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Stellar mass and velocity functions of galaxies

Backward evolution and the fate of Milky Way siblings

S. Boissier, V. Buat, and O. Ilbert

Laboratoire d'Astrophysique de Marseille, Université de Provence, CNRS (UMR6110), 38 rue Frédéric Joliot Curie, 13388 Marseille Cedex 13, France
e-mail: [samuel.boissier;veronique.buat;olivier.ilbert]@oamp.fr

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ABSTRACT

Context. In recent years, stellar mass functions of both star-forming and quiescent galaxies have been observed at different redshifts in various fields. In addition, star formation rate (SFR) distributions (e.g. in the form of far infrared luminosity functions) were also obtained. Taken together, they offer complementary pieces of information concerning the evolution of galaxies.
Aims. We attempt in this paper to check the consistency of the observed stellar mass functions, SFR functions, and the cosmic SFR density with simple backward evolutionary models.
Methods. Starting from observed stellar mass functions for star-forming galaxies, we use backwards models to predict the evolution of a number of quantities, such as the SFR function, the cosmic SFR density and the velocity function. Because the velocity is a parameter attached to a galaxy during its history (contrary to the stellar mass), this approach allows us to quantify the number density evolution of galaxies of a given velocity, e.g. of the Milky Way siblings.
Results. Observations suggest that the stellar mass function of star-forming galaxies is constant between redshift 0 and 1. To reproduce this result, we must quench star formation in a number of star-forming galaxies. The stellar mass function of these "quenched" galaxies is consistent with available data concerning the increase in the population of quiescent galaxies in the same redshift interval. The stellar mass function of quiescent galaxies is then mainly determined by the distribution of active galaxies that must stop star formation, with a modest mass redistribution during mergers. The cosmic SFR density and the evolution of the SFR functions are recovered relatively well, although they provide some clues to a minor evolution of the stellar mass function of star forming galaxies at the lowest redshifts. We thus consider that we have obtained in a simple way a relatively consistent picture of the evolution of galaxies at intermediate redshifts. If this picture is correct, 50% of the Milky-Way sisters (galaxies with the same velocity as our Galaxy, i.e. 220 km s^{-1}) have quenched their star formation since redshift 1 (and an even higher fraction for higher velocities). We discuss the processes that might be responsible for this transformation.

Key words. galaxies: luminosity functions, mass function – galaxies: high-redshift – galaxies: formation – galaxies: evolution

1. Introduction

In the past few years, analysis of many deep fields, together with improvements in techniques such as SED-fitting, has enabled many studies of the stellar mass function (SMF) of galaxies at both low and high redshifts (e.g. Bell et al. 2003, 2007; Borch et al. 2006; Bundy et al. 2005, 2006; Arnouts et al. 2007; Vergani et al. 2008; Perez-Gonzalez et al. 2008; Pozzetti et al. 2009; Ilbert et al. 2010). One of the somewhat surprising results is that it is generally found that the SMF of star forming galaxies (selected on the basis of color, morphology or spectroscopy) has not evolved much between redshift about unity and the present time (e.g. Bell et al. 2007; Cowie et al. 2008; Vergani et al. 2008; Pozzetti et al. 2009). Analysis of the evolution of the luminosity function has already suggested that the stellar mass of blue galaxies is constant, while the one of red galaxies increases with time (Faber et al. 2007).

Since star formation is ongoing in such galaxies, the stellar mass in each of them is bound to increase. This maintained status quo of the SMF thus indicates that a number of massive star-forming galaxies must evolve into early type, or at least quiescent galaxies (through quenching of their star formation), as noted in Bell et al. (2007) and Arnouts et al. (2007), while they are replaced by lower mass galaxies gaining mass with time (see also Pozzetti et al. 2009). This type of scenario was also advanced in Brown et al. (2007) to explain the doubling of the stellar mass in red galaxies over the past 8 Gyr. Such a quenching is also constrained by the evolution of the co-moving star formation rate (SFR) density, i.e. the SFR averaged over representative volumes of the universe, dropping by a factor 6 to 10 between redshift 1 and 0 (see the compilations of Wilkins et al. 2008; and Hopkins & Beacom 2006).

It is reasonable to think that even at "intermediate" redshifts (defined broadly as $0 < z < 1$), star formation takes place in "normal" star-forming galaxies, such as the precursors to present-day disk galaxies and the Milky Way. Smooth SFR histories are known to be realistic and capture enough of the physics of such galaxies (see e.g. models in Boissier & Prantzos 1999, 2000). This is especially suggested by us seeing star formation at intermediate redshift in rotating disks that should have formed through smooth accretion (e.g. Shapiro et al. 2008), and most of the galaxies forming the bulk of the infrared emission at redshift unity look like undisturbed disk galaxies (e.g. Bell 2005; Melbourne et al. 2005; Lotz et al. 2008). The tightness of the SFR-stellar mass relationship also suggests that the evolution is mostly driven by smooth evolution and not starbursts (Noeske 2009; Noeske et al. 2007). The kinematics and morphology are more disturbed at high redshift than in the local universe, but this is still consistent with minor merger and gas accretion (e.g. Ziegler et al. 2009), although it is still being debated (e.g. Neichel et al. 2008). Finally, it has also been shown that models of the chemical and spectro-photometric evolution of the Milky Way and nearby disk galaxies, when rolled backwards, fit the properties of redshift ∼0.7 star forming galaxies in a very reasonable way (Buat et al. 2008).

In this paper, we propose to combine these models with the information from the SMF in order to compute the evolution of the "velocity function", with the advantage that the velocity tags a galaxy, while the stellar mass evolves with redshift when star formation takes place (e.g. Noeske 2009 mentions the intrinsic difficulty in comparing galaxies of a given stellar mass at different redshifts). This allows us to check the global consistency of the SMF, the SFR of individual galaxies, the cosmic SFR density, and simple models of galactic evolution. It is then possible to derive the fraction of galaxies that were similar to the Milky Way (the "Milky Way siblings") and that must have quenched their star formation during the second half of the history of the universe. We acknowledge that this approach is simplistic but we think it is worth performing since it allows us to step back and have an overall look at all the important data of the problem (SMFs of quiescent and star forming galaxies, SFR functions, cosmic SFR density) in a simple, educational framework, while many studies focus on some of these aspects (with, however, interesting exceptions as e.g. Hopkins et al. 2010; or Bell et al. 2007).

In Sect. 2, we present the "backward" models of the evolution of star forming galaxies that we use. In Sect. 3, we compute the velocity function and its evolution assuming a constant SMF, as suggested by the observations. In Sect. 4, the consequences of our simple assumptions are discussed. In Sect. 5, a summary of our work is proposed.

2. Backward evolutionary models

Following the "backward" approach of Silk & Bouwens (1999), we make the assumption that the properties of star-forming galaxies at high redshift can be inferred by rolling backward models of the evolution of well-studied present-day disk galaxies. This is especially motivated by Buat et al. (2008), showing that such backward models reproduce the average specific SFR – stellar mass relationships observed in galaxies at redshifts 0 and 0.7.

In the present work, we used the same basic models and we recall their main ingredients below. These models are based on the grid proposed in Boissier & Prantzos (1999) and Boissier & Prantzos (2000) for the Milky Way and nearby spiral galaxies, calibrated to reproduce many observed trends in the local universe (e.g. color–magnitudes diagrams, luminosity-metallicity relationship, gas fractions, color and metallicity gradients). A comparison of this grid with the properties of galaxies at redshifts lower than 1 was proposed in Boissier & Prantzos (2001). Note that we changed the initial mass function (IMF) from Kroupa et al. (1993) to Kroupa (2001), motivated by this IMF being closer to the one used in general in studies of the SMF. It also provides a better fit to the UV surface brightness profiles of some of the SINGS galaxies (Muños Mateos et al., in preparation). The change mostly affects the most massive stars (hence the UV emission and metallicity output), leaving the SFR, gas, and stellar mass evolution changed by less than about 20%. This number is below the typical uncertainty that we can expect in our models. Indeed the calibrations used to measure stellar masses or SFR on which the models are based can easily be changed by a factor 1.5 to 2, for instance by adopting different IMFs (e.g. Bell et al. 2007). The efficiency of the star formation law, a basic ingredient in the model, also varies within a factor 2 between galaxies (e.g. Kennicutt et al. 1998). As a result, we do not expect such models to give results to a better accuracy than a factor 2.

The grid of models was constructed by adopting various circular velocities (V) and various values of the spin parameter (λ) measuring the specific angular momentum of the galaxy. With simple scaling relationships, this allowed reproduction of the observed ranges of stellar masses and sizes of disk galaxies (these scaling relationships imply that galaxies with higher velocities are more massive, and galaxies with larger spin parameters extend farther out). For each couple of values of the parameters (λ, V), the corresponding model provides a unique history of the galaxy that includes the evolution of the SFR and of the stellar mass, resulting from the combination of a star formation law (see e.g. Kennicutt 1998; Boissier et al. 2003) and the accretion of cold gas at a rate chosen to reproduce the observations in nearby galaxies. For simplicity and following Buat et al. (2008), we adopt here the average value of the spin parameter ($\lambda = 0.05$), and concentrate on the dependences on stellar mass: the mass of a galaxy depends on the circular velocity as $M \propto V^3$. A distribution of spin parameter would create a small dispersion around the main trends shown in the paper as a function of the stellar mass. That the mass is the main intrinsic parameter of the evolution of galaxies has already been found in "local" studies (e.g. Gavazzi et al. 1996) and confirmed in the recent years at high redshift (e.g. Noeske 2009). Thus, in this paper, for a given velocity, we have one star formation history, which can be seen in Fig. 6 of Buat et al. (2008). For high velocities, the SFR presents a rapid rise followed by an exponentially declining SFR. For $V = 220$ km s^{-1} (corresponding to the case of our Milky Way) the history is similar with a modest decline (in agreement with the observational constraints available in our Galaxy). Going to an even lower velocity (towards less massive galaxies), the SFR gently rises with time. In simple terms, the stars are formed earlier in galaxies with high velocities than in those with low velocities. We stress that these SFR histories have not especially been picked for this work. On the contrary, they result from the assumptions that one has to make to reproduce, among others, the distribution of metallicity in the Solar Neighborhood G-dwarf stars (Boissier & Prantzos 1999) implying a long timescale for the formation of our Galaxy, the colors, and metallicity (Boissier & Prantzos 2000), the star formation efficiency and gas fractions (Boissier et al. 2001) of nearby galaxies, especially as a function of the luminosity or the stellar mass. Of course, the evolution might be more complicated than in these models, and there is no unique solution; however, the general trends of these star formation histories are robust in view of the constraints involved.

Since stellar mass and SFR play a central role in our analysis, we show in Fig. 1 the relation between these two quantities in our models for various redshifts. The redshifts are chosen to correspond to the data of Ilbert et al. (2010) and Arnouts et al. (2007), to which we compare our results later in the paper. The dependence of the various quantities on the circular velocity were initially computed only for a few points. These relations were interpolated on a finer grid and smoothed in order to avoid oscillations or artificial breaks due to the limited number of computed points. This allows us to present a smooth curve in this plot and the others later in the paper.

As mentioned earlier, there is evidence that these simple models capture enough of the properties of star forming galaxies

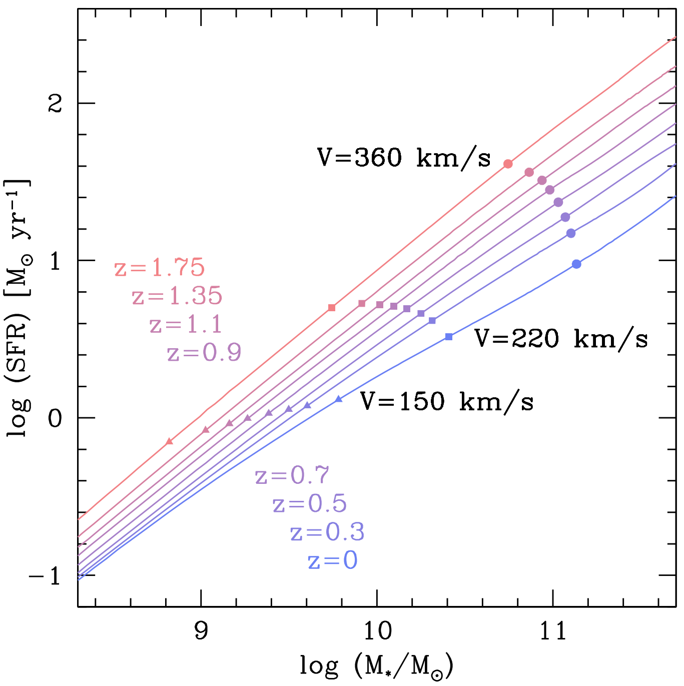

Fig. 1. Redshift evolution of the SFR – stellar mass relationship in the backward models. Symbols (triangles, squares, circles) show the values for three velocities (150, 220, 360 km s^{-1}).

up to redshift ~0.7 (Boissier & Prantzos 2001; Buat et al. 2008). In addition, we present in Fig. 2 the relationship between the stellar mass and SFR for a set of redshifts for which various observations are available. This simple comparison shows that up to redshift 1, the model reproduces the average trends found in observations quite well, with serious departures starting only to be present at redshifts higher than 1. Especially at redshift ~2, for galaxies more massive than 10^{10} $M_{\odot}$ (for which observations are available), the models tend to underestimate the actual SFR for a given stellar mass. This difference between observations and models has been found by other authors (e.g. Davé 2008; Santini et al. 2009) using semi-analytical or hydrodynamical models. Davé (2008) suggests that a solution might be to modify the IMF with redshift. As noted by Santini et al. (2009), Khochfar & Silk (2009) propose that the star formation efficiency in high redshift galaxies is higher owing to cold gas accretion. Neither of these effects (probably still to be debated) are included in our models, and our strongest conclusions will be limited to redshifts lower than about unity, where they are not needed.

The various quantities presented in the paper assume a Kroupa (2001) IMF and a (H_0 = 70, $\Omega_{\rm M}$ = 0.3, Ω_{λ} = 0.7) cosmology.

3. Derivation of the velocity function

The SMF of star forming galaxies has evolved little between redshifts 1 and 0. In Fig. 3, we present the observed SMF of Bell et al. (2003) at redshift 0 (with two different definitions of the star forming sample, based on either color or concentration), and those from Ilbert et al. (2010), Arnouts et al. (2007), and Borch et al. (2006) in various redshift bins (restricted to $z < 1$). This figure confirms that the evolution of the SMF for star-forming galaxies, if any, is quite limited (lower than 0.2 dex) with respect to the difference between the various studies that can reach about 0.5 dex.

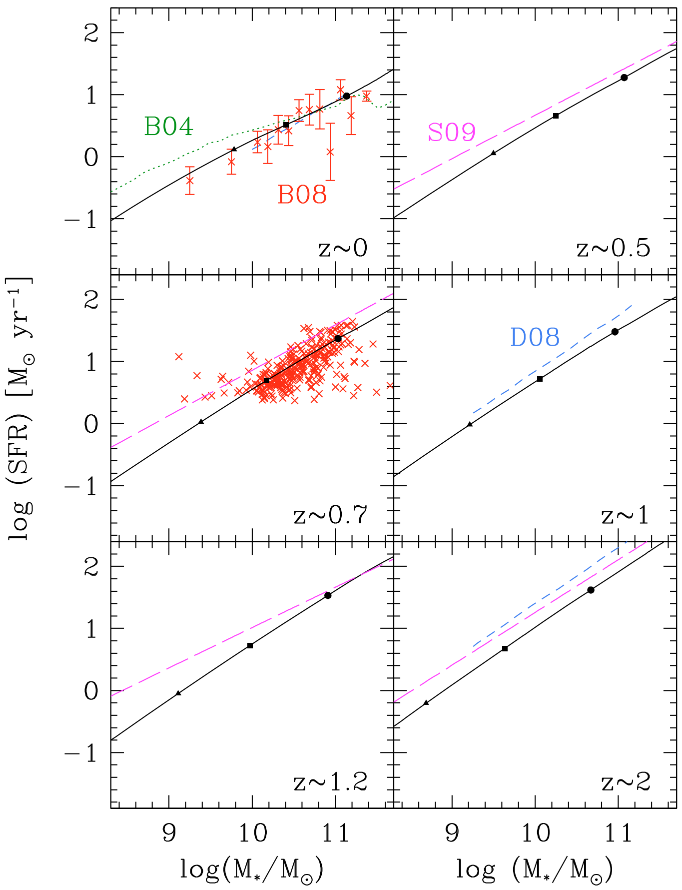

Fig. 2. Observed SFR – stellar mass relationship at various redshifts, compared to the models (solid line with the same symbols as in Fig. 1). Blue dashed lines (D08): observational trends reported by Davé (2008) on the basis of Elbaz et al. (2007) and Daddi (2007). Dotted line (B04): Brinchmann et al. (2004). Crosses (B08): Buat et al. (2008). Magenta long-dashed lines (S09): Santini et al. (2009).

Considering this dispersion and lack of clear evolution, we believe it is educational to adopt the assumption that the SMF is indeed constant with redshift, by defining an average mass function (AMF) as the average value among the curves shown in Fig. 3 (unweighted average of $\log(\Phi(M_*))$ after converting each work to the Kroupa et al. 2001, IMF), which is shown in the figure. Many other determinations of the SMF exist, and we limited ourselves to a few representative cases. Especially Bell et al. (2003) is often used as a local reference, and the SMF by Borch et al. (2006) were measured following the same methods at higher redshifts. Ilbert et al. (2010) and Arnouts et al. (2007) propose two slightly different approaches in identical redshift bins, and procure a good example of the dispersion that can be found in the data due to e.g. cosmic variance or differences in the adopted methods. Hopkins et al. (2010) also chose these last two studies for their analysis for the same reasons. Inspection of Fig. 3 thus shows that the AMF at each stellar mass has a typical uncertainty of 0.2 dex.

As stellar mass is obviously evolving in star-forming galaxies, the SMF being roughly constant for $0 < z < 1$ is actually hiding a definitive evolution. To get rid of this difficulty, we computed a model velocity function where the velocity is actually the parameter of the simple model presented in Sect. 2, and thus does not evolve. It is computed as

$$\phi(V) = \frac{\mathrm{d}N}{\mathrm{d}V} = AMF(M) \times \frac{\mathrm{d}M}{\mathrm{d}V}\cdot \quad (1)$$

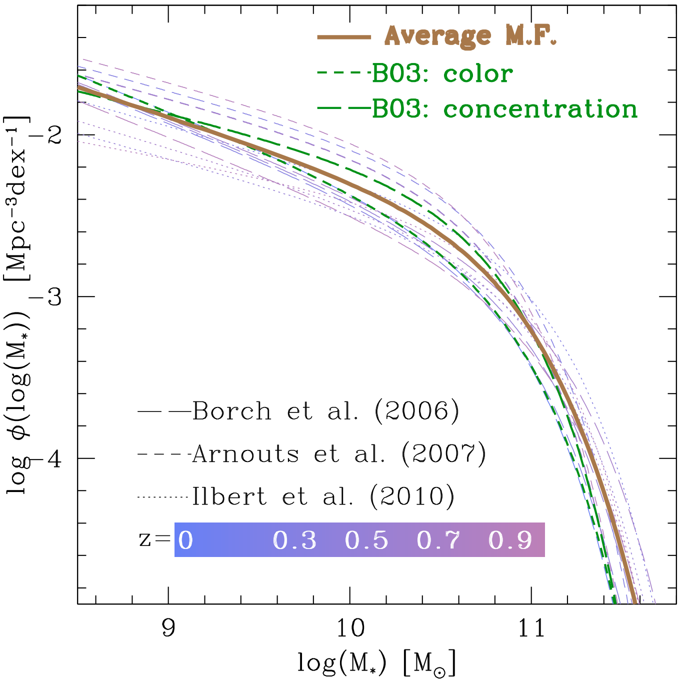

Fig. 3. Stellar mass functions (SMFs) for star-forming galaxies from Bell et al. (2003) (redshift 0, bold dashed curves for both the color-selected sample and the concentration-selected one), Ilbert et al. (2010) as dotted curves, Arnouts et al. (2007) as short-dashed curves, and Borch et al. (2006) as long-dashed curves (between redshifts 0 and 1). The resulting average mass function (AMF) is shown as the bold solid curve.

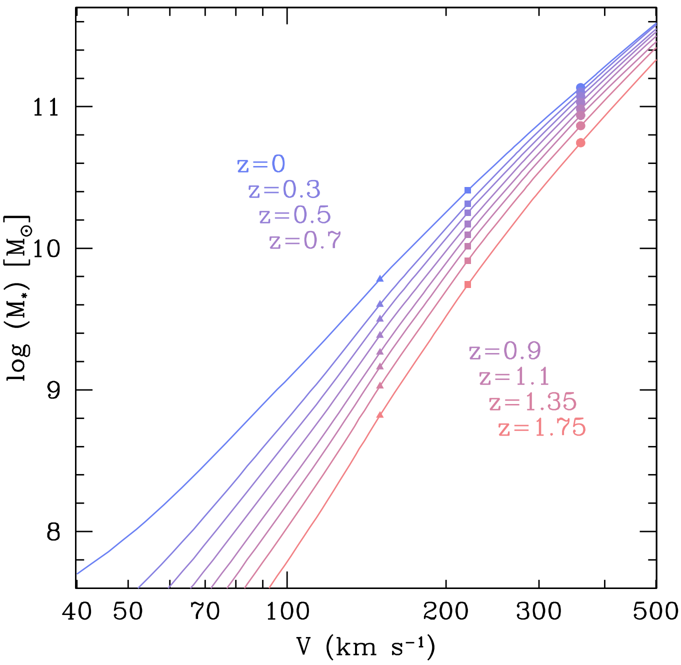

Fig. 4. Stellar mass – velocity relationship in the models (same color and symbol-coding as in Fig. 1).

In this equation, AMF(M) is the average mass function defined above, and the factor $\mathrm{d}M/\mathrm{d}V$ is obtained for each redshift by numerically deriving the velocity- stellar mass relationships of the models shown in Fig. 4: for each redshift, there is a one-to-one correspondence between the stellar mass and the velocity.

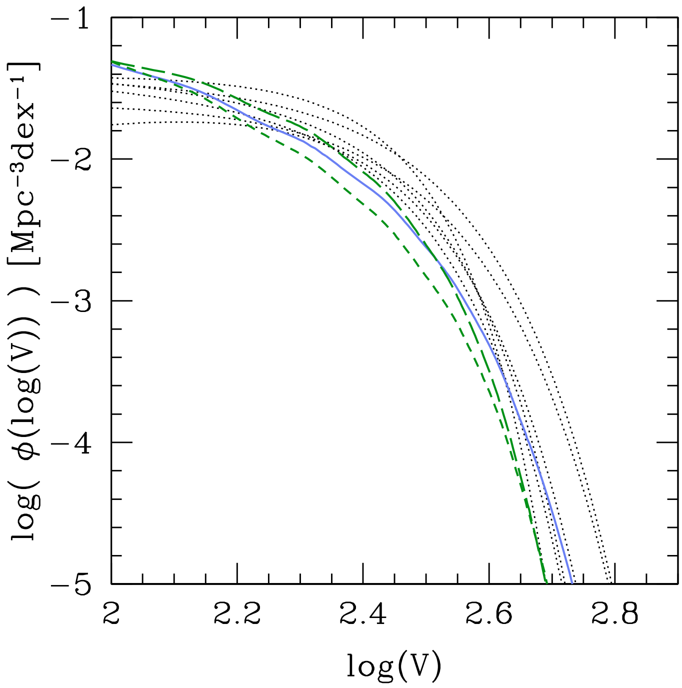

Fig. 5. Spiral galaxies velocity function at redshift zero, derived from the AMF using our models (solid line), compared to velocity functions empirically derived in the local universe by Gonzalez et al. (2000), using various observational sets (dotted lines). The dashed curves show the velocity functions obtained if the Bell et al. (2003) redshift 0 functions (shown in Fig. 3) are used instead of the AMF.

By definition, at redshift 0, the circular velocity can be identified with the observed rotational velocity. We thus compare in Fig. 5 the velocity function obtained for redshift 0 with the rotational velocity functions for spirals observationally derived by Gonzalez et al. (2000). They obtained their functions by combining various empirical luminosity functions and Tully-Fisher relationships available at that time. Taking into account the scatter they obtained for different inputs (about 0.4 dex at $V = 220$ km s^{-1}), and the scatter around the AMF (different studies and different redshifts cover a range of 0.5 dex), the agreement between our redshift 0 model velocity function and the ones in Gonzalez et al. (2000) is reasonable. We also show the velocity functions obtained if we replace the AMF by the redshift 0 observed SMFs from Bell et al. (2003), giving an idea of the uncertainty (the scatter in Fig. 3 is greater than the difference obtained in Fig. 5 when we use the AMF and when we use the Bell et al. functions).

4. Cosmic evolutions

4.1. Evolution of the velocity and SFR functions

In the previous section, we derived the velocity function at various redshifts from the combination of observations (a constant SMF, the AMF), and the stellar mass-velocity relationship of simple models. From this distribution at each redshift, many quantities and their distribution can be computed using the models. Figure 6 shows the evolution of the model velocity function in the top left panel. The "SFR function" evolution is shown in the top right panel, and the bottom panels shows the evolution of the contribution to the cosmic SFR density by galaxies of various stellar mass (left) and SFR (right). These panels illustrate that, at higher redshift, the cosmic SFR density is dominated

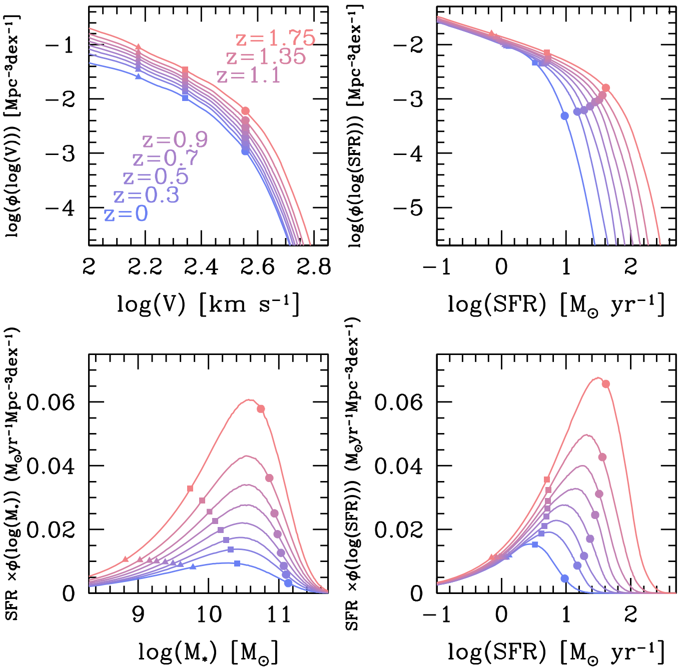

Fig. 6. Redshift evolution of the modeled velocity distribution (*top-left panel*), SFR function (*top-right panel*) and contribution to the cosmic SFR density (*bottom*) of galaxies of a given stellar mass (*left*) or SFR (*right*), assuming a constant SMF (the AMF, shown in Fig. 3). The redshifts and symbols are the same as in Fig. 1.

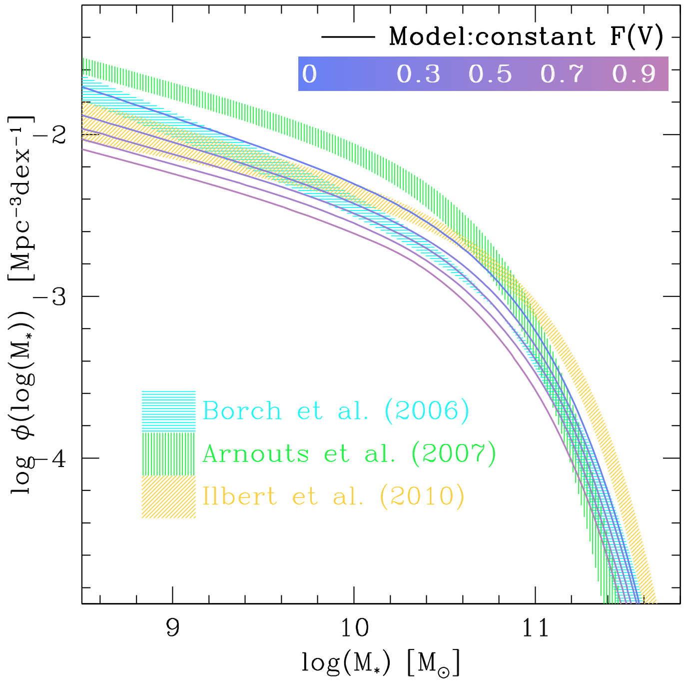

Fig. 7. Predictions at redshifts 0, 0.3, 0.5, 0.7, 0.9 for the SMF of star-forming galaxies assuming a constant velocity function (lines), compared to the observed ranges by Ilbert et al. (2010), Arnouts et al. (2007), and Borch et al. (2006) in the same redshift intervals.

by galaxies of higher SFR in our models. It is also dominated by galaxies of higher stellar masses at higher redshift, although the effect is weaker. The peak of the contribution to the cosmic SFR density moves from $\log(M/M_{\odot}) \sim 10.6$ (redshift 1.75) to $\log(M/M_{\odot}) \sim 10.3$ (redshift 0). In the following, we study some interesting details of the evolution summarized in this figure.

These results (and those in the remainder of the paper) were obtained by assuming that the SMF of star-forming galaxies is constant with time, while their velocity function changes. Before studying the consequences of our assumption in details, we first tried to see wether the opposite assumption is acceptable. We thus assumed that the velocity function is constant (we adopt the velocity function found at redshift 0 above, and shown in Fig. 5), and computed the evolution of the SMF then implied by the model stellar mass-velocity relationship. The results for redshift lower than 1 are shown in Fig. 7, together with the area occupied by the star-forming galaxies SMF observed in the same redshift interval by Ilbert et al. (2010), Arnouts et al. (2007) and Borch et al. (2006). We find a systematic decrease in the computed SMF with redshift. For $\log(M/M_{\odot}) = 10.5$–11, the decrease with respect to the redshift 0 value reaches 0.4 dex at redshift ~1. This number is not very far from the dispersion found among the observational studies. However, this dispersion is largely due to systematic differences between the various studies. Whithin the individual studies of Ilbert et al. (2010), Arnouts et al. (2007), and Borch et al. (2006), Fig. 7 shows that the evolution of the SMF is less than ~0.2 dex, a much lower value than the change we expect under the assumption of a constant velocity function. We thus conclude that the evolution of the star-forming galaxies' velocity function is clearly established.

4.2. Build-up of the "quiescent" stellar mass function

The model velocity function for star-forming galaxies shown in Fig. 6 evolves with redshift, with more star forming galaxies at higher redshift for any given velocity. This is another way to say that, at a given velocity, a fraction of galaxies have quenched their star formation between the redshift probed and now. We computed the velocity function with a $\Delta z = 0.2$ step in redshift. The difference between functions at different steps is the velocity function of galaxies that have quenched their SFR in this redshift interval, as shown in the top panel of Fig. 8 (normalized to be expressed as a flux). By combining this with the stellar mass-velocity relation at the beginning of each redshift interval (assuming the quenching is instantaneous at the beginning of the bin, since the stellar mass evolves little in such a small redshift interval), we can compute the quenched SMF in each interval (bottom panel). This function is normalized by the time elapsed within each redshift bin, so that it is actually a number density flux from star forming galaxies to quiescent ones. These numbers can be compared to, e.g., Pozzetti et al. (2009) who finds a red sequence growth rate of a few 10^{-4} gal Mpc^{-3} Gyr^{-1} dex^{-1} for $\log(M/M_{\odot}) < 11$ in the redshift range 0.3 to 0.9. With the quenched flux estimated above, it is easy to compute the cumulated quenched SMF between two redshifts. This is done in Fig. 9, between redshift 1.1 (beyond this point, the models start to be unreliable, see Sect. 2) and several redshifts for which we compare the results of our model to the increase in the quiescent SMF of Ilbert et al. (2010) and Arnouts et al. (2007). Considering the uncertainties in the derivation of SMF (especially at high redshift, see in the figure the difference between the two observational studies), the agreement is good above $\sim 3 \times 10^{10}$ $M_{\odot}$; i.e., the increase in the observed SMF of quiescent galaxies is compatible with the number of star forming galaxies that must quench their star formation in order to obtain their nearly constant SMF, within a few tens of dex, i.e. our uncertainties (see also Bell et al. 2007, for a simple approach; and Pozzetti et al. 2009). Below and around 10^{10} $M_{\odot}$, the model predicts a much larger number of quenched galaxies

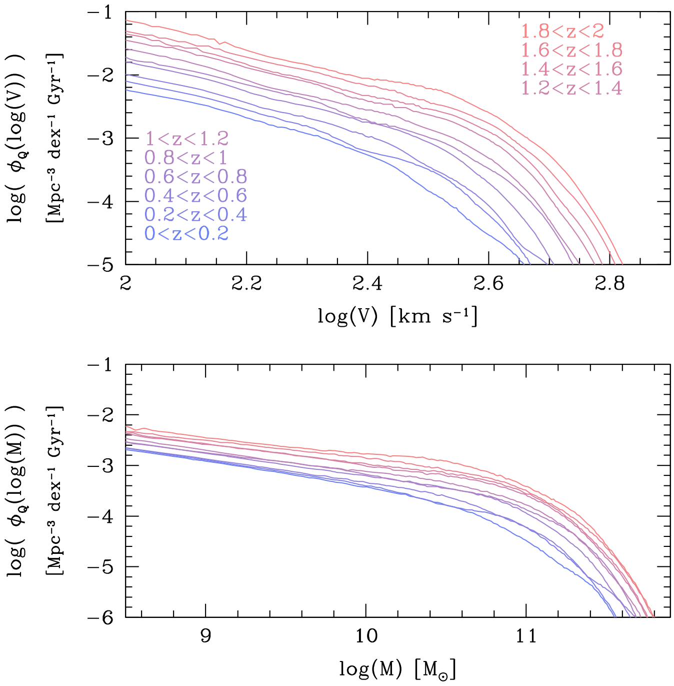

Fig. 8. Velocity function (*top*) and SMF (*bottom*) of galaxies that "quenched" their star formation within redshift bins of $\Delta z = 0.2$, as predicted in our model. The functions are normalized by the time elapsed within the corresponding redshift bins so that they correspond to number density fluxes.

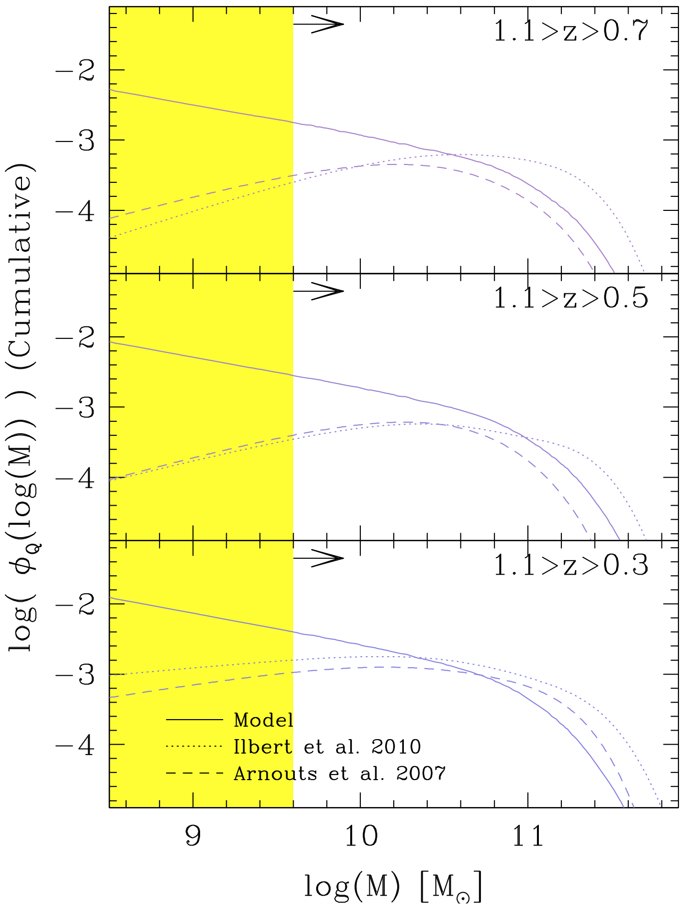

Fig. 9. The cumulated quenched SMF since $z = 1.1$ in our simple model is compared to the increase in the observed SMF of quiescent galaxies in Ilbert et al. (2010) and Arnouts et al. (2007). The comparison is meaningful only out of the shaded area, on the side indicated by the arrow (the limit corresponds to $\log(M) = 9.6$, the lower stellar mass used in Ilbert et al. (2010) at redshift 1.1, which we use as reference.

and a steeper slope than the differential evolution obtained in the observational studies. This results directly from the assumption that the SMF of star forming galaxies does not evolve, even at low stellar mass where it is not observed at high redshift (in this regime, the model is a mere extrapolation). To obtain less quiescent galaxies with stellar masses in the range 10^9–10^{10} $M_\odot$, we would need a change in the number of low-mass star-forming galaxies with redshift. Only future observations bringing constraints on the low-mass end of the SMF of star-forming galaxies at intermediate redshift will allow us to check whether it is the case. Pozzetti et al. (2009) computed the number evolution of quiescent galaxies in three stellar mass ranges between redshifts ~0.25 and 0.9. In Fig. 10, we show their data and compare them to the predictions of our model (integrating the cumulative quenched SMF such as the ones shown in Fig. 9 in the same stellar mass bins). We also show our computations of the same numbers using the observed stellar Mass Functions of Arnouts et al. (2007) and Ilbert et al. (2010), allowing estimates of the uncertainty on these numbers by comparing the various studies. When considering the top panels, one has to take into consideration that a number of quiescent galaxies are "formed" beyond redshift 1.1, while the model only shows the one formed by quenching after this epoch. For this reason, the two thin lines show the sum of the newly quenched galaxies (model) and of the quiescent galaxies already existing at redshift 1.1, taking the data of Ilbert et al. (2010) or Arnouts et al. (2007). We also show the relative number evolution with respect to $z \sim 0.9$ in the bottom panels. On the massive galaxies side, the quenching forms fewer quiescent galaxies than the number already present at $z = 0.9$: massive galaxies are already in place at this redshift. The model predicts a small increase in the number density in this stellar mass range, consistent with the estimations of a quasi-constant number density. Moving to the intermediate stellar mass bin ($10^{10.5-11}$ $M_\odot$), we predict a larger increase in the number of quenched galaxies, consistent with the data. We note, however, a large dispersion: the model tends to underpredict the evolution with respect to Pozzetti et al. (2009), but overpredict it with respect to Ilbert et al. (2010) or Arnouts et al. (2007). In the lower mass bin, the model is roughly consistent with the various studies when no normalization is done (top panel of Fig. 10). In the bottom panel, two of the observational works are found below the model curve, but this is mostly due to the $z = 0.9$ point. The figure suggests that most of the low-mass quiescent galaxies are formed between redshifts 1.1 and 0 through quenching of the star formation of star-forming galaxies.

4.3. The role of mergers

Figure 9 shows that the star formation quenching inferred from the model reproduces the observed increase on the massive side of the SMF for quiescent galaxies relatively well (even if uncertainties due to poor statistics are large). It overpredicts the quiescent SMF on the low mass-side. Even if the models are extrapolations at the lowest stellar masses, the slope seems steeper than the one observationaly found. How would those results be affected if in addition to the quenching itself, the mass is redistributed through mergers? A complete answer would need a full treatment of the halo occupation distribution and is beyond

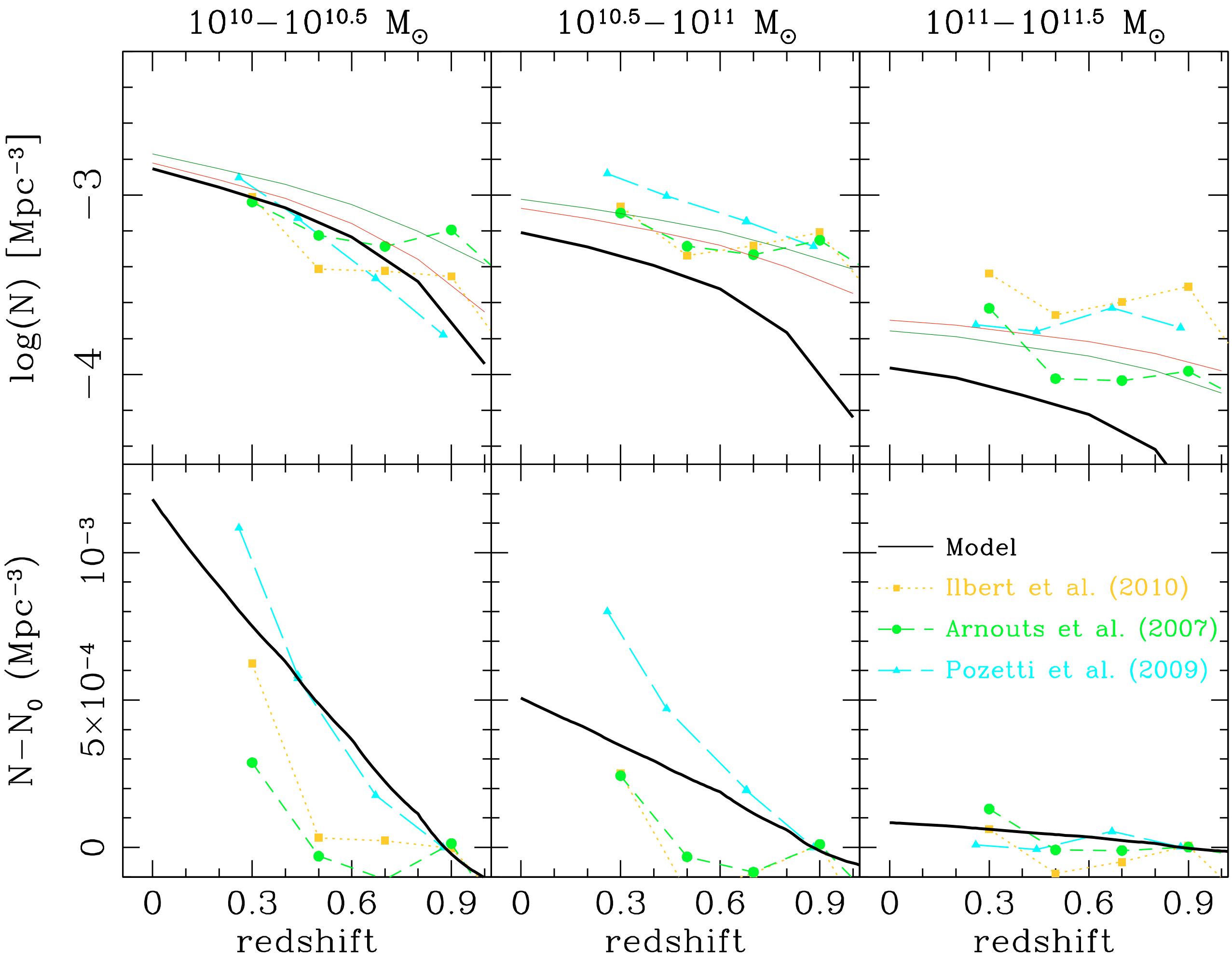

Fig. 10. *Top*: modeled evolution of the number density of quiescent galaxies (solid curves) in three stellar mass bins (left to right: $10^{10-10.5}$ $M_\odot$, $10^{10.5-11}$ $M_\odot$ and $10^{11-11.5}$ $M_\odot$) cumulated since redshift 1.1, compared to the data of Pozzetti et al. (2009) for the same mass ranges as the long dashed curves with triangles. We integrated the observed SMF of Ilbert et al. (2010) and Arnouts et al. (2007) within the same mass bins, the dotted with squares and dashed with circles curves). We also show as two thin solid curves how the model curve is shifted if we add to the newly quenched galaxies the number of quiescent galaxies already present at z = 1.1 according to the observed SMF of Ilbert et al. (2010) and Arnouts et al. (2007). *Bottom*: differential number density evolution in the same mass ranges (N_0 is the number density at redshift 0.9 in both the data and the model). See Sect. 4.2 for details.

the scope of this paper. However, we attempt to illustrate what could happen in two simple cases shown in Fig. 11. We thus start from the modeled SMF of quenched galaxies between redshifts 1.1 and 0.3 (within the mass range 10^8 to 10^{12} $M_\odot$). We then assume two merging scenarios, redistributing the mass in different ways:

– Case 1: Each quenched galaxy merge with another one, the mass of each merging galaxy being taken randomly from the initial distribution with lower mass limit 10^8 $M_\odot$ (mergers – random mass curve in Fig. 11), resulting in an average mass ratio of 0.14 for a final 10^{11} $M_\odot$ galaxy.
– Case 2: Each galaxy suffers one major merger in the redshift interval, computed by assuming that each galaxy merges with a galaxy of identical mass (same mass curve).

Jogee et al. (2009) estimates that 68% of galaxies with stellar masses higher than 2.5×10^{10} $M_\odot$ have undergone a merger of mass ratio higher than 1/10 over lookback times of 3 to 7 Gyr. After including stellar masses as low as 10^9 $M_\odot$, they find that 84% of galaxies have undergone one merger. Thus Case 1 may not be very far from the truth. Case 2 is highly biased in favor of major mergers given the results from several studies. For instance, Jogee et al. (2009) find that 16% of galaxies have undergone a major merger over lookback times 3–7 Gyr. Based on galaxy pairs, de Ravel et al. (2009) find that 22% of galaxies have undergone a major merger since $z \sim 0.9$. López-Sanjuan et al. (2009) find that 8% of galaxies more massive than $10^{10} M_\odot$ have undergone a merger since $z \sim 1$.

Case 1 shows that a few minor mergers have almost no effect on the SMF. Making e.g. ~ten minor mergers (an extreme case) rather than 1 would have an impact on the results; however, they would depend on the lower mass limit adopted for the computation, while the SMF is increasingly uncertain towards low masses.

Case 2 shows what happens if each galaxy goes through one major merger. In this case, the shape of the quenched SMF is modestly changed at low and intermediate mass where the number of galaxy at a given stellar mass is slightly reduced. Only the high-mass end of the distribution is significantly changed. In particular, major mergers seem to be the only way to build the more massive quiescent galaxies.

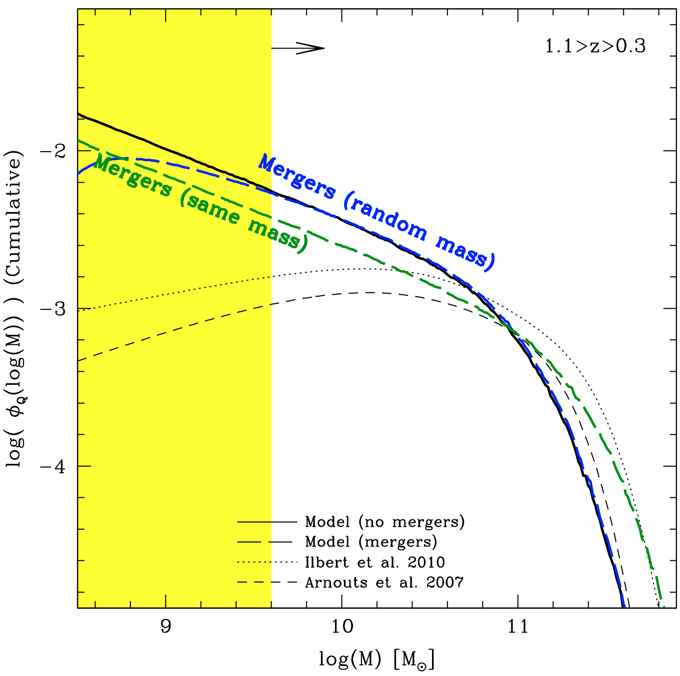

Fig. 11. The increase in the observed SMF of quiescent galaxies in Ilbert et al. (2010) and Arnouts et al. (2007) compared to Monte-Carlo realization of the cumulated quenched SMF between $z = 1.1$ and $z = 0.3$. One realization (black solid line) shows the same as Fig. 9 (i.e. result obtained by quenching star-forming galaxies by the right amount to keep a constant SMF) while others show the potential effect of various merger scenario on the mass function (see text).

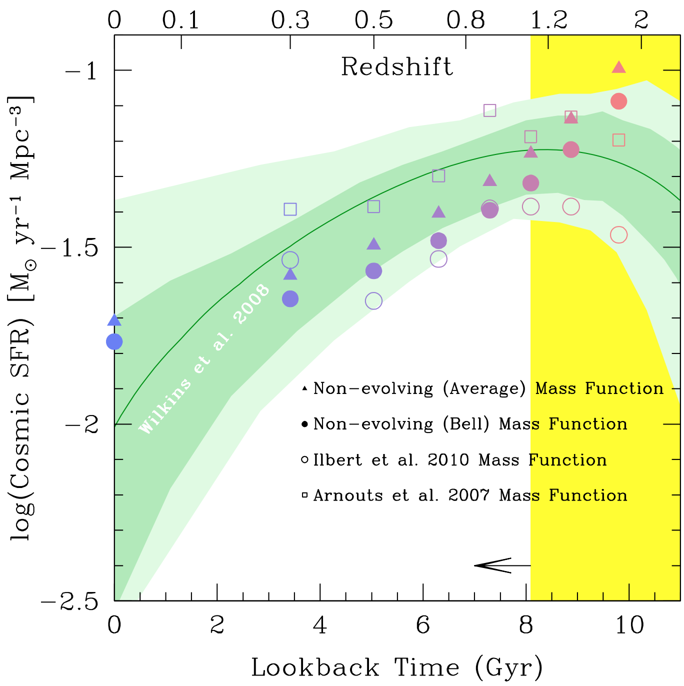

Fig. 12. Cosmic SFR density histories. The observational trend from Wilkins et al. (2008) is compared to model predictions assuming a constant SMF (filled circles assuming the Bell et al. 2003 SMF for a color-selected sample, filled triangles assuming the AMF), or using for each redshift the SMF observed at this redshift by Ilbert et al. (2010) (open circles) or Arnouts et al. (2007) (open squares). In the vertically shaded area ($z > 1.1$), the results from the models are mere extrapolations showing the limits of our approach beyond this redshift.

As seen earlier, the slope found in the intermediate/low mass range of the diagram is quite steep in the model with respect to the observations of Ilbert et al. (2010) or Arnouts et al. (2007). Figure 11 shows that simple merger models do not help solve the problem.

One assumption that has been implicitly made is that mergers do not enhance star formation. If this was not the case, a fraction of star forming galaxies woud have higher SFR than deduced from the models, and the result of the fusion would have a higher stellar mass than the one described in the basic approach of this section. However, Robaina et al. (2009) has recently shown that the additional SFR due to mergers is very modest (and then even more significant for the additional stellar mass). De Ravel et al. (2009) finds a net star formation enhancement in merging pairs of only 25%. This modest enhancement is also consistent with the merger simulations of Di Matteo et al. (2007). In fact, at this level, we do not exclude the possibility of mergers being related to the quenching itself. The merging of two star forming galaxies of similar mass may result in the quenching of their star formation, for instance through AGN formation and feedback (e.g. Sanders et al. 1988; Springel et al. 2005). This case would be exactly the same in our approach to two star-forming galaxies quenching their star formation, and to having their masses added together to form a new galaxy (Case 2 above).

In summary, in this section, we have only discussed the shape of the mass distribution of quiescent galaxies and the possible impact of mergers on it. Our conclusion is that the SMF of galaxies quenched at redshift lower than 1.1 originates in the shape of the SMF of star forming galaxies. Mergers only bring modest adjustment to the quenched SMF by re-distributing part of the mass. They probably play an important role at most at the high-mass end of the SMF.

4.4. Cosmic SFR density

In the past decade, many studies have put constraints on the cosmic SFR density history. A compilation can be found in Hopkins & Beacom (2006). In a more recent work, Wilkins et al. (2008) derives the cosmic SFR density history from a compilation of measurements of the cosmic stellar density at various redshifts. These two approaches give close results in the redshift range we are interested in, with the latter producing a smaller drop in the cosmic SFR density between redshift 1 and 0 (a factor of about 6 versus 10). We decided to use the results of Wilkins et al. (2008) as a reference for two main reasons: first, it is based on measurements of mass densities that are more consistent with our starting points of stellar mass functions than SFR measurements. Second, any evolution that we need to impose on our model to reproduce this trend is likely to be a lower limit on the actual evolution.

In Fig. 12, we reproduce the evolution provided by Wilkins et al. (2008) with their 1 and 3σ dispersion determination. We overplot the cosmic history of the SFR density obtained with the model velocity function derived at various redshift as explained before, in combination with the velocity-SFR relation from the models. Concentrating on the redshifts lower than 1 where we are confident in the models, the points are within the shaded area determining the compilation of data from Wilkins et al. (2008) even if the drop in SFR is not as great as usually considered (factor of ~3 rather than 6 since redshift 1). This is mostly because our AMF produces a relatively high cosmic SFR density at redshift 0. We also present in the figure the cosmic SFR density if the observed SMF of Bell et al. (2003), derived at redshift zero is used rather than the AMF. Very similar results are found, especially that our redshift 0 point is relatively high. This indicates a small inconsistency between the SMF of local star forming galaxies, the SFR-stellar mass relationship, and the cosmic SFR density measurements, the basic observables used to compute the redshift 0 point.

In this figure, we also attempt to relax the assumption of a constant SMF, and we use the mass functions derived by Ilbert et al. (2010) and Arnouts et al. (2007) for each redshift shown in place of the AMF for this redshift . The general trend is similar to the one obtained with the AMF, but introducing deviations around it. These deviations correspond to the scatter in the observed SMF. The approach consisting in using the AMF allows us to focus on general trends and filters out the peculiarities of individual studies (e.g. the effects of cosmic variance).

The points at redshift over 1 can be considered as extrapolations in which we have little confidence since the models are less and less reliable when moving at higher redshifts. The points show that our basic assumptions overpredict the cosmic SFR density at redshift 1.75 by a few tens of dex. Since the models underpredict the individual SFR in galaxies towards these redshifts but the cosmic SFR density is overpredicted, this means that our other assumption (the consistency of the SMF) cannot be applied at these redshifts. Indeed, the points computed with the SMF of Ilbert et al. (2010) and Arnouts et al. (2007) are in better agreement with the Wilkins et al. (2008) data.

A good way to understand the cosmic SFR density evolution is to look in Fig. 13 at the star forming galaxies SFR functions at each redshift for which they were observationally derived in Bell et al. (2007), Le Floc'h et al. (2005), and Rodighiero et al. (2010). The infrared luminosity functions from the two last papers were converted into SFR functions assuming $\log(SFR) = \log(L/L_{\odot}) - 9.97$ (Buat et al. 2008). Other references are available in the infrared, but we show Rodighiero et al. (2010) and Le Floc'h et al. (2005) for convenience as they are given for the same redshift bins, of interest to us. The latter study found slightly fewer very luminous galaxies than the former, as did Magnelli et al. (2009). For redshifts above 0.3, the modeled SFR functions are consistent with the data, especially for intermediate SFRs (a few to a few tens $M_{\odot}$ yr^{-1}) dominating the cosmic SFR density (see Fig. 6). The shape of the function does not evolve much, but is shifted towards higher SFR when moving to higher redshifts, both in the observations and the models (as normal disk galaxies had larger amounts of gas and SFR in the past). The models' distribution has a sharper drop at high SFR than the observations (especially at high redshift), which may indicate that we are missing a small number of galaxies with enhanced activity in the models. This is also the case when comparing our models to Ilbert et al. (2010) or Pozzetti et al. (2009).

We did not reproduce the "active" fraction of galaxies observed by these studies. However, because of the shape of the SFR function, such galaxies cannot dominate the cosmic SFR density , although they may contribute slightly to its evolution. To estimate this contribution, we used the Le Floc'h et al. (2005) data to compute the fraction of the cosmic SFR density that comes from galaxies with SFR higher than 10 $M_{\odot}$ yr^{-1} and that are not predicted by the models (i.e. computing the difference between the model and observed contributions to the cosmic SFR density above this SFR with respect to the total one). This fraction is equal to 13, 19, 23, 31, and 38% at redshifts 0.375, 0.5, 0.7, 0.9, and 1.1. This discrepancy was found in other simple models (e.g. Daddi et al. 2007; Davé et al. 2008). Part of the

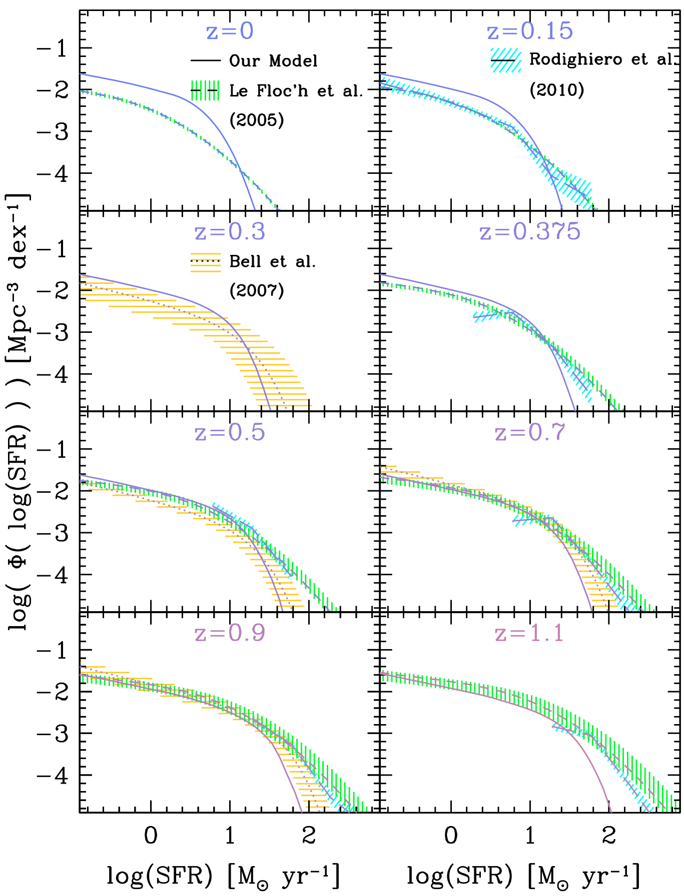

Fig. 13. Models SFR functions at various redshifts compared to observations of Bell et al. (2007) and to the infrared luminosity functions observed by Le Floc'h et al. (2005), and Rodighiero et al. (2010) converted into SFR functions assuming $\log(SFR) = \log(L/L_{\odot}) - 9.97$ (Buat et al. 2008).

difference could come from an enhancement of star formation during interactions that are not included in our approach. Actually, the recent studies of Robaina et al. (2009) and Jogee et al. (2009) suggest that major interactions trigger extra star formation. They contribute to less than 10% to the cosmic SFR density, but are responsible for some of the galaxies with the highest SFR as revealed by their infrared luminosity. This result is also recovered by the empirical models of Hopkins et al. (2010). Even so, our approach is still meaningful since these galaxies do not represent the bulk of the contribution to the cosmic SFR density.

We have seen above that the model is on the upper side of the cosmic SFR density at low redshift, thus predicting an evolution with redshift on the weaker side of the one allowed by the data. It is interesting to note that the modeled SFR functions at low redshift ($z < 0.3$ panels in Fig. 13) also overestimate the number of galaxies with intermediate SFR, around a few $M_{\odot}$ yr^{-1} (dominating the cosmic SFR density at this redshift) by up to 0.6 dex (almost a factor 4). This difference explains the excess in the cosmic SFR density obtained at low redshift in the models. The stellar mass-SFR relationship is relatively easy to construct, and different data sets provide very similar results for this amount of star formation (top left panel of Fig. 2: the average values are well within 0.2 dex of each other). The only other way to overestimate the cosmic SFR density and the SFR function in our approach is to overestimate the SMF. The AMF that we adopted is however very close to the one measured by Bell et al. (2003)

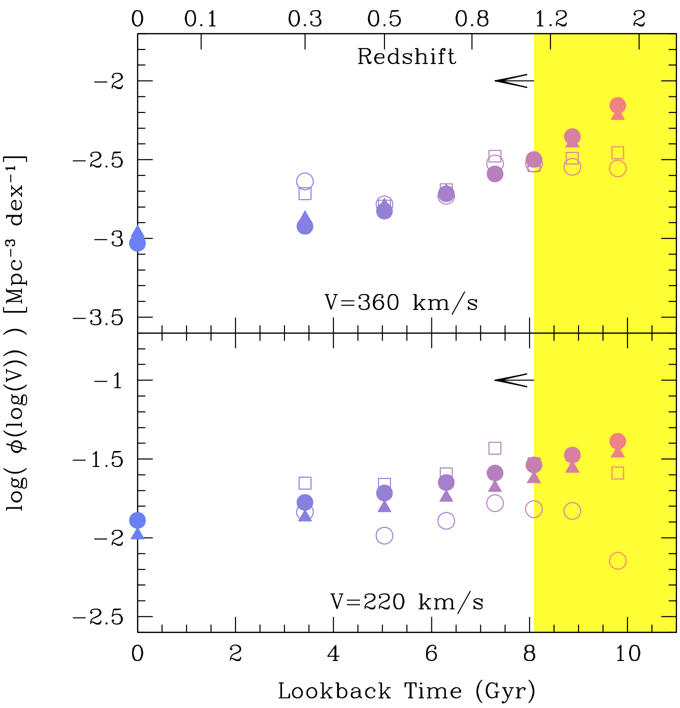

Fig. 14. Evolution of the number of Milky-Way type spirals (V = 220 km s^{-1}, *bottom*) and more massive galaxies (V = 360 km s^{-1}, *top*) with redshift. Symbols are the same as in Fig. 12.

at redshift 0. The simplest solution to this conundrum would be to consider that the local SMF reported in Bell et al. (2003) for star forming galaxies overestimates the number of galaxies with intermediate stellar mass (a few 10^{10} $M_\odot$ yr^{-1}) by a factor 2 to 4 and thus that the SMF in fact does evolve slightly at the lowest redshifts. Reducing the SMF for all redshifts would lead us to underestimate the cosmic SFR density at redshift ~0.5, thus we do need an evolution. The total observed SMF of Bell et al. (2003) is in good agreement with many other works, and is very probably fine. However, there is an intrinsic difficulty in splitting galaxies in star-forming and quiescent ones (see the dispersion at higher redshift between the various studies using various criteria for doing such a thing). Local studies are also very different in nature than higher redshift ones (local volume versus deep field). In summary, a small evolution of the SMF of star-forming galaxies at the lowest redshift could improve the agreement with SFR functions and the drop in the cosmic SFR density. Such an evolution is not visible in current data, possibly because of the combined effect of dispersion and of the intrinsic differences in local studies versus high redshift ones in terms of surveys and separation of the various types of galaxies.

4.5. The fate of the Milky Way siblings

Figure 14 shows the number evolution of star-forming galaxies of a given velocity. This is different from the number evolution of galaxies of a given stellar mass (shown more often) because the mass of star-forming galaxies evolves with time (e.g. Noeske 2009). In our approach, the velocity is attached to a galaxy. We show it for massive galaxies (V = 360 km s^{-1}, top panel) and for intermediate-mass galaxies, similar to the Milky Way (V = 220 km s^{-1}, bottom panel). This figure shows clearly that the number of galaxies with a given velocity has declined since redshift 1. The V = 220 km s^{-1} galaxies have declined by a factor of about 2 since redshift 1. Thus statistically, half of the Milky Way siblings at redshift 1 have disappeared since then! The fraction of more massive galaxies having survived is even lower. Given the discussion above, these numbers are probably lower limits: if as suggested by the SFR function, the SMF does evolve and is especially lower by a factor 2–4 at redshift zero, the evolution given above should be multiplied by a similar amount.

Beyond redshift ~1, our results are once again extrapolations that should be treated with caution. In particular, the trend obtained with a constant SMF for star-forming galaxies and the one adopting observed functions start to differ (similar to what is found with the cosmic SFR density in the previous section). The number of galaxies with V = 220 km s^{-1} is found to decline with increasing redshifts when we use the SMF from Ilbert et al. (2010; and flatten with Arnouts et al. 2007), indicating that we may reach another era when the SMF of star-forming galaxies is not constant with time, while this population is building up.

What are the processes and loci of the transformation of half of the Milky Way sisters between redshift 1 and 0? Many suggestions can be found in the literature. For instance, Pozzetti et al. (2009) propose that the transformation could be driven by several processes (aging of the stellar population, exhaustion of the gas reservoir, gas stripping, AGN feedback, truncation of gas accretion via infall or satellites, starvation, or strangulation), but they do not clearly identify it. Bolzonella et al. (2009) find some clues that the transformation is accelerated in over-dense regions; However, the environment is only roughly defined (5th neighbor). They propose a viable mechanism as a merging process triggering AGNs (but see discussion on mergers below) and finally propose strangulation (halo-gas stripping due to gravitational interaction with e.g. groups halos). On the other hand, Cowie & Barger (2008) find an effect of environment (traced by the projected nearest neighbor) only in massive galaxies (above 10^{11} $M_\odot$), while we definitively need an effect below. Martig et al. (2009) proposed the process of "morphological quenching" of the star formation, occurring when disks become dominated by a stellar spheroid stabilizing the disk against star formation. In this scenario, the spheroid can be built via major, minor merger, or disk instabilities. Although an interesting process, by itself this does not easily predict which fraction of disks are going to evolve into "red and dead" galaxies.

Regardless of the process responsible for quenching star formation, it cannot have happened only in clusters of galaxies that encompass a much smaller fraction of galaxies than the one we need to quench (point also noted in Bolzonella et al. 2009). Based on merger models, Koda et al. (2009) suggest that 70% of galaxies with a halo mass in the range 5×10^{10}–10^{12} $M_\odot$ have not suffered a merger with mass ratio greater than 0.05 after redshift 1. This point is also consistent with the results of Oesch et al. 2010, indicating that mergers cannot drive the morphological transformation at redshift less than unity. Observationally, Robaina et al. (2009) and Jogee et al. (2009) find relatively low rates of major mergers. Thus major mergers cannot explain the number decrease for Milky Way galaxies (50%) or more massive galaxies.

In summary, this major event in the history of a downsizing universe, halting star formation in previously star-forming galaxies (then becoming quiescent galaxies) must be a common phenomenom occurring on an intermediate scale, not specifically related to clusters or major mergers. Maybe we should look at the scales of groups to find the culprit (see also Tran et al. 2009, and references within). Several elements reinforce us in adopting groups as prime suspects, first that the number of galaxies in groups (55% in Eke et al. 2004) is large enough to be consistent with the large fraction of galaxies that must quench their star formation. Moreover, star formation is suppressed on the scales of groups according to Lewis et al. (2002) who find that the SFR depends on local density, regardless of the richness of groups or clusters. Kilborn et al. (2009) have recently studied HI in groups and conclude that transformation is taking place in groups in which galaxies lose gas through tidal stripping during galaxy-galaxy or galaxy-group interaction. Tanaka et al. (2007, 2009) also suggest that galaxy-galaxy interactions in groups play a major role in the build-up of the red sequence on the basis of a detailed spectroscopic analysis of galaxies embedded in filaments around two clusters at redshifts 0.55 and 1.24. Finally, Gavazzi et al. (in prep.) found that the red sequence is already formed in groups (as it is in clusters, but not among isolated galaxies).

5. Conclusions

This paper has presented an original and educational approach to working with SMFs of star forming galaxies. The main point consisted in combining observed SMFs with simple backward evolutionary models (assuming a smooth evolution driven by star formation in a galactic disk fueled by cold accretion) to obtain modeled velocity functions at various redshifts. The big advantage of the velocity is that it is a model parameter attached to a galaxy, contrary to stellar mass, which evolves with star formation. In the framework of such models, for a given velocity, the star formation history and the stellar mass history are known. Galaxies with high velocities are the precursor of today's massive star-forming galaxies (in the absence of quenching), with stars having formed at an early epoch. Galaxies with low velocities have been formed on average at later times. These histories are not ad hoc models for this paper, but have been shown to be consistent with many properties of nearby star-forming galaxies. Combining the velocity functions and the models, it is possible to compute the model predictions for several quantities and distributions at any redshift (e.g. SFR functions and cosmic SFR density).

At the current time, the empirical SMF are still rather uncertain (see the scatter between various studies). Assuming that, to the first order, the SMF is constant for star forming galaxies at redshifts lower than 1 (in accordance with the data), we obtained several interesting results:

1. A globally consistent picture is obtained in which a large fraction of star-forming galaxies quench their activity of star formation between redshift 0 and 1, building up the red sequence. The shape of the quiescent galaxies SMF is recovered above $\sim 3\times10^{10}\ M_{\odot}$. Mergers can only alter it slightly by redistributing the mass among galaxies. At most, their main effect could be seen only on the massive end of the SMF.
2. The evolution of the cosmic SFR density falls within the compilation of Wilkins et al. (2008). However, our decrease towards low redshifts is less than in the observations. The discrepency is especially due to our redshift 0 point. This may be related to a slight inconsistency between the SMF, SFR function, and stellar mass-SFR relationship of the local universe star forming galaxies.
3. The fraction of galaxies having quenched their star formation is high, in rough agreement with measurements. For example, we conclude that half of the Milky Way siblings (galaxies with circular velocities of 220 $\mathrm{km\,s^{-1}}$) have quenched their star formation since redshift 1, following a different evolutionary path than our Galaxy. This fraction is probably a lower limit since the model cosmic SFR density itself presents a relatively weaker evolution than the observed one.
4. The process responsible for this change has still not been clearly identified today. What is clear is that it is probably not related to cluster physics or to major mergers (which affect galaxies in numbers that are too small). Groups are our prime suspects because they are numerous enough to have a significant effect on the cosmic evolutions, and several studies indicate that transformations are indeed taking place in them.

In the future, we hope that wider, deeper fields and improvement in the analysis of SMFs will allow us to use the method explained in this paper on safer grounds. This will help us improve our models of galaxy evolution and build a more complete picture of the cosmic evolution of star-forming galaxies and their transformation into quiescent ones.

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