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Starburst Mergers: The IR Luminosity Function at High-z

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Abstract. At high redshifts, the observed galaxy mass functions are fit reasonably well by a Schecter function, having an exponential falloff on the high mass end, much like the mass functions for low-z galaxies. This is in stark contrast to the IR luminosity function which traces star formation activity is best fit with a power-law falloff at high luminosities.

In this contribution, I review the characteristics of galactic scale star formation in low redshift galaxies, arguing for two modes: a quiescent mode which depends linearly on the mass of molecular gas and a dynamically driven starburst mode exemplified by merging ULIRG systems. I then summarize recent analysis from the COSMOS survey relating to the cosmic evolution of the galaxy merger rate. This analysis shows the number of close galaxy pairs dramatically increasing as $(1 + z)^{2.5}$ at $z = 0.2 - 1.2$, indicating strong evolution in the galaxy merger rate. This cosmic evolution is similar to that derived for the dark matter (DM) halos in ΛCDM simulations. With this evolution of the galaxy merger rate, I have modeled the galaxy mass and star-formation luminosity functions in a Monte Carlo simulation starting from z = 6. The simulation is initiated with a galaxy mass function similar to that of the expected DM halos at z = 6, scaled down by the cosmic baryon/DM ratio, with 90% of the baryons being in the gas and10% in stars. We let the galaxies evolve – converting gas into stars via the quiescent and starburst modes of star formation, the latter triggered by galaxy-galaxy merging. In order to avoid exhaustion of the initial gas supply, it becomes clear that gas accretion from the large scale structure environment is required; otherwise the ISM contents of galaxies are far too low already by z ∼3. In this model, the power-law high L end of the SF luminosity function is the result of the merger-induced SB activity.

1. Introduction

In this contribution, I will attempt to synthesize our well-developed understanding of star formation (SF) in low redshift galaxies with constraints from theory and observations at high redshift to develop an intuitive model for the evolution of the galaxy mass and luminosity functions at high redshifts.

2. Star Formation in Low Redshift Galaxies – 2 modes

The vast majority of star formation (SF) in local galaxies occurs in giant molecular clouds. These are self-gravitating, massive ($\sim 2 \times 10^5 M_\odot$) structures with internal velocity dispersions implying an effective internal turbulent pressure typically 100 times the external diffuse ISM pressures. This suggests that disturbances in the external diffuse ISM will have little influence on the formation of stars within the GMCs. With this in mind, one might expect the general SF in galaxies to depend linearly on the overall

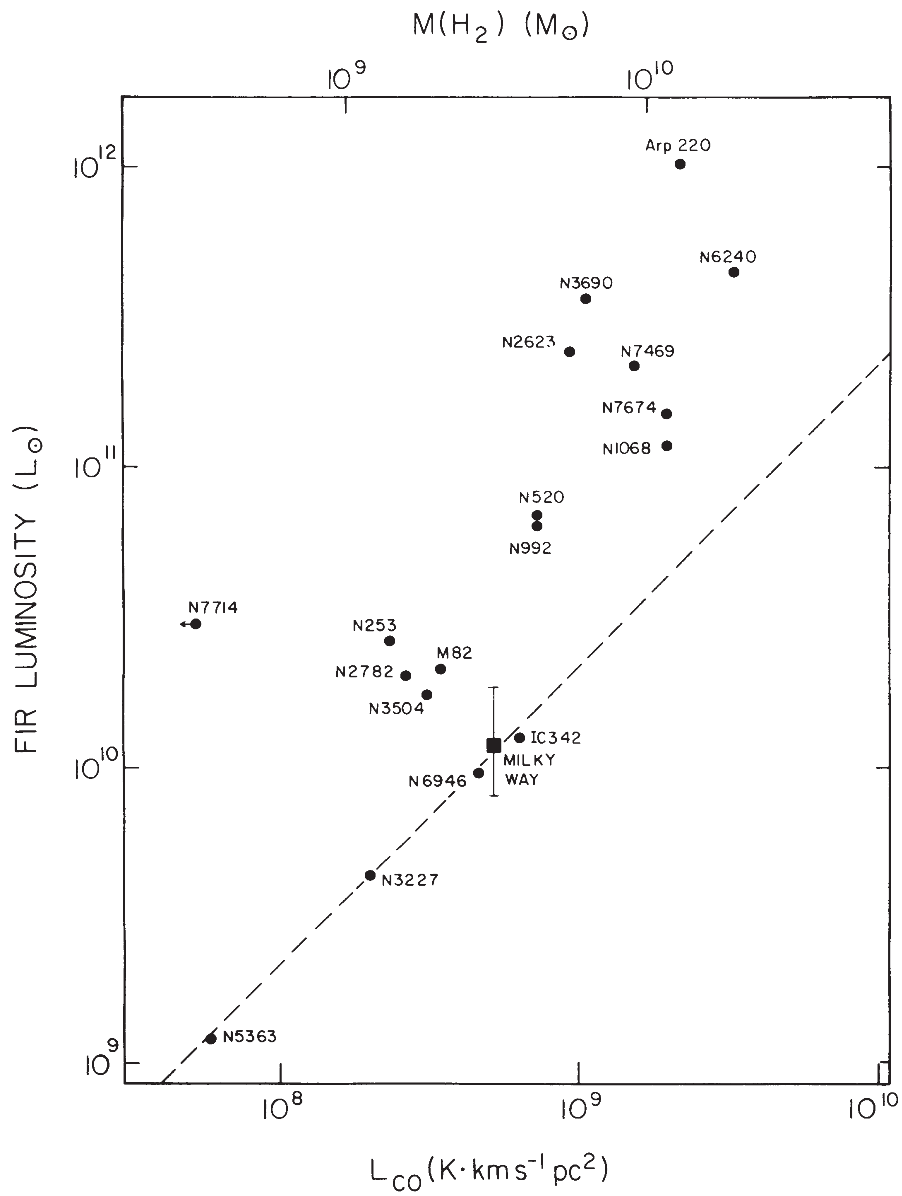

Figure 1.: The far infrared luminosity and H_2 masses are shown for a sample of nearby normal star forming galaxies and starbursting galaxies, including M82 and Arp 220 (Sanders & Mirabel 1985). For the normal galaxies there is a very linear correlation between this tracer of SF activity and H_2 mass, while for the starbursting galaxies the far infrared is elevated a factor $\sim$ 5–50.

mass of H_2 and little else (such as the galaxy type or the location within a galaxy). Indeed, observations of CO emission (tracing the mass of GMCs) and SF tracers (e.g. far infrared luminosity or Hα) have shown a linear proportionality between them. [In contrast, the atomic gas (HI) exhibits almost no correlation and is not directly relevant to the star formation, excepting that the HI gas may form molecular clouds!] The non-integral ($\sim$ 1.5) dependence of the SFR in the Kennicutt-Schmidt SF law is likely due to including HI in the analysis and in my opinion is without physical basis.] Thus there is good evidence (empirical and theoretical) for a linear mode of SF, and from local galaxies such as the Milky and M51, this can be calibrated at $1M_\odot$ per yr per 10^9 of H_2, or :

$$SFR = 10^{-9}\,(M_{H2}(M_\odot))^{-1} \quad M_\odot\, yr^{-1} \qquad (1).$$

At the same time, there are some galaxies (and even regions within galaxies) where the star formation efficiency (SFE) is clearly enhanced to a level such that they are classified as starbursts (SB). Examples include the luminous IR galaxies and the spiral arm GMSs in normal galaxies. Both have exceptionally high rates of massive OB star (and presumably low mass stars) formation. In such regions, the SFE is often enhanced by a factor 10 compared with Eq. 1 as judged by the ratio of L_{IR}/M_{H2}. In both instances, this higher SFE appears correlated with a high concentration of GMCs due to galaxy merging (and dissipative deposition of gas to the centers of the merging system) or spiral arm streaming motions which result in crowding of the GMC galactic orbits. Clearly when the cloud-cloud collision velocity is greater than the GMC internal velocity dispersion then such cloud collisions may severely influence the internal gas. This high SFE mode one could refer to as dynamically driven SB SF with a SFE 10-50 times that given in Eq. 1, but occurring only in galaxy mergers or localized regions of normal galaxy disks.

3. Star Formation at High Redshift – the same modes but different frequency

At high redshift, one might expect that the same two modes pertain, yet their relative importance could be quite altered. On the one hand, high redshift galaxies should have higher gas mass fractions than the 10% typical of low redshift spiral galaxies like the Milky Way – leading to high rates of SF associated with the quiescent linear mode of SF. But at the same time, one expects a greatly elevated rate of galactic merging/interaction to increase in the frequency of the SB mode. Which of these dominates is not at all clear without a numerical simulation to track their relative importance, keeping track of the rare and brief mergers.

3.1. Evolution of the Galaxy Merging Rates

Observational attempts to track the redshift evolution of galaxy mergers have yielded considerable divergence in the derived evolution – ranging from little or no evolution [$(1 + z)^{\sim 0.5}$; (Lin et al. 2004; Lotz et al. 2008) using AEGIS survey data)] to strong evolution [$(1 + z)^{3.1}$; Kartaltepe et al. (2007) using COSMOS data]. In Fig. 2, I show a recent analysis of closely paired galaxies selected from the COSMOS photometric redshift catalog (Ilbert et al. 2009), cross matched with the high spatial resolution COSMOS ACS-weak lensing catalog (Leauthaud et al. 2007). Here, for each L_* or brighter galaxy (with no evolution of L_*), I counted the number of galaxies brighter than 1 mag below L_* as a function of projected physical (not comoving) separation. This was done for galaxies binned in redshift out to z = 1.2 and then the evolution in each separation bin is fit by a separate power law.

The derived evolution of the pair fraction in all the bins out to 100 kpc separation is fit well by a power law: $\sim (1+z)^{2.3}$. This is in good agreement with the independent analysis presented at this workshop by Kevin Xu (2011) who finds a 1.8 power law index using the COSMOS galaxy sample but with a mass-selected galaxy sample. The steep evolution found in these studies is consistent with the dependence $\sim (1+z)^{2.5-3}$ derived for DM halos in ΛCDM simulations by Governato et al. (1999).

3.2. The Stellar Initial Mass Function (IMF) at High-z – an observational constraint

At high redshift, a fundamental issue arises from uncertainty in the stellar IMF – specifically, there are virtually no observational constraints on the lower end of the IMF. Thus, it is unresolved whether the low redshift IMFs (Salpeter or Chabrier) are applicable to galaxies forming stars at higher redshift. The lower metallicity of the high-z galaxies and the higher frequency of starbursting systems could both result in elevated ISM temperatures, leading to an IMF truncated on the low mass end (due to the higher Jeans masses). Several theoretical investigations (e.g. Baugh et al. 2005; Davé 2010) have in fact suggested truncation of the IMF at several $M_\odot$ or a flattening of the upper IMF so that the mean stellar mass was significantly raised (see also Bunker et al. 2009; Meurer et al. 1999). The motivation of these suggestions has been to reconcile the observed SFRs derived from the UV and submm (probing high mass star formation) with the stellar mass distributions of galaxies observed at low and intermediate redshift – a point emphasized by Carlos Frenk in this workshop. Thus claimed variations in the IMF are leading to uncertainties by factors ∼ 3 in the stellar mass estimates of galaxies in the early universe.

To explore observational tracers of the low mass stellar populations, we recently used the Starburst99 program (Vázquez & Leitherer 2005) to model such galaxies (Scoville & Li 2011). The Kroupa IMF used as a baseline by Scoville & Li (2011) is very similar to the Salpeter IMF (α= -2.35) on the high mass end, differing only at low masses with a flattening in the Kroupa IMF relative to Salpeter. We found that the 4000Å break and the Balmer break, arising from cool, lower mass stars, can provide a much-needed constraint on the presence of lower mass stars in the IMF. [In retrospect the realization that the 4000Åbreak might be used to constrain the low stellar mass populations seems obvious but to our knowledge hasn't been pointed out before.] To understand how strong this constraint is, we ran instantaneous starburst models with the IMF truncated on the low mass end at a variety of masses ranging from 0.1 to 20$M_\odot$. The results, shown in Fig. 3, clearly indicate that a strong D4000 index will only be seen in aging stellar populations if the initial mass function extends down to at least 5 $M_\odot$. For analyzing observations pertaining to the integrated light of entire galaxies, an instantaneous burst is unphysical since the coordination of SF over a large area is unlikely to be faster than a dynamical timescale (∼100 Myr), but the instantaneous burst models clearly illustrate the growth of the 4000Å break feature once the heavier stars expire. It is worth noting that low-z ULIRG Arp 220 actually shows the 4000Å and Balmer break features in optical spectra (Rodríguez Zaurín et al. 2008) indicating that extremely prodigeous starburst systems (> 200 $M_\odot$ yr^{-1}) can show the break features even in the presence of ongoing high mass star formation. This feature should be pur-

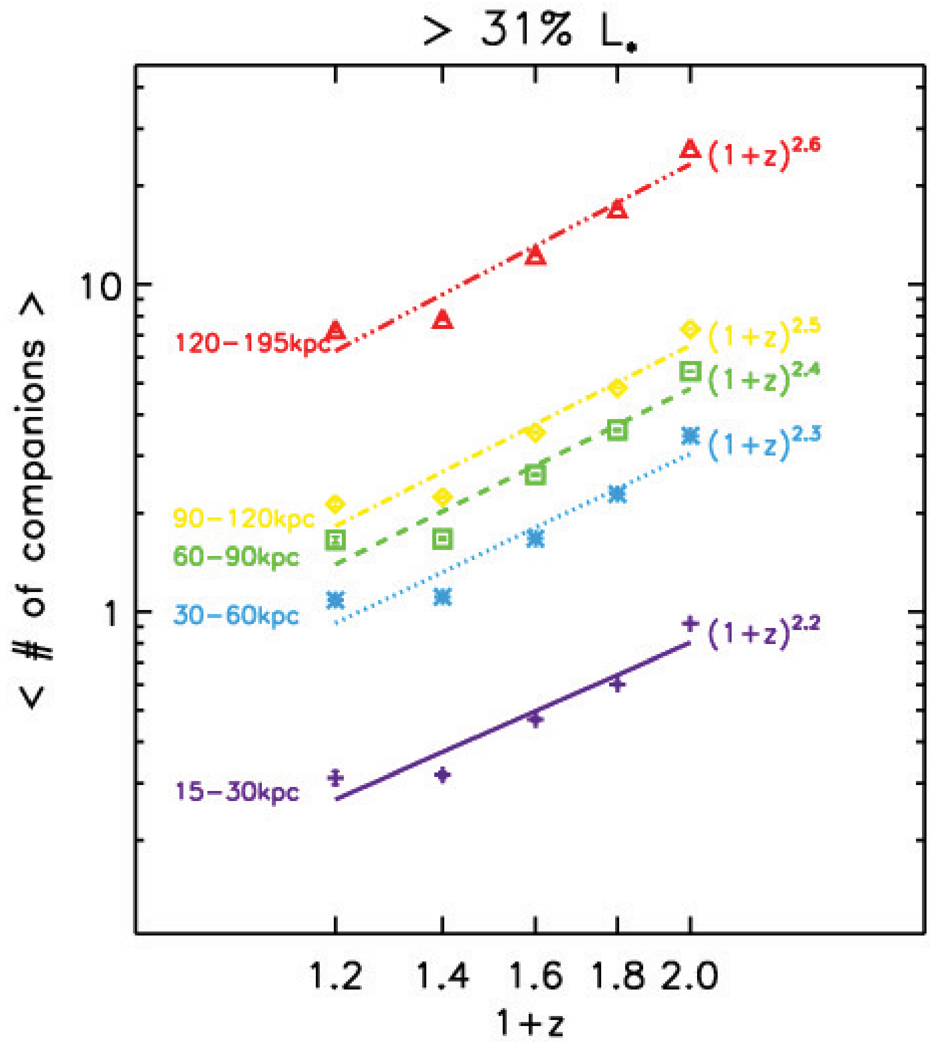

Figure 2.: The frequency of close pairs to L_* or brighter galaxies in COSMOS for bins of projected physical separation. Companions were counted down to 1 mag below L_*. Strong evolution is seen in the pair frequency, varying as $\sim (1 + z)^{2.3}$

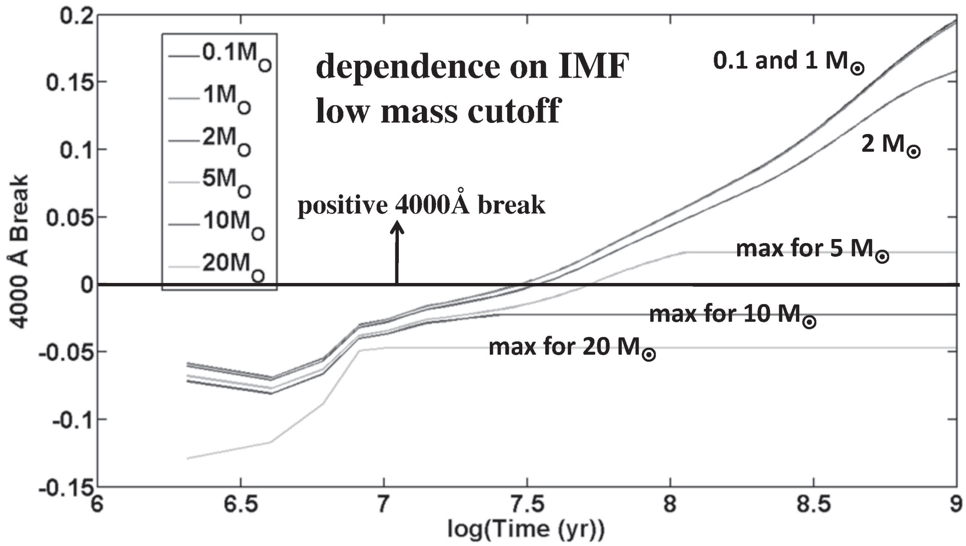

Figure 3.: The standard D4000 flux ratio (in magnitudes) used to measure the 4000Åbreak depends strongly on the low-mass truncation point of the IMF since the responsible absorption features occur only in cool star photospheres. Curves are shown for Kroupa IMFs truncated at M_{low} = 0.1, 1, 2, 5, 10 and 20 $M_{\odot}$ [From Scoville & Li (2011), obtained using Starburst99 (Leitherer et al. 1999; Vázquez & Leitherer 2005) with solar metallicity and an instantaneous burst of star formation]. A strong D4000 requires that the IMF extend down to $\sim 2--3\ M_{\odot}$ – **high redshift galaxies exhibiting a strong break cannot have their IMFs truncated at higher masses or be severely top-heavy** compared to the local Kroupa IMF. For dynamically driven starburst galaxies where the dynamical timescale is $\lesssim 10^{8}$ yrs, the 4000Å break will appear after 100 million yrs.

sued in the future to observationally constrain the low mass stellar populations in high-z starbust systems.

4. Cosmic Evolution: Stellar and ISM Masses and SF Luminosities

In order to test the framework developed above against the observed cosmic evolution of galaxies, a Monte Carlo simulation was developed – including: SF in the quiescent and merger driven burst modes, merging of DM halos and their contained galaxies and accretion of fresh gas from the external large scale structure environment. The simulation starts at z = 6 with a population of 10 million DM halos having a mass function approximating that seen in simulations for z = 6 (e.g. Heitmann et al. 2010). Each halo is started at z = 6 with a galaxy of baryonic mass equal to the DM mass times the universal baryon fraction with 90% of the baryons being gaseous ISM and 10% stellar mass. I then let the galaxy and DM halo population evolve with 50 Myr timesteps down to z = 1. At each timestep, gas is converted to stellar mass at the quiescent SF rate given by Eq. 1. At each timestep, halos are also randomly sampled for having undergone a merger with a probability weighted as $(1+z)^{2.5} M_{halo}^{0.125}$ (Fakhouri & Ma 2010). This merger rate is normalized such that 2% of the halos merge per 50

Myr at z = 6. The secondary galaxy for each merger was also selected randomly from the galaxy population weighted by $(massratio)^{-2.1}$(Fakhouri & Ma 2010). For those galaxies selected to merge, the SFE was increased by a factor of 10-50 (but only for one timestep). Gas accretion to the galaxy halo was taken as $M = 6.6(M_{halo}/10^{12})^{1.15}(1+z)^{2.25} \times 0.165$ (Dekel et al. 2009) for $M_{halo} < 10^{12} M_{\odot}$. For larger mass halos, we assumed simply that the accretion was cut off – either by the accretion shocks or by AGN feedback – the former is a departure from Dekel but some reduction of accretion is required in order to have the massive objects become gas poor ellipticals at modest redshifts as shown observationally.

Minor non-critical details which were included were that: 1) the effective accumulated of stellar mass was taken to be 70% of the integrated SF (i.e. assume 30% of the stellar mass is recycled eventually in mass loss), 2) the accretion of external gas to SF galaxy was delayed by 1 Gyr after it accreted to the halo boundary (to account for the infall time) and 3) during starbursts, ISM mass was shed from the galaxy at a rate equal to the SFR (only for the burst mode). The SF luminosity (motivated to model the IR luminosity function) was taken *very crudely* as the total luminosity from stars formed in the last 50 Myr plus that from young stars in earlier timesteps reduced by a factor 2 in each timestep. Specifically, the luminosity associated with recent SF was taken to be $10^{10} L_{\odot}$ per $M_{\odot}$ per yr of SF based on observations of local galaxies.

This simplistic model was remarkably useful to explore critical aspects of the evolutionary scheme involving quiescent and burst mode SF with a reasonable gas accretion hypothesis. Fig. 4 shows the evolved mass functions of star and ISM gas and the SF luminosity at z = 2.5 and 1. For this figure, the simulation included merging and their associated starbursts but was without accretion of gas from the environment. In this case, the ISM runs down at a rate given by local universe SF laws and the original gas content of the halos is exhausted by z = 2.5 to a level much less than that seen either at z = 2 or in present epoch galaxies. The simulation shown in Fig. 5 includes gas accretion as formulated above but without the starburst activity associated with galaxy merging. Now, the ISM and stellar mass functions exhibit characteristics similar to those observed at z = 2.5 and 1, i.e. $\lesssim$ 50% gas mass and 10%, respectively. However, even at z = 2.5, the SF luminosity function is lacking the power-law tail at the high luminosity end. To reproduce the power law tail, the starburst activity associated with galaxy merging is needed, as shown in Fig. 6. [The low mass and low luminosity ends of the distribution functions rise more steeply than is observed since no effort was made to model the behavior there – this shallow slope is often attributed to star formation winds driving galactic mass-loss at velocities above the escape velocity of lower mass galaxies.]

5. Conclusions

In this contribution I have attempted to summarize a physically intuitive approach toward understanding the characteristics of star formation in high redshift galaxies making use of our intuition gained from the low-z universe.

Given the known internal structure of the star forming GMCs, it is reasonable to expect that star formation activity will have two modes: 1) a quiescent mode in which stars form in GMCs at a rate roughly proportional to the mass of H_2 gas (accounting for the linear correlations observed between the CO emission and star formation tracers such as far infrared over the disks of local galaxies including our own) and 2) a dynam-

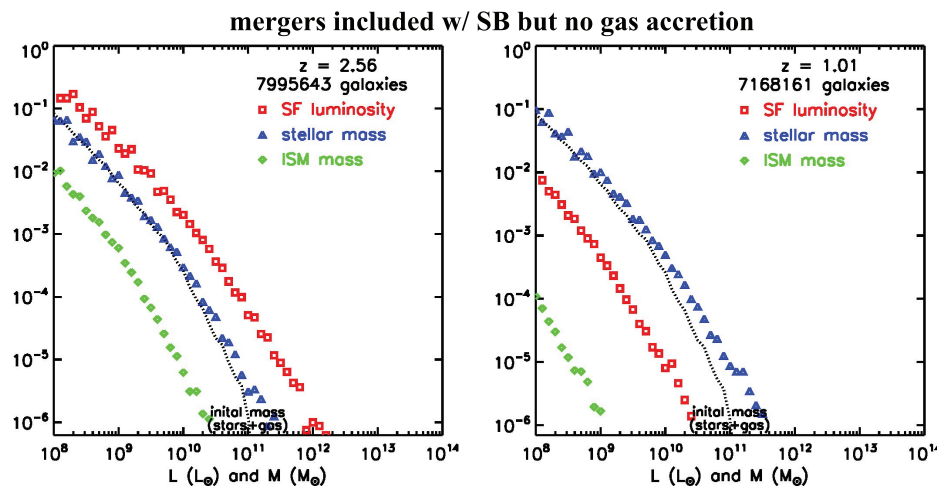

Figure 4.: The mass and luminosity functions for galaxies at z = 2.5 (left) and z = 1 (right) derived from Monte Carlo simulation including galaxy merging and associated starburst activity but no gas replenishment via accretion from the external environment. The dashed line is the original (z = 6) galaxy mass distribution (gas+stars). The original gas supply is exhausted far too quickly, even by z ∼ 2.

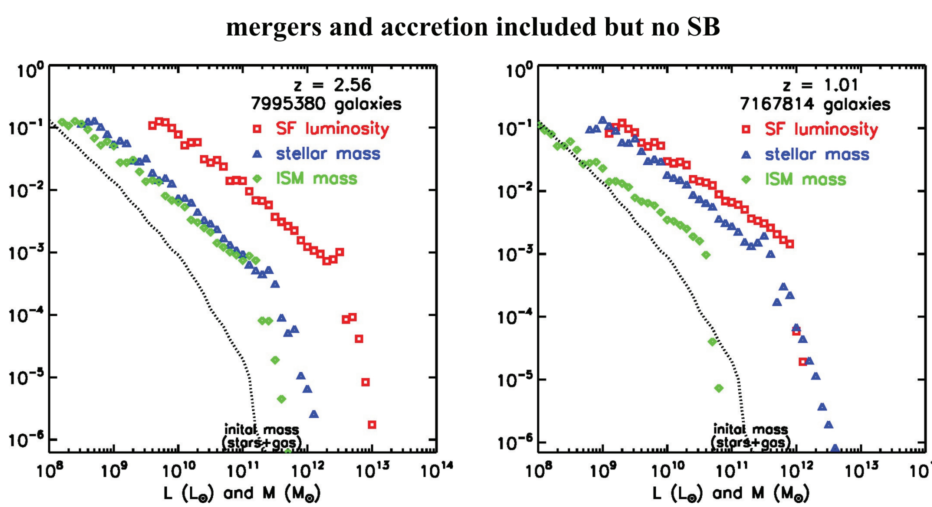

Figure 5.: Similar to Fig. 4 except that gas accretion at halo masses below $10^{12} M_\odot$ is included, following the prescription of (Dekel et al. 2009). In this simulation, the SB activity associated with merging has been removed and the high end of the luminosity function naturally must follow the exponential form of the mass distribution.

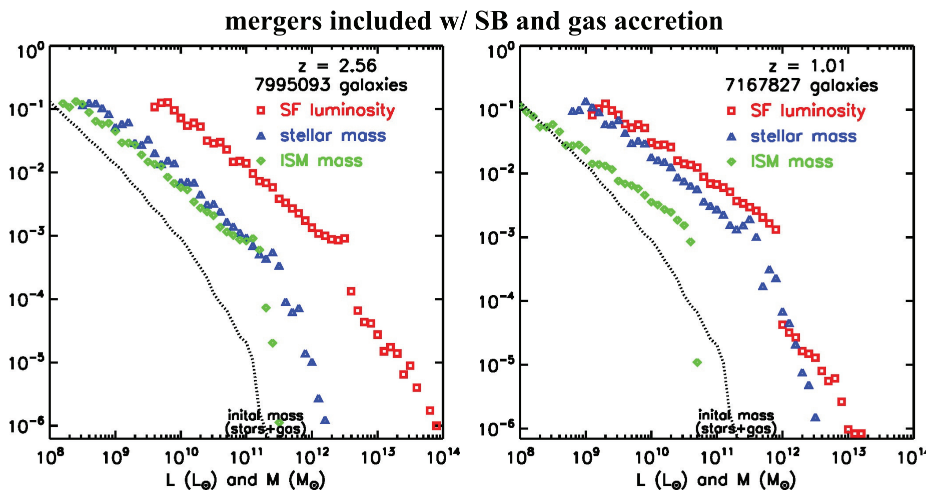

Figure 6.: Here both accretion and SB activity during galaxy merging are included, giving a reasonable qualitative match to the observed high end mass and luminosity functions.

ically triggered starburst mode in which the rate per unit gas mass is elevated by factors of 10-50 (accounting for the preferential formation of HII regions in spiral arms (despite the presence of GMCs throughout the disk) and the high luminosity to gas ratios seen in local ULRIG galaxies. For the starburst mode, the collisions of GMC clouds may significantly increase the internal structure/density of the H_2 gas and stimulated star formation due to supernovae and expanding HII regions).

At high redshift, the relative importance of these modes will be shifted, albeit in different directions, by two changes: 1) the higher gas-mass fractions (increasing the quiescent mode) and 2) the higher rates of galactic merging (increasing the starburst mode). Since observational determinations of the galaxy merger rates at high z have shown very discrepant results for the evolution, I present a recent analysis of evolution in the frequency of galaxy close pairs from COSMOS data – finding evolution as $(1 + z)^{2.3}$, in good agreement with the DM halo merger rates seen in simulations.

Another issue at high redshift, where the conditions in the gas may be quite different, is uncertainty in the stellar initial mass function since it has been speculated to be top-heavy in starbursts or low metallicity environments. I point out that this is not an insurmountable problem – observations of the 4000Å break may be used to constrain the mass of low mass stars. Until such observations are done, my conservative opinion would be to avoid the 'last refuge of scoundrels' since very little hard evidence is found in the local universe to support such variations.

To test whether the ingredients discussed above provide a reasonable basis for understanding high redshift galaxy evolution, I show the results of a Monte Carlo simulation starting at z = 6 with 10 million halos distributed in mass and with merging rates as found in ΛCDM simulations. Starting with galaxies for which the gas content is 90% of the baryonic mass, the galaxies are evolved including both star formation modes and gas accretion. The simulations clearly show the need for gas replenishment through accretion from the external environment; otherwise, the z = 2 and present epoch gas contents are far too low.

This need for accretion is simply a reflection at high-z of the well-known requirement of gas replenishment for the Milky Way. Specifically, for the Milky Way the SFR $\sim 3\ M_\odot$ per yr and the present gas content is $\sim 3 \times 10^9\ M_\odot$, implying an exhaustion timescale of only 1 Gyr. In the case of local galaxies, it does not appear that the accreting gas is HI since the high velocity HI clouds do not constitute a sufficient influx. More likely the inflow is in the form of diffuse ionized hydrogen (HII) for which imaging with high sensitivity to low surface brightness emission is required. Clearly, this is an important direction for future observations.

Another conclusion from the simulations is that the starburst mode triggered by galactic merging is necessary to account for the high luminosity power-law tail of the IR luminosity functions at high redshift. The quiescent mode cannot do this since the luminosity generated would simply reflect a scaled version of the galaxy mass function which is exponentially falling at the high mass end.

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