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The Intriguing Life of Massive Galaxies: The Connections between α_s, β and Merging

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Abstract. In this proceeding paper, we discuss the important underlying connections between the faint end slope α_s of the stellar mass function of star-forming galaxies, the logarithmic slope β of the sSFR-mass relation and merging through the continuity approach, as we introduced in Peng *et al.* (2010, hereafter P10) and (2012, hereafter P12).

Keywords. Galaxy Evolution, Mass Function, Star Formation

1. Introduction

The galaxy population appears to be composed of infinitely complex different types and properties at first sight. However, when large samples of galaxies are studied, it appears that the majority of galaxies just follow simple scaling relations while the outliers represent some minority. We demonstrate the astonishing underlying simplicities of the galaxy population emerged from large surveys and take a new approach to the topic of galaxy evolution and derive the analytical forms for the dominant evolutionary processes that control the galaxy evolution. This model successfully explained the observed evolution of the galaxy stellar mass functions (GSMF) and the origin of the Schechter form of the GSMF. All of these detailed quantitative relationships are indeed seen, to very high precision, in SDSS, leading strong support to our simple empirically-based model. This model also offers natural explanations for the "anti-hierarchical" age-mass relation and the α-enrichment patterns for passive galaxies and makes many other testable predictions. Although still purely phenomenological, the model makes clear what the evolutionary characteristics of the relevant physical processes must in fact be. This model thus offers a new powerful analytical framework to study galaxy evolution from low to high redshifts.

2. α_s of the stellar mass function of star-forming galaxies

In Figure 1 we show the evolution of the Schechter parameter α_s determined from observed stellar mass function of star-forming galaxies as a function of cosmic time from various literatures. Although the values of α_s change systematically from sample to sample, the α_s derived from a single homogeneous survey in a self-consistent way, such as the results from Pérez-González *et al.* (2008) and Ilbert *et al.* (2010), supports that the α_s of the stellar mass function of the star-forming galaxies is constant over a broad range of redshifts from z $\sim$ 0 up to z $\sim$ 2.

There might be a hint that the α_s is getting steeper at higher redshifts of z $>$ 4 from some observations as shown in Figure 1, but these measurements are highly uncertain since the completeness mass of a given survey progressively increases with increasing

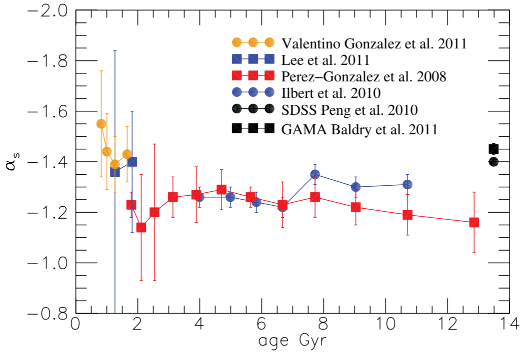

Figure 1. Evolution of the Schechter parameter α_s of the observed stellar mass function of star-forming galaxies with cosmic time in various literatures. Although the value of α_s changes systematically from sample to sample, for the α_s derived from a given homogeneous survey in a self-consistent way such as the results from Pérez-González *et al.* (2008) and Ilbert et al. (2010), it implies that the α_s of the stellar mass function of the star-forming galaxies is constant over a broad range of cosmic time.

redshift. The value of α_s can only be determined reliably if the completeness mass is well below the M* at a given epoch. To make it more difficult, the M* of the mass function at higher redshifts of z $>$ 4 is expected to be smaller than the M* in the local universe (see the discussion in P10), thus it will require a lower completeness mass to reliably determine the α_s comparing to the mass function at low redshifts. Also it is still unclear that whether the galaxy main sequence has already been in place at z $>$ 4 and thus the slope β is essentially unconstrained at these redshifts. There are some indirect evidences that the α_s of the SFR functions show no clear evolution with cosmic time from z $\sim$ 0 to z $\sim$ 7 (Smit *et al.* 2012). If we naively convert the SFR function to the mass function of the star-forming galaxies by assuming that the galaxy main sequence is already in place at z $\sim$ 7 and β is constant over cosmic time, it would imply that the α_s of the mass function of the star-forming galaxies is also constant from z $\sim$ 0 to z $\sim$ 7. In this work we will mainly focus on the redshift range where the α_s is observed to be more or less constant with time and explore its consequence through the continuity equation.

3. The connection between α_s and β

As discussed in P10, a negative value of β implies that the low mass galaxies grow faster than the more massive ones. If we do not consider any quenching and merging process, a negative β will apparently lead to the steepening of the faint end slope of the star-forming mass function, as shown in Figure 2. This will also cause the steepening of the global mass function as well, since the low mass end of the mass function is dominated by star-forming galaxies.

It can be shown analytically from the continuity equations that for negative β, α_s quickly diverges with time and for positive β, α_s converges towards the value of 1+β. Therefore, for negative β, the mass function of the star-forming galaxies is dynamically unstable and α_s will quickly steepen with time, unless $\alpha_s = -(1+\beta)$. The differential steepening will also quickly destroy the Schechter form of the mass function. Since essentially all the observations favor a negative value of β up to z $\sim$ 2, there is an apparent conflict between the observed negative value of β and the fact that the mass function of the star-forming galaxies is a Schechter function with α_s being more or less constant with epoch up to at least of z $\sim$ 2.

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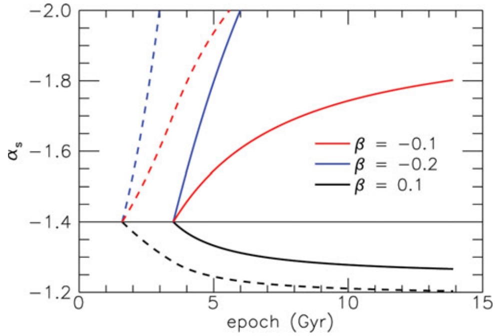

Figure 2. For non-zero β, the predicted evolution of the Schechter parameter α_s of the stellar mass function of the star-forming galaxies with cosmic time. The solid lines show if we start the evolution with $\alpha_s = -1.4$ at $z = 2$, the steepening (for negative β) or the flattening (for positive β) of the α_s. The dashed lines show that the divergence of α_s is even faster if we start with the same α_s and β, but at an earlier epoch of $z = 4$.

Destroying low mass galaxies by merging them into larger galaxies and increasing the mass of the larger galaxies, will however act to counter this steepening effect and keep the α_s constant over time. It becomes more efficient for high mass ratio mergers, i.e. minor mergers or mini mergers, to control the evolution of α_s. Since one massive galaxies can merge and destroy many low mass galaxies with only a small increase of its own stellar mass, this will help to reduce the number density of the low mass galaxies and thus to flatten α_s.

4. Constraints on mergers through the destruction of galaxies

In this section we explore the constraints on mergers via destruction of galaxies to keep the α_s constant and demonstrate the underlying connections between α_s, β and merging.

We introduce κ as the destruction rate of the galaxies by mergers. Analogous to the sSFR, we introduce the sMMR as the specific rate of mass added to a given galaxy through mergers. One key question in studying the galaxy stellar mass assembly is to understand the relationship between the sSFR and sMMR. We find the sMMR/sSFR ratio to be around 0.1 for the often observed values of $\alpha_s \sim -1.4$ (e.g. P10; Baldry *et al.* 2008 and 2012) and $\beta \sim -0.1$ (e.g. Elbaz *et al.* 2007; Daddi *et al.* 2007; Dunne *et al.* 2009; P10), i.e. sMMR $\sim 0.1\,$sSFR. This implies that on average across the whole population, mergers bring about 10% of the stellar mass that is assembled through star-formation. In other words, stellar mass assembly through merging is significant but not dominant relative to the in situ star-forming as indicated by the observed sSFR.

We also find that there is a strong dependence of the sMMR/sSFR ratio on β. More negative values of β make it increasingly hard to keep α_s constant. It becomes impossible to control α_s when $\alpha_s+\beta+2 \leqslant 0$, i.e. for $\beta \leqslant -(\alpha_s+2)$. This thus strongly argues against any claim of the possibility of having the logarithmic slopes of the sSFR-m relation that are significantly steeper than -0.1.

The galaxy merger rate at a given stellar mass m, defined as the number of galaxies that have been merged into the primary galaxy of mass m per unit time, is given by

$R(m) = x{*}\mathrm{sMMR}(m)$,

where x is the mass ratio between the merging galaxies pair.

With sMMR $\sim 0.1\,$sSFR for $\alpha_s \sim -1.4$ and $\beta \sim -0.1$, it implies a merger rate of order $0.1x\,$sSFR. For the major merger defined as having a mass ratio of $1 \leqslant x \leqslant 3$, this implies

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a major merger rate of order 0.1 sSFR$\sim$ 0.3 sSFR. If we simply take the average mass ratio of $\langle x \rangle \sim 2$, we find an average major merger rate of order 0.2 sSFR. Encouragingly, these predicted major merger rates show excellent agreement with the observed values from various literatures (e.g. Bridge *et al.* 2010; Lotz *et al.* 2011).

5. The connection between the sMMR and the assembly of dark matter halos

In the previous section we show that sMMR $\sim$ 0.1 sSFR will be able to keep α_s constant over cosmic time for $\beta \sim -0.1$, which implies a major merger rate of order $\sim$ 0.2 sSFR. As mentioned in P10 and P12, it is important to notice that both the average sSFR of star-forming main sequence galaxies and the specific dark matter Mass Increase Rate (sMIR) of typical haloes are only weakly dependent on mass, with $\beta_{DM} \sim +0.1$ (Faucher-Giguere *et al.* 2011) and $\beta \sim -0.1$. Both quantities have similar time dependence of $\sim (1+z)^{2.2}$, at least in the redshift range from $z = 0$ to $z \sim 2$. The similarity of the sSFR and the sMIR suggests that the sSFR of a star-forming galaxy is closely linked to the assembly of its dark matter halo and the star-forming galaxy may have been built up through the conversion of some fraction of the baryonic mass in the halo into stars. Thus it is not surprising to find that our phenomenological analysis requires a merger rate that is closely linked to the cosmic sSFR. The connection between the sSFR and sMIR will be further discussed in our future papers.

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