for different halo masses, are presented in Table 1.

### 4.2 Re-accretion of the ejected gas

The assumption that gas is lost forever is strong and likely unrealistic. The outflow propagates along the intrahalo and/or infall medium and even if gas escapes from the current gravitational potential it will be slowed down and stopped by further interaction with the intergalactic medium, and then re-accreted later by the halo–galaxy system (see e.g. Bertone et al. 2007; Oppenheimer & Davé 2008). The motion of an ejected disc gas element can be calculated by taking into account the halo–galaxy gravitational potential and the viscosity of the surrounding gas. Once the ejected gas element stops with respect to the gas around it, both the ejected gas element and the circumgalactic gas will fall together on to the disc galaxy. This is a rather complex hydrodynamic process, demanding in computing time and, in any case, uncertain due to the stochastic nature of the problem. Instead, we adopt here a simple approach that can be easily implemented in our numerical code. Let us consider that during the time interval elapsed between the ejection of a gas element and its re-infall on to the disc, a certain amount \( M_{\text{reg}} \) of primary cosmological gas (see above for a definition) accretes on to the disc. The information related to the surrounding gas that breaks the outflow (mostly related to the infalling cosmological gas), as well as the dynamics of the gravitational field, are actually summarized in the parameter \( M_{\text{reg}} \) (see Dubois & Teyssier 2008 for a similar statement). In other words, the physics concerning the outflow/re-accretion process can be parametrized through \( M_{\text{reg}} \). With this idea in mind, we follow the next simple approach for calculating gas re-accretion in our code. For a given disc gas element, as soon as it is ejected, the accumulated amount of the accreted primary cosmological gas is calculated numerically for each time. When this amount reaches the value of \( M_{\text{reg}} \), then the given mass element is reintegrated to the disc. This procedure is applied to each ejected gas element at any time. Adopting such an approach, the physics reduces to fixing \( M_{\text{reg}} \) in a parametric fashion.

In fact, we introduce a lognormal distribution around our parameter \( M_{\text{reg}} \) in order to take into account the stochastic nature of the problem. This distribution is defined by

\[
dP = \frac{\alpha}{\sqrt{\pi}} e^{-\alpha^2 [\ln(M_{\text{reg}}') - \ln(M_{\text{reg}})]^2} \ d \ln (M_{\text{reg}}'),
\]

where \( \alpha \) regulates the width of the distribution around the logarithmic mean value \( \ln (M_{\text{reg}}) \); \( \alpha \) and \( M_{\text{reg}} \) are \( e^{[\ln(M_{\text{reg}})]} \) are introduced as free parameters.

By means of cosmological hydrodynamical simulations, Oppenheimer & Davé (2008) have found that the re-accretion time scales with galaxy mass roughly as \( M_{\text{gal}}^{1/2} \) and they interpret this to be the case in which environmental effects dominate in the retardation of outflows. Such behaviour implies in our case that \( M_{\text{reg}} \)

<table>
<thead>
<tr>
<th>( n )</th>
<th>( \epsilon )</th>
<th>\log ( (m) )</th>
<th>( \alpha )</th>
<th>( M_* )</th>
<th>( \log M_* )</th>
<th>( \log ) SSFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.83</td>
<td>9.38</td>
<td>9.63</td>
<td>10.00</td>
<td>10.48</td>
<td>-1.39</td>
</tr>
<tr>
<td>2</td>
<td>0.62</td>
<td>9.22</td>
<td>9.54</td>
<td>10.00</td>
<td>10.60</td>
<td>-1.36</td>
</tr>
<tr>
<td>5</td>
<td>0.024</td>
<td>8.65</td>
<td>9.18</td>
<td>10.00</td>
<td>10.90</td>
<td>-1.30</td>
</tr>
<tr>
<td>1</td>
<td>7.23</td>
<td>10.0</td>
<td>1.0</td>
<td>0</td>
<td>9.05</td>
<td>9.43</td>
</tr>
<tr>
<td>1</td>
<td>3.18</td>
<td>10.5</td>
<td>1.0</td>
<td>0</td>
<td>9.20</td>
<td>9.51</td>
</tr>
<tr>
<td>5</td>
<td>5.95</td>
<td>10.0</td>
<td>0.5</td>
<td>0</td>
<td>9.15</td>
<td>9.49</td>
</tr>
<tr>
<td>1</td>
<td>9.61</td>
<td>10.0</td>
<td>1.0</td>
<td>-1</td>
<td>8.73</td>
<td>9.15</td>
</tr>
<tr>
<td>1</td>
<td>6.46</td>
<td>10.0</td>
<td>1.0</td>
<td>1</td>
<td>9.38</td>
<td>9.63</td>
</tr>
<tr>
<td>2</td>
<td>2.32</td>
<td>10.0</td>
<td>1.0</td>
<td>1</td>
<td>9.21</td>
<td>9.53</td>
</tr>
</tbody>
</table>

should be roughly constant or moderately decreasing with mass.\footnote{The properties of \( M_{\text{pcg}} \) can also be estimated by simple momentum or energy conservation arguments. Let us consider a given outflow of mass \( M_0 \) moving in a given solid angle at the ejected velocity \( V_0 \) in the halo potential; then \( M_0 V_0^2 = (M_0 + M_p) V^2 \), where \( M_p \) is the mass piled by the outflow, \( V \) is the shock velocity and \( u = 1 \) or 2 for momentum or energy conservation, respectively. A rough and general estimate for \( V \) could be the typical halo circular velocity, \( V_c \), which approximately scales with the halo mass as \( V_c \propto M^{1/3} \). Therefore, the mass piled by the outflow is \( M_p \approx (M_0 V_0^2)^{3/2}/M^{1/3} \). This mass will drag the mass element \( M_b \) back to the disc. In other words, \( M_b \) is reintegrated to the disc when, within the given solid angle, the amount of mass \( M_p \) of primary gas is accreted. Thus, \( M_{\text{pcg}} \) is just \( M_p \) scaled to the entire solid angle \( 4\pi \). From this crude approximation, \( M_{\text{pcg}} \approx M_b^{1/3} \) or \( M_p^{2/3} \), dependences that are within the range explored below by us.} Therefore, for massive galaxies, \( M_{\text{pcg}} \) is soon attained and gas re-accretion consequently becomes efficient (galactic fountains), while for lower mass galaxies attaining \( M_{\text{pcg}} \) takes longer; for the smallest galaxies, it may takes a period longer than the current Hubble time, in which case the gas does not return. Given the large uncertainties in the physics of the process, we introduce a parametric expression for \( M_{\text{pcg}} \):

\[
M_{\text{pcg}} = \frac{m}{M_\odot} \left( \frac{2 \times 10^3 M_\odot}{2 \times 10^3 M_\odot} \right)^\alpha,
\]

where \( m \) and \( \alpha \) are parameters to be probed.

Regarding the angular momentum of the re-accreted gas, the situation is even more uncertain. We assume that the specific angular momentum of this gas is a fraction \( f_j \) of that corresponding to the currently hierarchically infalling cosmic gas. The results to be presented here depend weakly on the assumed fraction, within the reasonable range of \( f_j \approx 0.3-0.7 \).

In Fig. 2(b), the thick black curves show our results for the outflow model with \( n = 1 \) (see equation 3) and constant values of the re-accretion \( M_{\text{pcg}} \) parameter, i.e. with \( \mu = 0 \) (see equation 5): \( m = 10^{10} \) (solid line) and \( m = 10^{10.5} \) (dashed line), in both cases using \( \alpha = 1 \) in the probability distribution of \( M_{\text{pcg}} \) (equation 4) and \( m = 10^{10} \) with \( \alpha = 0.5 \) (dot–dashed line). The corresponding slopes of the \( M_s - M_\star \) relation in the range \( 9.5 \leq \log M_\star \leq 10.5 \) are 0.58, 0.57 and 0.52, close to the slope of the observations. For outflow models with \( n \) larger than 1, after taking into account re-accretion, the \( M_s - M_\star \) relations become significantly shallower than the observational relations. In Table 1 we report our results at \( z = 0 \) (\( M_\star \) and SSFR for different halo masses) for the re-accretion parameter mentioned above as well as for some cases with \( \mu = 0 \) and for \( n = 2 \). As expected, including re-accretion and trying to reproduce the \( M_s - M_\star \) relation implies very high outflow efficiencies. We see also that the results actually depend weakly on the dispersion parameter \( \alpha \) (e.g. compare rows 4 and 6 in Table 1).

### 4.3 Strategy

A given galaxy model is defined by the halo mass, \( M_\odot \), its MAH, and its \( \lambda_b \). The initial baryon fraction is assumed to be equal to the universal one, \( f_b,\text{gal} = f_b,\text{Univ} \), but the feedback-driven outflow and gas re-accretion parameters define the actual value of \( f_b,\text{gas} \). Since we are interested here in generic evolutionary trends related to the SFR and \( M_\star \) histories as a function of mass, we study only the ‘central’ models of different masses characterized by

(i) the averaged MAH corresponding to the given halo mass \( M_\odot \),

(ii) a value of \( \lambda_b = 0.03 \), which is somewhat smaller than the mean of all relaxed haloes measured in numerical simulations (e.g. Bett et al. 2007).

Note that these physical ingredients in fact have probability density distributions (not taken into account here) that, of course, will produce an intrinsic scatter in the values of the galaxy properties studied.

We first study models with galactic outflows only, and then include the possibility of gas re-accretion. In all cases, the parameters of the feedback-driven outflows and gas re-accretion are chosen appropriately to reproduce the \( M_s - M_\star \) relation inferred semi-empirically (Fig. 2). Our aim is to explore whether the model SSFR histories for different masses agree in general with the observational trend of SSFR–DS discussed in Section 2 (Fig. 1).

### 5 RESULTS

The observational data in the SSFR versus \((1 + z)\) diagram (Fig. 1) refer to curves of constant \( M_\star \) corresponding to galaxy populations at different redshifts rather than to curves equivalent to the evolution of individual galaxies. However, as discussed in Section 2, at least for \( z \approx 1 \), the later curves seem to be only slightly steeper than the former ones in the SSFR versus \((1 + z)\) diagram. Bearing in mind this small difference (note that at \( z \approx 0 \) the comparison of models and observations is completely fair), below we compare the observational data with the results for individual galaxy evolution models, which end at \( z = 0 \) with stellar masses similar to those corresponding to the data: \( \log (M_\star/M_\odot) = 9.5 \), 10.0 and 10.5. The massive case, \( \log (M_\star/M_\odot) = 11.0 \), is out of the scope of the problem studied herein, as has been explained in Section 4. Recall that our models are constrained here to agree with the \( M_s - M_\star \) relation inferred semi-empirically (Fig. 2).

#### 5.1 Galactic outflows only

We first experiment with the usual ejecting SN feedback model, where the gas in the outflows (galactic superwinds) is assumed to be lost forever from the halo (Section 4.1). In Fig. 2 we showed that the semi-empirically derived \( M_s - M_\star \) relation is better reproduced by the \( n = 2 \) outflow model (‘energy-driven’ outflows). The SSFR evolution for this case and for the present-day masses \( \log (M_\star/M_\odot) = 9.5 \) and 10.5 are plotted in Fig. 3 with dotted cyan (lower curve) and green (upper curve) lines, respectively. The SSFR tracks corresponding to masses in this range lie within these two curves.

For all masses, the SSFR increases with \( z \) with a trend that is in rough agreement with observations, but there is a small but systematic trend toward higher SSFRs as the mass increases, opposite to the strong observed SSFR–DS phenomenon. A good fit to the model results from \( z = 0 \) to \( z \sim 3 \) is

\[
\text{SSFR} = 0.005 \, M_\odot^{-0.1} (1 + z)^{0.2} \, \text{Gyr}^{-1}.
\]

Such behaviour is a consequence of the following.

(i) The CDM halo MAHs, which drive the gas infall process and consequently the SF histories: the less massive the haloes, the lower the specific mass aggregation rates at late epochs (see Fig. 1).

(ii) To a lesser extent, the fact that the disc outflow gas ejection is more efficient for lower mass haloes.

The SSFR histories of low-mass models have significantly over- or under-energized present-day SFRs, i.e. their stellar masses had to be adjusted with SFRs in the past higher than the current one. In

© 2010 The Authors. Journal compilation © 2010 RAS, MNRAS 404, 1100–1110
Galaxy outflows and downsizing

In Section 4.2 we described our parametric model to account for the re-accretion of the ejected gas by feedback-driven galactic outflows. The models with re-accretion agree with the SSFR–$M_*$ relation for local SDSS galaxies by Salim et al. (2007). They report the fit for star-forming galaxies only (solid blue line) and for both this sample and the sample of galaxies with AGNs (short-dashed red line). In both cases the galaxy SSFRs significantly decrease as $M_*$ increases. The three long-dashed magenta curves shown in this plot correspond to models with only outflow and with values of $n = 5, 2$ and $1$ from top to bottom, respectively (see also Table 1). A thick line is used for our preferred $n = 2$ case (see Fig. 2a). The difference between models (weak upsizing) and observations (strong downsizing) in the trend of the SSFR–$M_*$ relation is significant. In particular, for $M_* \lesssim 10^{10.5} \, M_\odot$, the lower the mass, the bigger the differences between the model SSFRs and those inferred from observations. For $M_* > 10^{10.5} \, M_\odot$, the differences tend to disappear.

5.2 Galactic outflows + re-accretion

In Section 4.2 we described our parametric model to account for the re-accretion of the ejected gas by feedback-driven galactic outflows. The models with re-accretion agree with the $M_\text{gal}-M_*$ relation only for outflows with $n = 1$ (see Fig. 2b). In Fig. 3, the case with $n = 1$, $\mu = 0$, $m = 10^{10}$ (see equation 5) and $\alpha = 1$ (see equation 4) is plotted for two models that end at $z = 0$ with $\log(M_*/M_\odot) = 9.5$ (upper dashed cyan line) and 10.5 (lower dashed green line). We have also experimented with many other re-accretion parameters (see Table 1). As expected, the SSFRs are higher for the models with re-accretion. This is because the rate of later re-accretion of the ejected gas adds to the hierarchical halo accretion rate, raising the SFR. From Fig. 3 we see that the SSFR increases with $(1 + z)$ to a power not strongly dependent on mass and, in fact, similar to the case of no re-accretion (dotted curves; see equation 6). It is obvious that if re-accretion is included then the mass loading in the outflow model should be increased in order to reproduce the same $M_\text{gal}-M_*$ relation as without re-accretion. For example, compare the models given in rows 1 and 4 in Table 1 ($n = 1$ outflow case), where $\epsilon$ increased from 1.83 to 7.23; note that the SSFR increased for all masses, but more so for the more massive models.

The physics of the model is rather complex. For $M_{\text{pfg}} = \text{constant}$, the larger the mass the shorter the time period of gas re-incorporation into the disc because $M_{\text{pfg}}$ is equalised quickly by the accreted primary cosmological mass in more massive galaxies. Furthermore, a given mass element can be ejected and re-accreted several times depending on the outflow efficiency. Given that massive galaxies recover their ejected gas sooner than low-mass galaxies, then the same stellar mass ($M_\text{gal}-M_*$ relation) is reached by decreasing the power $n$ of equation (3), i.e. decreasing the low-mass galaxy outflow with respect to that for massive galaxies.

The behaviour of the SSFR with mass is again against the SSFR–DS. For the value of $M_{\text{pfg}} = 10^{10} \, M_\odot$ used here, models with $M_* \sim 10^{10.5} \, M_\odot$ raise their SSFR to values slightly lower on average than observational inferences, while the lowest mass models only very slightly raise their SSFR at late epochs, far away from the values required to reproduce the high SSFRs inferred for low-mass disc galaxies.

Further, we have experimented with cases where $\mu$ in equation (5) is varied. For $\mu < 0$ and for a fixed value of $m$, the epoch when the SSFR becomes higher due to gas re-accretion is delayed with...
respect to the case \( \mu = 0 \). This increase is early and large for more massive galaxies, but with time the SFR ejection–re-accretion process is stabilized. For small galaxies, the influence of re-accretion over the SSFR begins at late epochs. Overall, taking as an example the case \( \mu = -1 \), galaxies that end with \( M_\star \gtrsim 10^{10.5} \, M_\odot \) have SSFR histories close to those inferred from observations. For smaller galaxies, while their SSFRs are now higher than in previous cases, they remain far from the observational constraints. Models keep showing a trend in disagreement with the SSFR–DS trend. Regarding the cases with \( \mu > 0 \), the SSFRs of less massive galaxies are found to be even lower than in the \( \mu = 0 \) case.

In Fig. 4 the loci of the different re-accretion models in the \( z = 0 \) SSFR–\( M_\star \) diagram are plotted (see also Table 1). The \( \mu = 0, m = 10^{10} \) fiducial case is shown with the thick dot–dashed black line. The uppermost dot–dashed curve corresponds to our \( \mu = -1 \) case. The dot–dashed curve immediately below the fiducial case is for the same values as this case but for \( \alpha = 0.5 \). The next lowest curve is as the fiducial case but for \( m = 10^{10.5} \). Then follow the curves corresponding to our \( \mu = 1 \) and \( n = 2 \) cases (see Table 1). As is seen, for a reasonable range of values for the re-accretion model parameters the SSFR as a function of \( M_\star \) remains in conflict with observations, and the SSFRs of low-mass models are too low.

6 SUMMARY AND DISCUSSION

By means of self-consistent models of disc galaxy evolution inside growing \( \Lambda \)CDM haloes, the effects of feedback-driven disc ejective outflows (galactic supernovas) and gas re-accretion on the evolution of the SSFR for low-mass galaxies \(( M_\star \lesssim 10^{10.5} \, M_\odot \) at \( z = 0 \)) have been explored. We have studied only the ‘central’ (average) models corresponding to different halo masses, since our main goal was to probe general trends regarding the evolution of the SSFR and its dependence on mass.

6.1 The effect of gas outflows

The rate of mass ejection was assumed to be proportional to the local SFR and inversely proportional to the local escape velocity \( V_{\text{esc}} \) to a given power \( n \) (see equation 3, for \( n = 2 \) and \( n = 1 \) the outflows are expected to be energy- and momentum-driven, respectively). The parameters of the outflow models were explored in the light of the \( M_{\text{h}}-M_\star \) relation at \( z = 0 \) (galaxy efficiency) inferred from a semi-empirical approach that makes use of the observed luminosity \(( M_\star \) function (Fig. 2).

Our best outflow models were chosen to be those that agree with the \( M_{\text{h}}-M_\star \) relation inferred for disc (blue) galaxies and haloes that did not suffer a major merger since \( z = 0.85 \). We have found that the slope of the \( M_{\text{h}}-M_\star \) relation at masses \( M_\star \lesssim 3 \, 10^{10} \, M_\odot \) is better attained for the outflow model with \( n = 2 \) (energy-driven SN feedback, equation 3) and for a high SN energy efficiency, \( \epsilon = 0.62 \) (Fig. 2, panel a).

For the \( n = 2 \) outflow case, the SSFR of all masses rises with redshift proportional to \((1 + z)^{2.2} \) up to \( z \sim 3 \) with a little dependence on (present-day) mass, as \( M_\star^{0.1} \) (equation 6). The SSFRs at low redshifts for models with \( M_\star \lesssim 10^{10.5} \, M_\odot \) are well below the constant-SF curve \( s(t) \) (see Section 3), which means quiescent late SF activity, and fail miserably in reproducing the observational inferences (Fig. 3). In particular, the models show a trend contrary to the observed SSFR–DS phenomenon. Such a conflict is clearly seen in the SSFR versus \( M_\star \) diagram for local galaxies \(( z \sim 0 \)) where the observational data are more reliable: while the SSFR of observed galaxies significantly decreases with \( M_\star \), the models show a slight increase with \( M_\star \). The situation is similar for model outflows with \( n = 1 \) and \( n = 5 \) (Fig. 4).

We stress that the conflict is not related to the observed low SSFRs of massive disc galaxies \(( \gtrsim 10^{10.5} \, M_\odot \)) with respect to models, but instead is related to (i) the observed trend of SSFR increasing as the mass decreases (SSFR–DS), and (ii) the overly high values of the SSFRs of galaxies with masses \( M_\star < 10^{10} \, M_\odot \), both items applying since \( z \sim 1 \).

In the models, on one hand the SFR history is largely driven by the hierarchical halo mass aggregation rate, which on average increases with redshift at nearly the same rate for all masses, but at a given \( z \) massive haloes have rates slightly higher than less massive haloes (see Fig. 1 and equation 2). On the other hand, the ejective feedback scheme used here produces proportionally more gas loss (and hence less later SF) for lower mass discs than for massive ones. We conclude that the low SSFRs of low-mass disc galaxy models with outflows, and the (slight) increase of such SSFRs with \( M_\star \), is in opposition to the observed strong SSFR–DS phenomenon – the lower the mass, the higher the SSFR. This is a natural consequence of the \( \Lambda \)CDM halo-assembling and, at a minor level, of the feedback-driven outflow schemes commonly used to reproduce the local \( M_{\text{h}}-M_\star \) relation.

6.2 The contribution of gas re-accretion

We further explored the possibility that the gas ejected from the disc–halo system can be re-accreted later on to the disc. Our scheme for such a process is very general and encompasses a large range of possibilities for the unknown and complex outflow hydrodynamic and radiation transfer processes. Instead of introducing as a key parameter the time elapsed between ejection of a given mass element and its re-accretion, we use as a parameter the primary cosmological gas mass that will be accreted during this period, \( M_{\text{pcg}} \). This way, we take into account in some way the amount of circumgalactic mass that interacts with the outflow, an amount of mass that in our models is related to the MAH of the given halo. We use a parametrization for \( M_{\text{pcg}} \) given by equation (5), and a lognormal distribution (equation 4) for such a parameter is considered in order to introduce a (natural) dispersion around the re-accretion times of the ejected mass shell.

Our results show that gas re-accretion may raise the SSFR of disc galaxies but it does so in the incorrect direction regarding mass: while for low-mass galaxies the increase in SSFR is small, for massive galaxies the increase is significant at all epochs (Fig. 3). We have experimented with several cases: \( M_{\text{pcg}} \) constant for all masses and \( M_{\text{pcg}} \) decreasing or increasing with mass. The decrease of SSFR as \( M_\star \) decreases (upsetting) is seen in all cases (for \( z \sim 0 \), see Fig. 4).

We conclude that for models of disc galaxy formation and evolution in the context of the \( \Lambda \)CDM cosmogony, the problem of SSFR–DS is not solved by an interplay of outflows and re-accretion of gas.

---

\footnote{In our models, the SFR history also depends on the local disc gas surface density and on some disc dynamical and hydrodynamical properties. Nevertheless, the dominant factor in the SFR histories of our modelled disc galaxies is the cosmological gas infall rate.}
6.3 Is the SSFR–DS phenomenon well-established?

We have shown in a clear and transparent way the difficulty that galaxy evolution models have in the context of the ΛCDM cosmology in explaining the SSFR–DS phenomenon, which is related mainly to sub-$L_*$ star-forming (late-type) galaxies. Before discussing some caveats of the models and possible cures to the problem, it should be stressed that at the level of observational inferences there are still large uncertainties.

The use of SPS models to fit observational data and infer $M_*$ and SFR should be regarded with caution, due mainly to the uncertainties in stellar evolution (for example in the thermally pulsating asymptotic giant branch (TP-AGB) and horizontal branch phases) and to our poor knowledge of the initial mass function (IMF) as well as degeneracies like the one between age and metallicity (see Maraston et al. 2006; Bruzual 2007; Tonini et al. 2009; Conroy, Gunn & White 2009a; Conroy, White & Gunn 2009b for recent extensive discussions). For example, Conroy et al. (2009a) estimate that stellar evolution uncertainties can introduce up to $\sim 0.3$ dex statistical error in $M_*$ at $z \sim 0$. Regarding systematic errors, these are more difficult to evaluate. Maraston et al. (2006) claim that the stellar masses of galaxies with dominating stellar populations of $\sim 1$ Gyr age could be on average $60\%$ per cent lower if their assumptions for convective overshooting during the TP-AGB phases are used. It is not easy to estimate the direction in which these statistical and systematic uncertainties could influence the SSFR–$M_*$ dependences at different redshifts; at least, it is not obvious that the SSFR–DS phenomenon could be eliminated.

It is healthy to stress that the approach we follow for comparing models and observations is the recommended one in the sense of minimizing uncertainties. Conroy et al. (2009b) show that it is better first to infer the physical properties of observed galaxies (e.g. stellar mass and SFR) by using the SPS technique and then to compare them with galaxy evolution models, rather than applying the SPS technique to models in order to compare their predictions with the direct observables.

Other significant sources of uncertainty in the inferred SSFR–$M_*$ relations at different redshifts are the selection effects due to the incompleteness of the sample, dust absorption, environmental effects and/or limited detection of the tracers of SF due to flux limits or low emission-line signal-to-noise ratios; in addition, obscured AGN emission could be contaminating the infrared flux and some of the optical lines used to estimate SFR (e.g. Daddi et al. 2007; Chen et al. 2009). The main concern regarding the SSFR–DS phenomenon among these issues is that selection and environmental effects could bias the observed trend that the SSFR increases as $M_*$ increases. For example, the high SSFRs of low-mass galaxies could be due to transient starbursts if the SF regime of these galaxies is dominated by episodic processes (external, like mergers, or internal, like statistical fluctuations in massive star formation); if, among the low-mass galaxies, those with low SFRs are missed due to detection limits, then the SSFRs of low-mass galaxies will be biased on average toward higher values of SSFR, a bias that increases for samples at higher redshifts. Nevertheless, in most of the observational studies reporting the SSFR–DS phenomenon the authors suggest that, while this is possible at some level, it would hardly be the dominant factor in the SSFR–DS phenomenon observed since $z \sim 1$ (see for example Noeske et al. 2007a).

On the other hand, the analysis of very local surveys certainly helps to disentangle whether episodic starbursting events dominate the SF history of low-mass disc galaxies. From a study of the SF activity of galaxies within the 11-Mpc Local Volume, Lee et al. (2007; see also Bothwell, Kennicutt & Lee 2009) have found that intermediate-luminosity disc galaxies ($-19 \leq M_B \leq -15$ or $50 \leq V_{\text{max}} \text{km s}^{-1} \leq 120$) show relatively low scatter in their SF activity, implying factors of 2–3 fluctuation in their SFRs; above $V_{\text{max}} \approx 120 \text{km s}^{-1}$ the sequence turns off toward lower levels of SSFRs and larger bulge-to-disc ratios. These results are for nearby galaxies, where selection effects are minimal, and imply that the SSFRs of disc galaxies with $M_* \geq 5 \times 10^9 \text{M}_\odot$ follow a relatively tight sequence, without strong fluctuations. For galaxies smaller than $V_{\text{max}} \sim 50 \text{km s}^{-1}$ (dwarfs) the situation seems different. The results by Lee et al. (2007) show that a significant fraction of such galaxies are undergoing strong episodic SF fluctuations due to the large scatter in their SSFRs. Another observational study of nearby galaxies by James, Prescott & Baldry (2008) also concluded that there is little evidence in their sample of predominantly isolated field galaxies with significant SF through brief but intense starburst phases. Therefore, it seems that the tight sequence found for normal star-forming (disc) galaxies in the SSFR–$M_*$ plane in large surveys such as the Sloan Digital Sky Survey (SDSS: Brinchmann et al. 2004; Salim et al. 2007; Schiminovich et al. 2007) is intrinsic and due to a high degree of temporal self-regulated SF within individual galaxies. This sequence (called the ‘main sequence’ in Noeske et al. 2007a) seems to persist back to redshifts $z \sim 1$, as discussed above.

6.4 Outlook

If the SSFR–DS phenomenon is definitively confirmed by observations, then, as we have argued, it poses a serious difficulty for current disc galaxy evolution models in the context of the hierarchical ΛCDM scenario. This difficulty, at one level or another, is also present in other galaxy evolution approaches, e.g. the SAMs (Somerville et al. 2008; Fontanot et al. 2009; Lo Faro et al. 2009). These models show, more from a statistical point of view than at the individual galaxy evolution level, that the population of relatively small galaxies ($M_* \approx 10^8–10^{10.5} \text{M}_\odot$) is mostly assembled at higher redshifts, becoming older, redder and with (much) lower SSFRs at later epochs than the observed galaxies in the same mass range.

Our models clearly show that less massive galaxies assemble their stars early because their dark haloes assemble early (earlier on average than more massive ones), and that SN-driven outflows, which are more efficient for less massive galaxies, contribute to quenching later SF. Gas re-accretion helps to increase the SSFR moderately, but not enough to agree with observations for low-mass galaxies. The SF-feedback efficiencies used here to produce galactic outflows able to recover the required $M_{\text{gas}}–M_*$ relation are too large according to hydrodynamical simulations (c.f. Dubois & Teyssier 2008; Oppenheimer & Davé 2008). Additionally, it should be taken into account that a significant fraction of SF feedback energy is actually dissipated into disc ISM turbulence. Concerning the SF physics in our models, it should be recalled that the SF is assumed to be stationary (self-regulated) and related only to disc internal processes (isolated galaxy). Most of the model predictions (dynamics, structure, gas fractions, etc.) describe present-day normal disc galaxies well, but we stress that we are not modelling, for example, interaction-induced SF and/or SF in a bursting (non-stationary) regime.

The delay of SF activity apparent from the SSFR–DS trends could be produced by external effects; for example large-scale gas pre-heating or the introduction of new physical ingredients in the intrahalo medium hydrodynamics and gas-cooling process. Finally,
it could be that the SSFR–DS problem, more than a physical phenomenon related to the cosmic gas accretion, is a manifestation of some local process related to star formation in environments that change with the galaxy mass and cosmic time and/or of a varying stellar initial mass function.

ACKNOWLEDGMENTS

We are grateful to the referee, Dr B. Oppenheimer, for thoughtful comments and suggestions on our paper, which largely improved its presentation. VA-R acknowledges PAPIIT-UNAM grant IN114509 and CONACYT grant 60354 for partial funding. AR-P acknowledges a graduate student fellowship provided by CONACYT.

REFERENCES


This paper has been typeset from a \LaTeX\ file prepared by the author.