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On the mass assembly of sub-Milky-Way galaxies

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Abstract. The emerging empirical picture of galaxy mass assembly seems to be in conflict with current models/simulations based on the ΛCDM scenario, specially for sub-Milky-Way galaxies. In order to get insight into this potential issue, we developed a parametric ΛCDM-based model for calculating average star formation rates, and halo and stellar mass ($M_{\rm h}$ and $M_{\rm s}$) assembly histories of galaxies as a function of mass. The parameters of the model are constrained with the observed star formation rate-$M_{\rm s}$ and $M_{\rm s}$-$M_{\rm h}$ relations out to $z \sim 3$.

1. Introduction

Recent observational works helped us to understand how the stellar mass build-up proceeds in galaxies: the lower the stellar mass ($M_{\rm s}$), the higher is the specific star formation rate (sSFR = SFR/$M_{\rm s}$) on average at least up to $z \sim 1$ (*downsizing in sSFR*; e.g., Salim et al. 2007; Karim et al. 2011). This implies that the assembly of M_s occurs later as the smaller is the mass. On the other hand, the halo mass assembly in the ΛCDM scenario is by *hierarchical clustering*, with the smallest halos forming on average earlier than the larger ones (an *upsizing trend*). Then, the smaller the halo mass $M_{\rm h}$, the more delayed is the $M_{\rm s}$ growth of the galaxy (e.g., Firmani & Avila-Reese 2010), a trend that is difficult to reproduce in current numerical simulations of galaxy evolution (e.g., Avila-Reese et al. 2011). In this work, we present a "toy model" aimed to quantify the deviations of the average galaxy stellar mass growth from that of the halo as a function of mass and redshift. Since these inferences are based on observations, they help to constrain the physical processes involved in galaxy evolution and serve as a guide to evaluate the results from numerical simulations.

2. The model and results

We start by assuming that the baryonic infall rate is driven by the dark matter halo aggregation rate, $\dot{M}_{\rm bar}(z) = f_{\rm b,u} \times \dot{M}_{\rm h}(z)$, where $f_{\rm b,u} \approx 0.17$ is the universal baryonic fraction, and $\dot{M}_{\rm h}(z)$ is the average halo mass aggregation rate taken here from the fits to the Millennium simulation as a function of mass and z by Fakhouri et al. (2010; their Eqn. 2). Our second step is to define the galaxy SFR as a function of $M_{\rm h}$ and z as:

$$\mathrm{SFR}(M_{\rm h}, z) \equiv \dot{M}_{\rm bar} \times T(M_{\rm h}, z) \times \epsilon, \qquad (1)$$

where $T(M_\mathrm{h}, z)$ represents the "stellar deviation function" and ϵ is the normalization (efficiency). The deviation function encodes all the highly complex astrophysical mechanism that affect the M_s assembly in galaxies. We assume that it affects galaxies of different masses in a different way: for low-mass galaxies, mainly the UV background and the stellar-driven feedback reduce systematically the amounts of SF, and for high masses, the longer gas cooling times as well as the AGN-driven feedback, diminish the possibility of SF, too. Accordingly, for simplicity we assume that $T(M_\mathrm{h}, z)$ is a double power law,

$$T(M_\mathrm{h}, z) = \frac{2T_0}{\left[\left(\frac{M}{M_1}\right)^{-\alpha} + \left(\frac{M}{M_1}\right)^{\beta}\right]}, \tag{2}$$

normalized in such a way that $T(M_\mathrm{max}, z) = 1$, where M_max is the mass at which the function has its maximum; it is related to the other parameters by $M_\mathrm{max} = (\alpha/\beta)^{1/(\alpha+\beta)} M_1$. In addition, we allow the parameters to change with time as linear functions of $\log(1+z)$ and $(1+z)$ for α and β, respectively, and $\propto c_1 + c_2(1+z)^\gamma$ for M_max. In the following, we assume that M_s actually grows by in-situ and ex-situ modes; the latter represents the accretion of stars formed outside the galaxy and assembled to it by mergers,

$$\Delta M_\mathrm{s} = \mathrm{SFR} \times \Delta t \times (1 - R) + \Delta M_\mathrm{ex}(M_\mathrm{h}, z), \tag{3}$$

where $R = 0.5$ is the recycling factor due to stellar mass loss. We assume that the SFR is constant over a period of $\Delta t = 0.1$ Gyr. The ex-situ mode is parameterized by a function that increases with mass and time since $z \sim 2$.

By generating a grid of evolutionary tracks, the parameters of the toy model are constrained to fit the empirical sSFR-M_s and M_s-M_h relations (isochrones) out to $z \sim 3$ (Fig. 1). In spite of the several free parameters, this task is not easy: (1) There is a tension at low masses between the steep sSFR-M_s relation and the relatively slow evolution of the $M_\mathrm{s}/M_\mathrm{h}$-$M_h$ relation; however, recent new inferences of the latter relation by Yang et al. (2011) show a faster evolution. (2) It is difficult to fit the $M_\mathrm{s}/M_\mathrm{h}$-$M_\mathrm{h}$ high-mass slopes (Fig. 1, bottom panel); the shift with z of the peak of this relation and the drop in the sSFR for high masses require such slopes. (3) An increasing with mass of the ex-situ M_s growth contribution is required (Fig. 2, left panel) in order to reproduce the peak decrease in the $M_\mathrm{s}/M_\mathrm{h}$-$M_\mathrm{h}$ relation with z (up to $z \sim 2$). This left panel resumes the results of our approach, showing the average M_s growth of galaxies as a function of mass: while massive galaxies finished their growth by SF in the remote past (they grow yet a little but by dry mergers), the lowest mass galaxies are actively growing by SF at late epochs. Results from cosmological numerical simulations by de Rossi et al. (2012, in prep.) show this trend, but not as pronounced as our inference.

The best fit to observations of the ΛCDM-based parametric model (Fig. 1) was attained with the stellar deviation functions and efficiencies shown in Fig. 2, right panel. They are strongly dependent on mass and z. The M_h where the galaxy formation efficiency is maximal, M_max, decreases with time, and this peak efficiency is roughly the same at all epochs. At $z = 0$, $M_\mathrm{max} \approx 2.5 \times 10^{11}\ M_\odot$ ($M_\mathrm{s} \approx 6 \times 10^9\ M_\odot$). For individual evolutionary tracks, the more massive the present-day galaxy, the higher the z at which it has its maximum

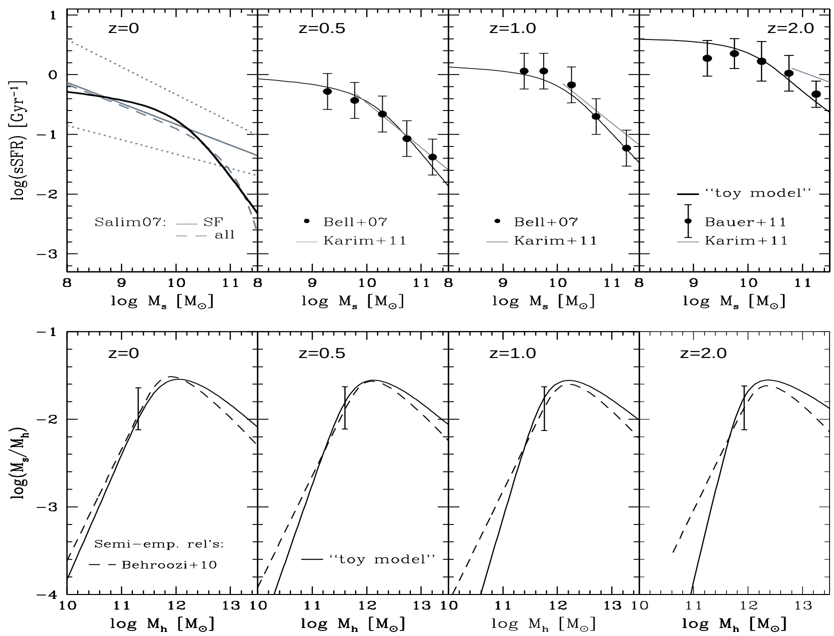

Figure 1. *Top:* sSFR vs M_s at $z = 0.0$, 0.5, 1.0 and 2.0 (solid black lines) as given by the best "constrained toy model". The grey solid line at $z = 0$ is the linear fit carried out by Salim et al. (2007) to the sub-sample of star-forming galaxies from $\sim 50,000$ SDSS galaxies (the intrinsic scatter is shown with dotted lines), while the long-dashed line is the fit to the entire sample. The points and fit lines in the high-redshift panels correspond to different observational estimates reported in the works indicated inside the panels. *Bottom:* Stellar mass fractions vs M_h (solid black line). The long-dashed curves in each panel are semi-empirical inferences as reported in Firmani & Avila-Reese (2010) based on Behroozi et al. (2010). The error bars represent the typical 1σ uncertainty of these inferences.

galaxy formation efficiency. Galaxies less massive than $M_s \approx 3 \times 10^9\ M_\odot$ did not yet attain this maximum, i.e. their efficiencies are yet increasing.

3. Conclusions

By means of a ΛCDM-based evolutionary "toy model" we showed that:

- the observed "downsizing trends" can be reproduced if strong mass and z dependent deviations from CDM halo mass aggregations rates are introduced. These deviations are physically motivated (see Sect. 2, after Eqn. 1) but at lower masses are probably too extreme (new astrophysical mechanisms might be required).
- it is difficult to reconcile the observed high sSFRs of low-mass galaxies since $z \sim 1$ with the inferred evolution of their M_s/M_h ratios.

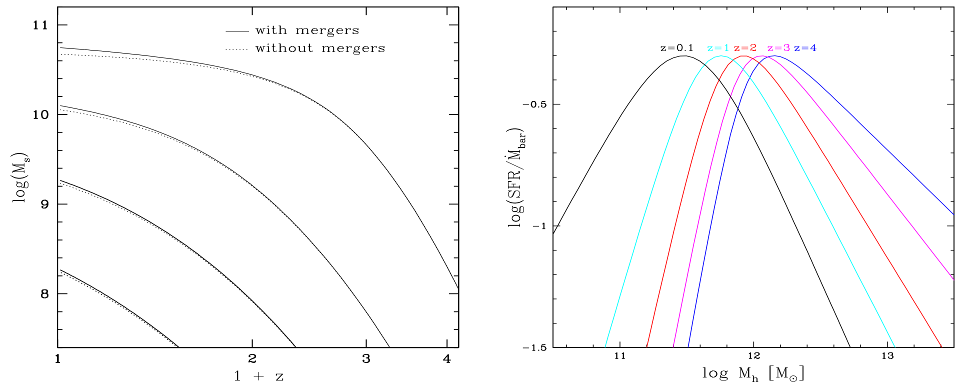

Figure 2. *Left:* Mass aggregation histories for the constrained toy model considering both modes of increment in $M_{\rm s}$ (solid lines), and only with the in-situ mode (dotted lines). *Right:* Star formation efficiency (SFR/$\dot{M}_{\rm bar}$) as function of $M_{\rm h}$ for different z.

What is behind the delay of stellar mass assembly in low-mass galaxies (*downsizing in sSFR*)? It is possible that molecular gas formation is systematically delayed in low-mass low-metallicity galaxies (e.g., Krumholz & Dekel 2011), or that the local SFR is less efficient in these small systems at higher redshifts. It should be also taken into account that the SFR, at lower masses could proceed in more bursting episodes; hence, the measured SFRs represent only the "on" population giving this rise to the steep sSFR–$M_{\rm s}$ relations. A more radical possibility is that the underlying ΛCDM scenario needs a modification related to the mass assembly of low-mass halos.

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