A different approach to galaxy evolution

Alvio Renzini*
INAF – Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, I-35122 Padova, Italy

Accepted 2009 June 25. Received 2009 June 23; in original form 2009 May 6

ABSTRACT

The consequences are explored of an observationally established relationship of the star formation rate (SFR) of star-forming galaxies with their stellar mass ($M$) and cosmic time ($t$), such that $\text{SFR} \propto M t^{-2.5}$. It is shown that small systematic differences in SFR dramatically amplify in the course of time: galaxies with above-average SFR run into quasi-exponential mass and SFR growth, while galaxies with below-average SFR avoid such exponential growth and evolve with moderate mass increase. It is argued that galaxies following the first path would enormously overgrow if they keep forming stars all the way to the present, hence should quench star formation and turn passive. By the same token, those instead avoiding the quasi-exponential growth may keep forming stars up to the present. Thus, it is conjectured that this divergent behaviour can help us to understand the origin of the dichotomy between passive, spheroidal galaxies and star-forming, disc galaxies.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift.

1 INTRODUCTION

In this Letter, I propose a different approach towards understanding galaxy evolution. Instead of starting from first physical principles and proceeding deductively, as in the widely explored cold dark matter approach, I will attempt a fully inductive, bottom-up approach based exclusively on a few established pieces of empirical evidence.

Indeed, in recent years a formidable body of multiwavelength data has been accumulated on galaxies at all redshifts up to $z \lesssim 6$. Such data are especially extensive for $z \lesssim 3$, hence encompassing the major epoch of galaxy growth peaking at $z \sim 2$, when the morphological differentiation into (spiral) discs and (elliptical) spheroids is well under way. Various multiwavelength photometric and spectroscopic data bases have allowed several groups to derive major galaxy quantities such as redshifts, star formation rates (SFR), stellar masses ($M$), etc.

One important result of these observational studies, based on the Great Observatories Origins Deep Survey (GOODS) data base (Giavalisco et al. 2004; Vanzella et al. 2008, and references therein), was the recognition that at $1.4 \lesssim z \lesssim 2.5$ the SFR of star-forming (SF) galaxies tightly correlates with the stellar mass, with $\text{SFR} \propto M$, while some galaxies have already ceased to form stars and evolve passively (Daddi et al. 2007). As illustrated in Fig. 1, at these redshifts galaxies are either actively SF or already passive, with very few galaxies lying out of these two main branches, i.e. the active branch with $\text{SFR} \propto M$ and the passive one with $\text{SFR} \propto 0$. This evidence leads us to recognize that the vast majority of the SF galaxies are not in a starburst phase, even if their SFRs are hundreds of $M_\odot \, \text{yr}^{-1}$. Instead, they are steadily forming stars at high rates over a major fraction of the $\sim 2\, \text{Gyr}$ of cosmic time from $z \sim 3$ to 1.4.

The same pattern, with galaxies either lying on a tight SF branch with $\text{SFR} \propto M$ or being already passive, has been recognized also at lower redshifts from $z \sim 1$ (Elbaz et al. 2007) all the way to $z \sim 0$, hence revealing a steady decrease of the SFR of galaxies in the SF branch – at a fixed mass by a factor of $\sim 30$ between $z \sim 2$ and 0 (Daddi et al. 2007, see their fig. 17). Due to its tightness, the SF branch has been dubbed the main sequence of SF galaxies (Noeske et al. 2007).

In Daddi et al. (2007), the SFRs of $1.4 \lesssim z \lesssim 2.5$ galaxies have been derived with the traditional method based on the rest-frame ultraviolet (UV) flux, plus extinction correction from the slope of the UV continuum. SFRs in full agreement with these UV-derived ones have been recently obtained from stacking the 1.4 GHz fluxes of $\sim 12\,000$ SF galaxies in the COSMOS field (Pannella et al. 2009), hence confirming the reliability of the classical procedure for the extinction correction. In particular, an almost-perfect linear relationship of the SFR with $M$ is recovered, hence implying a specific SFR (SSFR = SFR/$M$) independent of mass. As in Daddi et al. (2007), $1.4 \lesssim z \lesssim 2.5$ galaxies were selected using the $BzK$ criterion introduced by Daddi et al. (2004), and applying it to the deep $K$-band-selected catalogue of galaxies in the COSMOS field (McCracken et al. 2009).

Combining their own data for galaxies at $1.4 \lesssim z \lesssim 3$ with those at $z \sim 1$ (Elbaz et al. 2007), $z \sim 0.7$ (Noeske et al. 2007) and $z \sim 0$ (Brinchmann et al. 2004), Pannella et al. (2009) have then obtained the following best-fitting relation for galaxies on the SF branch:

$$\langle \text{SFR} \rangle \simeq 270 \times M_\odot (t/3.4 \times 10^9)^{-2.5} \quad (M_\odot \, \text{yr}^{-1}), \quad (1)$$

*E-mail: alvio.renzini@oapd.inaf.it
where $M_{\odot}$ is the stellar mass in units of $10^{11} M_{\odot}$ and $t$ is the cosmic time in years. The factor $\eta = \text{SFR}(t = 3.4 \times 10^{9})/270$ has been introduced here, with $\eta = 1$ for the best-fitting relation presented by Pannella et al. (2009), but the effects of assuming other values will also be investigated. Note that a quite similar relation, consistent with equation (1), can be derived from fig. 17 in Daddi et al. (2007).

SFRs and stellar masses used in establishing equation (1) were obtained assuming a Salpeter (1955) initial mass function (IMF). Adopting other IMFs such as those of Kroupa (2001) or Chabrier (2003) would affect SFRs and masses by the same factor, as indicated. Also shown is the corresponding evolution with time of the SFR, following equation (3), for the same values of $\eta$. The three curves are initially offset by a factor $\eta$ to show the initial differences in their SFRs (i.e. at $t = 2$ Gyr). One can appreciate that SFRs for given mass and time that differ by only a factor of a few lead to vastly different evolutionary paths.

2 THE GROWTH OF GALAXIES

Equation (1) describes how the stellar mass of individual galaxies grows as a result of their star formation, and it does so as a function of stellar mass and time. Hence, one can integrate the equation $dM/dt = \text{SFR}$, with SFR given by the right-hand side of equation (1). This leads to a galaxy growth with time described by the equation:

$$\frac{M(t)}{M(2 \text{ Gyr})} \approx \exp(13.53 \eta) \exp(-38.26 \eta t^{-1.5}),$$

which represents the growth factor of galaxy mass as a function of cosmic time. Note that I do not attempt here to explore galaxy evolution beyond $z = 3$ ($t \lesssim 2$ Gyr), as equation (1) is observationally established only for $z \lesssim 3$, but just to follow the mass growth from $t \sim 2$ Gyr onwards. Combining equations (1) and (2), one then derives the corresponding evolution with time of the SFR of individual galaxies:

$$\frac{\text{SFR}(t)}{\text{SFR}(2 \text{ Gyr})} = 5.66 \times \frac{M(t)}{M(2 \text{ Gyr})} \times t^{-2.5}.$$  

One intriguing aspect of the SFR as given by equation (1) is that its normalization $\eta$ appears in the exponential in equations (2) and (3). Hence, the effects of relatively small differences in $\eta$ dramatically amplify as time goes by. This is illustrated in Fig. 2 where the cases with $\eta = 1$, $1/2$ and $1/4$ are shown. Let us first focus on the $\eta = 1$ case. Note the extremely rapid growth of the stellar mass amounting to more than a factor of $\sim 10^3$, if equation (1) were to hold true from $t = 2$ Gyr to the present (from $z \sim 3$ to $z = 0$). Clearly, observations do not support such a dramatic overgrowth. However, with $\eta = 1/4$, i.e. just a factor of 4 lower SFR for given mass and time, the corresponding growth is much smaller, i.e. just a factor of $\sim 30$.

The parameter $\eta$ is meant to describe two independent aspects of equation (1): (i) exploring the effects of a possible systematic offset of the derived SFRs, which certainly cannot be currently excluded.
and (ii) exploring the effect of departures of the SFRs of individual galaxies from the average, i.e. being systematically higher/lower than the average by a factor $\eta$. For the first aspect, Fig. 2 shows that the true value of the SSFR at a given time critically determines the subsequent growth rate of the stellar mass of galaxies: a factor of just a few difference making enormous differences in the subsequent evolution. This means that the average SSFR would need to be measured with extreme accuracy in order to accurately predict such a subsequent evolution. Current systematic SFR uncertainties are indeed a factor of $\sim 2$ or 3, hence $\eta$ in equation (1) will have to be used as an adjustable parameter within these observational uncertainties.

The second aspect is perhaps more attractive. It implies that at a given mass and cosmic time galaxies whose SSFRs differ by a relatively small factor experience radically different mass evolutions: some enjoy a rather modest mass growth, with secularly declining SFRs, while others suffer a runaway, quasi-exponential mass growth, which certainly cannot be sustained for more than $\sim 1$ Gyr. Equation (1) refers to the average SFR, hence quite naturally one expects some galaxies to have SFRs systematically lower than the average, and others to have SFRs higher than the average. However small this dispersion can be, it naturally tends to dramatically amplify in the course of time, as demanded by equations (2) and (3) and illustrated in Figs 2 and 3.

The likely origin of such a dispersion is environment. As mentioned above, the tight SF branch of galaxies indicates that they experience (quasi-)steady star formation. This picture is in agreement with recent hydrodynamical simulations in which star formation in galaxies is continuously fed by cold stream gas accretion from the environment (Dekel et al. 2009). Therefore, galaxies in different environments are likely to experience different rates of gas accretion, hence different SSFRs. Actually, equation (1), in spite of its simplicity, may capture both nature and nurture aspects of galaxy evolution, which to some extent undoubtedly must coexist. Indeed, the stellar mass, certainly a main driver in galaxy evolution, clearly stands for nature, and a dispersion of $\eta$ results from a dispersion in the physical properties of the local environment of individual galaxies (nurture). Moreover, the $t^{-2.5}$ factor in equation (1) describes the global, cosmological evolution of the environment, a combination of cosmic expansion and the progressive consumption of the cold-gas reservoir, as more baryons are shock heated to virial temperatures, or even above it by feedback effects (galactic winds).

Note that in galaxies undergoing rapid mass accretion ($\eta \gtrsim 1$) the SFR increases quasi-exponentially with time, i.e. just the opposite of what was assumed in the so-called $\tau$-models in which SFR decreases exponentially with time. The unfitness of such models to describe some major aspects of galaxy evolution was pointed out by Cimatti et al. (2008) and is further explored by Maraston et al. (in preparation).

### 3 A CONJECTURE ON THE ORIGIN OF MORPHOLOGICAL DIFFERENTIATION

The origin of the sharp separation into the early-type (spheroid) and late-type (disc) families of galaxies remains a central question in galaxy evolution studies. Based on the above arguments, I would like to propose here a conjecture that may help to understand the origin of this dichotomy. I assume that equation (1) for the average SFR holds true for SF galaxies with $\eta = 1$ (but a slightly lower value of $\eta$ may work even better; see below). Then, individual galaxies evolve according to equations (2) and (3), each with its specific value of $\eta$, with a dispersion of $\eta$ values similar to the empirical dispersion of the SFRs shown in Fig. 1. In practice, a range of $\eta$ within a factor of 3–4 about its mean value should encompass the vast majority of galaxies in the SF branch.

As shown in Fig. 2, galaxies with $\eta \gtrsim 1$ undergo extremely fast mass growth that cannot be sustained indefinitely. At some point in time, a SFR as given by the right-hand side of equation (1) cannot apply any longer, which is to say that galaxies must leave the SF branch described by equation (1). As suggested by Pannella et al. (2009), the only way this can happen is by completely quenching star formation, thereby galaxies join the passive branch (indeed, they have no other place to go in Fig. 1). This star formation quenching can happen in a variety of ways. Just to mention one, extremely high gas accretion by, and SFRs in, massive discs at $z \sim 2$ likely results in disc instabilities, with massive clumps coalescing at the centre to form a bulge, feeding an AGN and its ensuing feedback (Immeli et al. 2004; Elmegreen & Elmegreen 2006; Genzel et al. 2008).

Galaxies with subaverage gas accretion and SFR ($\eta \lesssim 1$), in contrast, avoid the quasi-exponential mass and SFR growth; their mass increases moderately and they exhibit a slowly decreasing SFR over most of the cosmic time (Figs 2 and 3). Disc galaxies with subaverage SFRs are therefore likely to avoid global disc instabilities, hence retaining their disc structure all the way to the present.

Note also that those galaxies that experience a quasi-exponential growth naturally develop an $\alpha$-element enhancement, which is typical of ellipticals and bulges (e.g. Thomas et al. 2005; Zoccali et al. 2006). Instead, those galaxies that avoid a quasi-exponential growth experience a chemical enrichment to which both supernova types contribute substantially, hence resulting in near-solar abundance ratios.

In summary, the tenet of the conjecture is that the morphological differentiation of galaxies is the result of a SSFR (almost) independent of mass working as a very efficient amplifier of galaxy-to-galaxy differences of SSFR. Galaxies with above-average SFRs experience a runaway mass accretion resulting in global instabilities and spheroid formation. Instead, those with subaverage SFRs
experience only a modest mass growth, avoid instabilities and survive as discs. Differences in SSFR likely arise from differences in cold gas accretion from the environment, which can also help to understand the origin of the morphology–density relation.

4 CAVEATS

This scenario completely neglects mergers, and assumes in situ star formation as the only process leading to the growth of galaxy mass. In recent years, there has been a marked shift of emphasis from (major) mergers to cold stream accretion as the main driver of galaxy evolution (Genzel et al. 2008; Dekel et al. 2009, and references therein). Even so, mergers must occur and play a role that may indeed be dominant at very high redshifts (say \(z \gtrsim 3\)), but then steadily declines (e.g. Masjedi, Hogg & Blanton 2008; Conselice, Yang & Bluck 2009) and is superseded by cold stream accretion (Dekel et al. 2009). In any event, a full description of galaxy evolution must also include merging processes. As is done here for star formation alone, one could include this effect using empirical merger rates once they are firmly established.

In the simplified approach presented here, it is assumed that SF galaxies evolve following equations (2) and (3), each with a fixed value of \(\eta\). Actually, gas accretion and the ensuing SFR must fluctuate up and down as a function of time, an aspect that may indeed be regarded as a series of minor merger events (Dekel et al. 2009). So, the evolution of individual galaxies cannot be so smooth as implied by equations (2) and (3) and shown in Fig. 2. Yet, apart from short time-scale fluctuation, one should expect that different galaxies (in different environments) experience systematically higher/lower-than-average gas accretion and SFRs, once averaged over sufficiently long time-scales. It is indeed this kind of noise-suppressed evolution that is described by equations (2) and (3).

On the other hand, as is clear from Fig. 2, what matters most is the value of \(\eta\) during the relatively short interval of cosmic time (2 < \(t\) < 4 Gyr) when the quasi-exponential growth may or may not take place. Later, the SFR tends to decrease (and the mass growth to slow down) no matter what the value of \(\eta\) is, as the factor \(r^{-\eta}\) begins to dominate. Actually, it is unlikely that environmental effects on SFRs maintain the same direction at all redshifts. For example, overdensity may promote higher SFRs at high \(z\) when cold gas is more abundant, but at low \(z\) overdense regions such as clusters may become detrimental to star formation, as most gas has been shock heated to high temperatures within the cluster potential well. Thus, typical values of \(\eta\) are likely to depend on a non-separable combination of overdensity and cosmic epoch.

5 PERSPECTIVES

As surveys of the galaxy populations at high redshifts progress, along with those of their large-scale structure distribution, it becomes increasingly urgent to try to understand how galaxy populations at some high redshift map into those at a lower redshift. For example, whether some SF discs in a certain environment are more likely to remain SF discs, or will suffer a major, catastrophic event turning them into passive spheroids. The conjecture presented here may help to identify one of the major mechanisms driving galaxy evolution, including its bifurcation into SF discs and passive spheroids. Yet, certainly many critical issues remain open.

First, nothing is said here on the evolution prior to \(t = 2\) Gyr, i.e. on how galaxies form and grow during the first 2 billion years of cosmic evolution. Available data at \(z > 3\) are presently insufficient to attempt an empirical approach similar to that followed here at lower redshifts.

Assuming an empirically motivated stellar mass function for galaxies at \(z = 3\), equations (1)–(3) can in principle be used to evolve such a mass function to lower redshifts. Such an evolution would be critically dependent on several assumptions, worth mentioning and discussing here.

1. The average value of \(\eta\), i.e. the absolute normalization of the SSFR, in equation (1). All estimates, including those of Daddi et al. (2007) or Pannella et al. (2009) adopted here, are certainly affected by a systematic error, hard to pinpoint from observations. As alluded to above, one can suspect that an average \(\eta\) somewhat less than 1 (e.g. \(\eta \sim 1/2\)) may give a more realistic share between galaxies running into catastrophic growth and those evolving more peacefully. Critical to emphasize here is the important role played by such a normalization.

2. The dispersion of \(\eta\) values, which along with the average \(\eta\) concur in determining the evolution of the mass function.

3. The star formation quenching mechanism, and its dependence on galaxy mass, environment and cosmic epoch. We empirically know, from evidence at low (Thomas et al. 2005) as well as high redshifts (e.g. Cimatti, Daddi & Renzini 2006; Renzini 2006; Bundy et al. 2006; Cimatti et al. 2008), that massive galaxies are the first to turn passive, around \(z \sim 2\). Then, as time goes by, a fraction of galaxies of lower and lower masses cease to form stars, while others maintain such activity all the way to the present. This mass-phasing of the star formation quenching process is not a natural consequence of the conjecture presented in Section 3, and requires additional physics besides the mass-dependent SFR given by equation (1). Indeed, a SSFR for actively SF galaxies that is independent of mass inherently does not include a downsizing effect, as all masses grow at the same relative rate (see Pannella et al. 2009). Hence, downsizing in star formation quenching must involve physical phenomena that are not described by a SSFR(M, t) relation for SF galaxies.

4. Assuming that minor, gas-rich mergers are automatically included in equation (1), the effects of major mergers are left out by such an approach, a limitation that could again be alleviated with either empirically or theoretically motivated merger rates.

In conclusion, playing with these assumptions and exploring the parameter space may in the future help our understanding of galaxy evolution. For the time being, I just wish to emphasize that an empirical relation between SF, stellar mass and cosmic time naturally predicts an extreme amplification of small differences in SFR during the major epoch of star formation at \(z \sim 2\).

ACKNOWLEDGMENTS

I wish to thank Andrea Cimatti and Emanuele Daddi for the many stimulating discussions on galaxy evolution and high-redshift galaxy surveys, and Laura Greggio for a critical and constructive reading of a draft of this Letter. The GOODS and COSMOS Teams are collectively acknowledged for the monumental data bases they have produced on high-redshift galaxies. I also wish to acknowledge the kind hospitality of the Osservatorio Astronomico di Padova, and INAF for financial support via a ‘PRIN’ 2007 entitled ‘VVDS/cCOSMOS: Measuring the Joint Evolution of Galaxies and the Large-Scale Structure of the Universe’ (PI Gianni Zamorani).

© 2009 The Author. Journal compilation © 2009 RAS, MNRAS 398, L58–L62
REFERENCES

Brinchmann J., Charlot S., White S. D. M., Tremonti C., Kauffmann G., Heckman T., Brinkmann J., 2004, MNRAS, 351, 1151
Bundy K. et al., 2006, ApJ, 651, 120
Chabrier G., 2003, PASP, 115, 763
Cimatti A., Daddi E., Renzini A., 2006, A&A, 453, L29
Cimatti A. et al., 2008, A&A, 482, 21
Conselice C. J., Yang C., Bluck A. F. L., 2009, MNRAS, 394, 1956
Cowie L. L., Barger A. J., 2008, ApJ, 686, 72
Daddi E., Cimatti A., Renzini A., Fontana A., Mignoli M., Pozzetti L., Tozzi P., Zamorani G., 2004, ApJ, 617, 747
Daddi E. et al., 2007, ApJ, 670, 156
Dekel A. et al., 2009, Nat, 457, 451
Dunne L. et al., 2009, MNRAS, 394, 3
Elbaz D. et al., 2007, A&A, 468, 33
Elmegreen B. G., Elmegreen D. M., 2006, ApJ, 650, 644
Erb D. K., Steidel C. C., Shapley A. E., Pettini M., Reddy N. A., Adelberger K. L., 2006, ApJ, 647, 128
Genzel R. et al., 2008, ApJ, 687, 59
Giavalisco M. et al., 2004, ApJ, 600, L93
Immeli A., Samland M., Gerhard O., Westera P., 2004, A&A, 413, 547
Kroupa P., 2001, MNRAS, 322, 231
McCracken H. J. et al., 2009, ApJ, submitted
Masjedi M., Hogg D. W., Blanton M. R., 2008, ApJ, 679, 260
Noeske K. G. et al., 2007, ApJ, 660, L43
Pannella M. et al., 2009, ApJ, 698, L116
Renzini A., 2006, ARA&A, 44, 141
Salpeter E. E., 1955, ApJ, 121, 161
Santini P. et al., 2009, A&A, in press (arXiv:0905.0683S)
Thomas D., Maraston C., Bender R., Mendez de Oliveira C., 2005, ApJ, 621, 673
Vanzella E. et al., 2008, A&A, 478, 83
Zoccali M. et al., 2006, A&A, 457, L1

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