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The Nature of Sub-millimetre Galaxies in Cosmological Hydrodynamic Simulations

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ABSTRACT

We study the nature of rapidly star-forming galaxies at $z = 2$ in cosmological hydrodynamic simulations, and compare their properties to observations of sub-millimetre galaxies (SMGs). We identify simulated SMGs as the most rapidly star-forming systems that match the observed number density of SMGs. In our models, SMGs are massive galaxies sitting at the centres of large potential wells, being fed by smooth infall and gas-rich satellites at rates comparable to their star formation rates (SFR). They are not typically undergoing major mergers that significantly boost their quiescent SFR, but they still often show complex gas morphologies and kinematics. Our simulated SMGs have stellar masses of $M_* \sim 10^{11-11.7} M_\odot$, SFRs of $\sim 180 - 500\ M_\odot$/yr, a clustering length of $\sim 10\,h^{-1}$Mpc, and solar metallicities. The SFRs are lower than those inferred from far-IR data by $\sim \times 3$, which we suggest may owe to one or more systematic effects in the SFR calibrations. SMGs at $z = 2$ live in $\sim 10^{13} M_\odot$ halos, and by $z = 0$ they mostly end up as brightest group galaxies in $\sim 10^{14} M_\odot$ halos. We predict that higher-M_* SMGs should have on average lower specific SFRs, less disturbed morphologies, and higher clustering. We also predict that deeper far-IR surveys will smoothly join SMGs onto the massive end of the SFR$-M_*$ relationship defined by lower-mass $z \sim 2$ galaxies. Overall, our simulated rapid star-formers provide as good a match to available SMG data as merger-based scenarios, offering an alternative scenario that emerges naturally from cosmological simulations.

Key words: galaxies: formation, galaxies: evolution, galaxies: high redshift, galaxies: starburst, submillimetre, methods: N-body simulations.

1 INTRODUCTION

Sub-millimetre galaxies (SMGs; Blain et al. 2002) are among the most enigmatic objects in the Universe. SMGs were originally identified using the Submillimetre Common-User Bolometer Array (SCUBA) at 850μm and 450μm on the James Clerk Maxwell Telescope, with multi-wavelength follow-up from the radio to the X-rays. Their most remarkable property is their enormous bolometric luminosity, sometimes exceeding $10^{13} L_\odot$, most of which is emitted as dust-reprocessed light in the far infrared (IR). Because the sub-millimetre band probes a falling (versus wavelength) portion of the galaxy's spectral energy distribution (SED), SMGs have the fortuitous property that their apparent brightness is relatively invariant over a large redshift range. In principle, this can be exploited to probe star formation and/or black hole growth over a large fraction of cosmic time, but in practice this requires ancillary data to both locate the object precisely and to obtain its redshift. Radio interferometry has proven useful for this, enabling precise location of an optical counterpart for which a redshift can be obtained. In this way, the majority of SMGs are found to lie at $z \sim 1.5 - 3$ (Aretxaga et al. 2007), with the most distant one currently known at $z = 4.76$ (Coppin et al. 2009). However, the sensitivity of current radio interferometers dies out at $z \gtrsim 3$, meaning that such a selection may bias the overall redshift distribution to lower redshifts. Recent data using AzTEC at 1.1 μm suggests a somewhat higher mean redshift for these sources than the 850-μm selected ones by including 24μm counterparts (Chapin et al. 2009). In any case, it is clear that SMGs probe the brightest galaxies during the most active cosmic epoch for galaxy assembly.

Observational studies of SMGs are among the fastest-growing areas of extragalactic astronomy. Uniform and complete samples of SMGs are now being obtained such as the SCUBA Half-Degree Extragalactic Survey (SHADES; Coppin et al. 2006) covering 0.5 square degrees to a depth of 2 mJy, and there are other large samples such as that of Chapman et al. (2005). Such surveys can in principle provide interesting discriminants between models for the origin of SMGs (van Kampen et al. 2005). With new instruments such as LABOCA on the Atacama Pathfinder Experiment, AzTEC, and eventually SCUBA-2 on JCMT, and upcoming facilities in the near future such as the Large Millimeter Telescope, catalogues of SMGs will continue to improve rapidly.

Despite rapidly accumulating data, the nature of the SMGs remains poorly understood. Locally, the most bolometrically luminous galaxies are ultraluminous IR galaxies with luminosities of $L_{IR} >\sim 10^{12}L_\odot$ (ULIRGs; Sanders & Mirabel 1996), and are seen to be ongoing major gas-rich mergers, e.g. Arp 220. By the First Law of Ducks[1], it was (and often continues to be) assumed that SMGs are analogous merger events at high redshift, simply scaled up to larger luminosities owing to the higher gas content of early galaxies. The major merger hypothesis is supported by the preponderance of close neighbours (e.g. Ivison et al. 2007) and their often disturbed morphologies (Menéndez-Delmestre et al. 2007; Tacconi et al. 2008). Although recent models suggest a strong coevolution of stellar and black hole growth in major mergers (e.g. di Matteo, Springel, & Hernquist 2005), observations indicate that star formation dominates the bolometric luminosity, and active galactic nuclei (AGN) provide only a minor contribution (Alexander et al. 2005; Menéndez-Delmestre et al. 2007; Pope et al. 2008; Clements et al. 2008). This isn't necessarily a difficulty for the merger scenario if the peak star formation occurs at an earlier phase in the merger relative to peak black hole growth, as such models suggest (e.g. Narayanan et al. 2009a). But it does mean that the far-IR luminosity of SMGs can be plausibly translated into a star formation rate (SFR) without the fear of large contamination by AGN. If one adopts local calibrations (SFR$= 4.5 \times 10^{-44} L_{\rm FIR}$ erg/s; Kennicutt 1998a), the inferred SFRs are typically many hundreds to several thousands of solar masses per year.

Hierarchical models of galaxy formation have traditionally had difficulty reproducing the observed numbers and fluxes of SMGs. Two theories have figured prominently in recent discussions, both exploiting the large enhancement in star formation rates believed to accompany gas-rich major mergers: (1) SMGs are large, gas-rich, merger-induced starbursts, caught in a special phase where their luminosity is significantly enhanced over their quiescent state (e.g. Narayanan et al. 2009a) and (2) SMGs are modest-sized merger-induced starbursts whose bolometric luminosity is greatly enhanced by an extremely top-heavy stellar initial mass function (IMF; Baugh et al. 2005).

The first scenario, large major mergers, is the canonical one, and it has had recent success reproducing the detailed SEDs and CO properties of SMGs from merger simulations (Chakrabarti et al. 2008; Narayanan et al. 2009a,b). However, owing to the rarity of such large galaxies at high-z and the short duration of their merger-induced boost, this scenario may have difficulty reproducing the number density of SMGs within a hierarchical context. To be quantitative, to produce SMG fluxes (~ 5 mJy), Narayanan et al. (2009a) needed to merge galaxies with stellar masses of $\sim 3\times 10^{11} M_\odot$. Such galaxies are above L_* at these epochs and at $z\sim 2$ the stellar mass function of Marchesini et al. (2009) and Kajisawa et al. (2009) indicates that their number density is $\approx 5\times 10^{-5}$ Mpc^{-3} (comoving). In addition, the dimensionless major merger rate for such objects is around unity per Hubble time at $z \sim 2-3$ (even allowing for up to $3:1$ mergers; Guo & White 2008; Hopkins et al. 2009), meaning that if such objects are observable as SMGs for 100 Myr (as indicated in Figure 1 of Narayanan et al. 2009a), then at $z = 2$ the predicted number density of SMGs would be $\sim 2\times 10^{-6}$ Mpc^{-3}. The observed number density is up to an order of magnitude higher than this, $1-2\times 10^{-5}$ Mpc^{-3} (Borys et al. 2005; Swinbank et al. 2006; Dye et al. 2008). Similar merger simulations by Chakrabarti et al. (2008) found that even higher masses are required to produce SMG fluxes, which would result in even lower abundances. The stellar mass functions at $z\sim 2$ are still subject to significant systematics (e.g. Muzzin et al. 2009; Kajisawa et al. 2009), so the discrepancy could be less. Genel et al. (2008) found that there are enough halos with sufficient accretion rates undergoing major mergers to account for perhaps a quarter to a half of the observed SMGs, albeit with some assumptions about how rapid galaxies merge compared to their halo merger times. Dekel et al. (2009) have also proposed that rapidly star-forming galaxies at high redshift are powered primarily by smooth accretion and minor mergers, though they suggested that some SMGs themselves might still be powered by major mergers. Hence while large gas-rich mergers can certainly produce objects that look like SMGs, it is possible that a large fraction of SMGs are in fact not such objects.

An alternative scenario for SMGs was presented by Baugh et al. (2005), based on semi-analytic galaxy formation models. Owing to the paucity of large major mergers in hierarchical models, Baugh et al. (2005) were driven to argue that more common mergers of sub-L_* galaxies give rise to SMGs. But such modest-sized mergers fell far short of reproducing the observed SMG fluxes. To boost the flux, they then invoked an IMF that is flat above $1M_\odot$ during the merger event. This model can match both the number density and far-IR fluxes of SMGs (although the actual SFRs are well below those inferred using standard conversion factors), at the cost of introducing a radically top-heavy IMF in such systems. However, subsequent data on SMGs has not supported this model. For instance, this scenario predicts stellar masses significantly lower than that recently inferred for SMGs from near-IR data (e.g. Swinbank et al. 2008). Also, the IMF directly inferred from CO and dynamical observations of SMGs disfavours such dramatic departures from a standard (e.g. Chabrier 2003) IMF (Tacconi et al. 2008). Swinbank et al. (2008) discusses some possible ways to reconcile these discrepancies, but a fully consistent scenario has yet to be put forth.

[1] http://www.bpd411.org/duck.html

A third, less discussed scenario for SMGs was presented in Fardal et al. (2001). This work considered the nature of SMGs in cosmological hydrodynamic simulations, and showed that for reasonable values of dust temperatures such simulations can reproduce the observed 850μm number counts. In these models, SMGs were galaxies forming stars at high rates, $> 100\ M_\odot$/yr, but were massive systems doing so on relatively long timescales rather than in short merger-induced bursts. A similar conclusion was reached by Finlator et al. (2006). In this work on the properties of $z = 4$ galaxies from cosmological hydrodynamic simulations, it was noted that a few galaxies had extremely high star formation rates, including two exceeding 1000 $M_\odot$/yr. These galaxies were not undergoing a large burst of star formation owing to a major merger, but instead were massive galaxies that had been forming stars at hundreds of $M_\odot$/yr for some time. Such high SFRs are expected at high redshifts because the dense intergalactic medium (IGM) and short cooling times yield large accretion rates (Kereš et al. 2005; Dekel & Birnboim 2006; Kereš et al. 2009). This scenario, therefore, suggests that SMGs are not associated with major mergers at all, but are instead super-sized versions of normal star-forming galaxies.

In this paper, we follow on the works of Fardal et al. (2001) and Finlator et al. (2006) to examine in detail the nature of simulated galaxies with high SFRs at redshift $z \sim 2$, and how their properties compare to the wealth of recently obtained multiwavelength data on SMGs. We employ cosmological hydrodynamic simulations including a heuristic implementation of galactic outflows that has been shown to match observations of more typical $z \sim 2$ galaxies reasonably well, described in §2. In §3 we study the stellar masses, star formation rates, gas fractions, metallicities, environments, and clustering of simulated SMGs, and show that the "super-sized star-former" scenario comes interestingly close to reproducing many of their observed properties. In §4 we study four simulated SMGs in more detail, including their morphology, kinematics, and star formation and enrichment histories. A significant challenge to our scenario is that the SFRs inferred for SMGs are factors of few higher than in our simulated SMGs at a fixed number density. In §5 we suggest that SMG star formation rates have been modestly overestimated, and place this idea in a broader context of galaxy evolution at those epochs. We summarise and discuss the implications of our results in §6.

2 SIMULATIONS

We employ our modified version of the N-body+hydrodynamic code GADGET-2, described more fully in Oppenheimer & Davé (2008); here we review the basic ingredients. GADGET-2 uses a tree-particle-mesh algorithm to compute gravitational forces on a set of particles, and an entropy-conserving formulation of Smoothed Particle Hydrodynamics (SPH; Springel 2005) to simulate pressure forces and shocks on the gas particles. We include radiative cooling from primordial (following Katz et al. 1996) and metal (based on Sutherland & Dopita 1993) elements, assuming ionisation equilibrium. Star formation follows a Schmidt (1959) Law calibrated to the Kennicutt (1998) relation; particles above a density threshold where sub-particle Jeans fragmentation can occur are randomly selected to spawn a star with half their original gas mass. The interstellar medium (ISM) is modelled through an analytic subgrid recipe following McKee & Ostriker (1977), including energy returned from supernovae (Springel & Hernquist 2003).

Chemical enrichment is followed in four individual species (C, O, Si, Fe) from three sources: Type II SNe, Type Ia SNe, and stellar mass loss from AGB stars. The former instantaneously enriches star-forming particles, whose metallicity can then be carried into the IGM via outflows (described below). Type Ia modelling is based on the fit to data by Scannapieco & Bildsten (2005), as a prompt component tracing the star formation rate and a delayed component (with a 0.7 Gyr delay) tracking stellar mass. Stellar mass loss is derived from Bruzual & Charlot (2003) population synthesis modelling assuming a Chabrier (2003) IMF. Delayed feedback adds energy and metals to the three nearest gas particles; Type Ia's add 10^{51} ergs per SN, while AGB stars add no energy, only metals. We use Limongi & Chieffi (2005) yields for Type II SNe; yields for Type Ia and AGB stars come from various works (see Oppenheimer & Davé 2008, for details). Solar metallicity is, in our case, defined as a total metal mass fraction of 0.0189.

Kinetic outflows are also included emanating from all galaxies. Gas particles eligible for star formation can be randomly selected to be in an outflow, by which the particle's velocity is augmented by v_w in a direction given by $\mathbf{v}\times\mathbf{a}$, where $\mathbf{v}$ and $\mathbf{a}$ are the instantaneous velocity and acceleration. The ratio of probabilities to be in an outflow relative to that to form into stars is given by η, the mass loading factor. Hydrodynamic forces on wind particles are "turned off" until a particle reaches one-tenth the threshold density for star formation, or a maximum time of 20 kpc/v_w, which attempts to mock up chimneys where outflows escape that would otherwise be unresolvable in cosmological simulations of appreciable volume.

The choices for v_w and η define the "wind model". Here we use scalings expected for momentum-driven winds (Murray, Quatert, & Thompson 2005), though note that such scalings can be generated by other physical scenarios (Dalla Vecchia & Schaye 2008). In this model, $v_w = 3\sigma\sqrt{f_L - 1}$, and $\eta = \sigma_0/\sigma$, where σ is the velocity dispersion of the host galaxy identified using an on-the-fly galaxy finder. We estimate σ from the galaxy's stellar mass following Mo, Mao, & White (1998), as described in Oppenheimer & Davé (2008). f_L is randomly chosen to lie between $1.05 - 2$, based on observations of local starbursts by Rupke, Veilleux & Sanders (2005). This choice also gives outflow velocities consistent with that seen in $z \sim 1$ (Weiner et al. 2008) and $z \sim 2 - 3$ (Steidel et al. 2004) star-forming galaxies. σ_0 is a free parameter, and is adjusted to broadly match the cosmic star formation history; we choose $\sigma_0 = 150$ km/s. This yields $\eta \sim$unity for L_* galaxies at $z = 2$, which is in agreement with the constraints inferred from $z \sim 2$ galaxies by Erb (2008).

This momentum-driven wind model has displayed repeated and often unique success at matching a range of cosmic star formation and enrichment data. This includes observations of IGM enrichment as seen in $z \sim 2 - 4$ C IV systems (Oppenheimer & Davé 2006, 2008), $z \sim 0$ O VI systems (Oppenheimer & Davé 2009) and $z \sim 6$

metal-line absorbers (Oppenheimer, Davé, & Finlator 2009). Concurrently, it also matches the galaxy mass-metallicity relation (Davé, Finlator, & Oppenheimer 2007; Finlator & Davé 2008), and the enrichment levels seen in $z = 0$ intragroup gas (Davé, Oppenheimer, & Sivanandam 2008). It also suppresses star formation in agreement with high-redshift luminosity functions (Davé, Finlator & Oppenheimer 2006; Marchesini et al. 2007) and the cosmic evolution of UV luminosity at $z \sim 4-7$ (Bouwens et al. 2007). Hence although this model is heuristic and does not describe the detailed physics of wind driving, it appears to regulate star formation in high-z galaxies in broad accord with observations.

The primary simulation analysed here contains 512^3 gas and 512^3 dark matter particles, in a random cubic periodic volume of 96 Mpc/h (comoving) on a side with a gravitational softening length (i.e. spatial resolution) of 3.75 kpc/h (comoving, Plummer equivalent). We assume a WMAP-5 concordant cosmology (Komatsu et al. 2008), specifically $\Omega_m = 0.28$, $\Omega_\Lambda = 0.72$, $H_0 = 70$ km/s/Mpc, $\Omega_b = 0.046$, $n = 0.96$, and $\sigma_8 = 0.82$. This yields gas and dark matter particle masses of $1.2\times10^8 M_\odot$ and $6.1\times10^8 M_\odot$, respectively. The initial conditions are generated with an Eisenstein & Hu (1999) power spectrum at $z = 199$, in the linear regime, and evolved to $z = 0$. We have found through resolution convergence tests that this is the coarsest possible mass resolution that adequately models the star formation histories of $z \sim 2-4$ galaxies. Given that this quarter billion particle simulation took several months on ≈ 100 Harpertown cores, it represents the state of the art for studying rare large galaxies within a random cosmologically-representative volume. Fortunately, its volume is well-matched to current surveys of SMGs.

We identify galaxies using Spline Kernel Interpolative DENMAX (SKID), and halos using a spherical overdensity criterion; see Kereš et al. (2005) for more details. A galaxy's instantaneous star formation rate is the sum of star formation rates of all star-forming particles in the galaxy. When we quote metallicities, they are star formation rate-weighted, since this corresponds most closely to nebular emission line measures of gas-phase metallicities. Resolution tests indicate that galaxies with $\geqslant 128$ star particles have well-converged star formation histories; for our 96 Mpc/h box, this corresponds to $7.7 \times 10^9 M_\odot$. We take this as our galaxy mass resolution limit. Note that stellar mass functions are converged to at least half that mass (Finlator et al. 2006), but we are being conservative here. In any case, this paper will be concerned with substantially more massive systems. There are 6437 galaxies at $z = 2$ in our resolved galaxy sample.

3 SIMULATED SMGS

The defining characteristic of SMGs is their high bolometric luminosity, which most likely implies a high star formation rate. Hence to identify SMGs in our models, we make the ansatz that SMGs are the most rapidly star-forming galaxies in our simulated universe. In that case, we can identify simulated SMGs as all galaxies above a chosen SFR threshold whose number density matches the observed number density of SMGs. At $z \sim 2$, the observed observed number density is $1-2\times10^{-5}$ Mpc^{-3} (Chapman et al. 2005; Tacconi et al. 2008). Adopting a value of 1.5×10^{-5} Mpc^{-3}, the required threshold for star formation rate in our simulations is 180 $M_\odot$/yr. None of our conclusions are significantly altered had we chosen a SFR threshold higher or lower within the observationally-allowed range. Our chosen threshold yields 41 galaxies in our simulated volume of 2.58×10^6 Mpc^3. We will call this our simulated SMG sample.

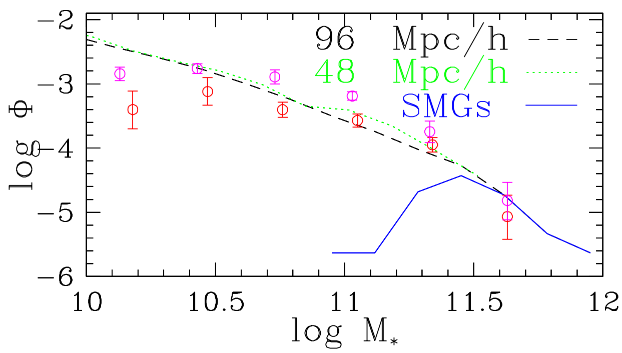

Figure 1. The stellar mass function (in number per dex per Mpc^3) at $z = 2$ from simulations (lines) and observations of Marchesini et al. (2009, points). The dashed line shows results from our fiducial 96 Mpc/h volume, while the dotted green line shows a higher-resolution 48 Mpc/h volume; the overlap demonstrates good numerical convergence. The blue line shows the mass function of our simulated SMG sample. Data points are shown at $2 < z < 3$ (red) and $1.3 < z < 2$ (magenta). Agreement with the simulations is good, particularly for $M > 10^{11} M_\odot$, which is key for this study. Note that the quoted observational errors do not include systematic uncertainties in the redshift determination or SED fitting; see Marchesini et al. (2009) for those.

3.1 Stellar mass function

In Figure 1 we show the $z = 2$ stellar mass function of our fiducial simulation (dashed line) compared to recent data from Marchesini et al. (2009) at $2 < z < 3$ (red points) and $1.3 < z < 2$ (magenta). The agreement is reasonably good, particularly at the massive end that is relevant for this work. This is critical because the number density of large galaxies (which is a key barometer of SMG models) depends sensitively on feedback prescriptions, cosmology, etc. We note that the models used in Fardal et al. (2001) and Finlator et al. (2006) overpredicted the number densities at the bright end. We suspect that the calculation of Dekel et al. (2009), in which most of the gas accreted at the virial radius ends up forming stars, would also show this flaw.[2] Hence our current simulation, and particularly its momentum-driven wind feedback prescription, provides a more plausible platform to investigate the nature of SMGs.

This figure also demonstrates numerical resolution convergence of our stellar masses. The green dotted line shows

[2] In addition, the simulation volume of Dekel et al. (2009) is seven times smaller than that used here, so it cannot statistically model a population of galaxies as rare as SMGs.

the stellar mass function from a higher-resolution simulation identical in every way to our fiducial simulation (including the same number of particles), except with half the box size (48 Mpc/h), and half the softening length (1.875 kpc/h). The agreement in the overlapping mass range with the larger-volume simulation is excellent. Overall this shows that our simulation produces a robust and observationally consistent set of galaxy stellar masses at $z = 2$.

The simulated SMGs (blue line) occupy the most massive end of the stellar mass distribution. They range in mass from $10^{11} - 10^{12} M_\odot$, and above $3 \times 10^{11} M_\odot$ nearly every galaxy is identified as a SMG. Hence, SMGs are among the most massive galaxies at this epoch in our simulations. The fact that the most rapidly star forming galaxies coincide with the most massive galaxies is our first key result, and our first prediction for the nature of SMGs.

3.2 Stellar masses

Figure 2 (top left) shows star formation rates versus stellar mass for our simulated SMG sample (green circles) and for our resolved galaxy sample (red points). The simulated SMGs lie on the SFR$-M_*$ relation defined by the lower mass galaxies, i.e. these systems are not outliers as would be expected if their SFRs are being substantially boosted by mergers. In fact, there is nothing particular that distinguishes SMGs from the remainder of the galaxy population, with the exception of their large stellar masses.

The observational data on SMG stellar masses currently span a wide range, likely owing to the numerous systematics involved with deriving stellar masses from photometric near-IR data. We show a selection of data from various authors in the figure. A key point to note is that the systematic differences in stellar masses between observational samples are significantly larger than the range of stellar masses within any given sample. To illustrate this, one can compare the Hainline (2008) data (cyan squares) with the Michalowski et al. (2009) data (blue triangles). These two analyses, for the most part, use exactly the same data for exactly the same galaxies, but employ two different algorithms to obtain their stellar masses – yet the Hainline (2008) stellar masses are on average factor of 6 lower! In general, other analyses have tended to find masses agreeing with the higher mass range; the SHADES Lockman Hole galaxies analysed by Dye et al. (2008) are shown as the magenta squares, with SFRs determined from a subset of those for which 350μm data was obtained by Coppin et al. (2008) to more accurately characterise the dust temperature. Borys et al. (2005) and Swinbank et al. (2006) also find typical SMG masses well above $10^{11} M_\odot$. However, it may be that these analyses have substantially overestimated the stellar masses owing to contamination in the rest-frame H-band (observed *Spitzer*/IRAC) by AGN (Hainline et al. 2009). In contrast, Michalowski et al. (2009) argue that the AGN contamination is small owing to a similar far IR-to-radio flux ratio in SMGs as that found in local star-forming galaxies. Clearly, the last word has not yet been spoken on the stellar masses of SMGs.

Our simulations agree well with the SHADES data and Michalowski et al. (2009) analysis showing high stellar masses. This is a strong motivating factor for preferring our interpretation of SMGs. If instead Hainline (2008) were correct and the other determinations are biased too high, then our conclusions would be significantly altered, and our scenario would not be as viable. Determining the stellar masses of SMGs to even within a factor of two would be a major step towards understanding their nature.

3.3 Star formation rates

Turning to the star formation rates, here there is clear disagreement between the simulations and the observations: the simulated SMGs have SFRs that are systematically too low by a factor of a few compared to the real SMGs. Observationally, SMGs show SFRs from $\sim 400 - 2000\ M_\odot$/yr (derived from far-IR data), whereas the simulated SMG range from $180 - 570\ M_\odot$/yr. Hence our star formation rates are too low by a factor of $\sim 2 - 4$. All the observational analyses agree for the most part, since they typically just translate far-IR flux into SFR using Kennicutt (1998a), though significant uncertainties still remain particularly owing to poor constraints on the dust temperature.

At face value, the mismatch in SFRs would seem to be a catastrophic failure of this model; clearly these galaxies need some significant boost of star formation, such as might occur in a major merger. Our simulations do not have the numerical resolution to follow the detailed dynamical processes within merging galaxies that trigger a starburst, hence one might suppose that they are systematically missing such a strongly starbursting population.

However, the answer is not so simple. As we pointed out in the introduction, hierarchical models predict that the major merger rate (i.e. $< 3:1$) of such massive galaxies is around unity per Hubble time (Guo & White 2008). Hence of our 41 simulated galaxies, one would expect that approximately 1 should be undergoing a major merger, assuming a ~ 100 Myr duration for the SFR boost. Indeed, we see one galaxy with a significantly boosted SFR, which upon inspection is undergoing a merger: It has a SFR of 574 $M_\odot$/yr (the highest among our simulated SMGs), with a stellar mass of $2.8 \times 10^{11} M_\odot$, whereas a more typical galaxy at this stellar mass has a SFR of $\sim 150 M_\odot$/yr (we will examine this galaxy further in §4). It may be that had we resolved this galaxy better the starburst might be stronger and be in better agreement with the observed SMG star formation rates. But in the larger picture, this cannot explain the boosted SFR seen in essentially *all* SMGs relative to the model expectations. Hence, mergers might obtain the correct far-IR fluxes but not the correct number density at these large masses.

One way to reconcile all of this is if SMGs probed mergers further down the mass function. If one out of every 30 galaxies were undergoing a merger (which is a maximal assumption, since the major merger rate falls to lower masses), this would imply that SMGs would have to have masses down to $\sim 3 \times 10^{10} M_\odot$ to achieve the correct number density. In that case, the observed large stellar masses would be poorly fit in the models, although this might be better accommodated if the stellar masses from Hainline (2008) are correct. This is (qualitatively) the dilemma faced by the semi-analytic models of Baugh et al. (2005), which as discussed in Swinbank et al. (2008) match the number density but fail to match the stellar masses. Furthermore, such

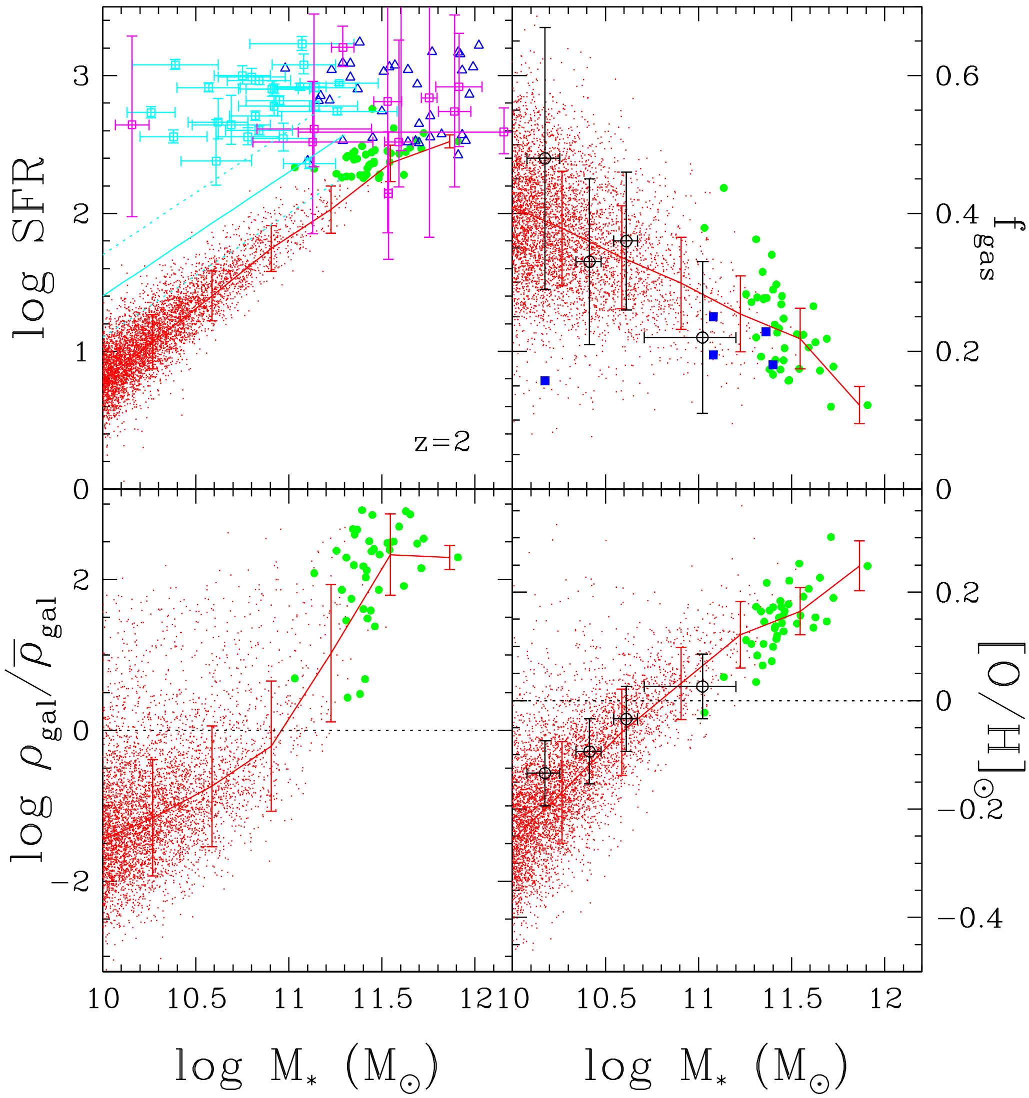

Figure 2. *Top left:* Star formation rate versus stellar mass for the simulated SMG sample (green circles), all other simulated galaxies (red points), and observed SMGs from Hainline (2008) (cyan squares), Michalowski et al. (2009) (blue triangles), and Dye et al. (2008) (magenta squares). The red line shows the median SFR$-M_*$ relation for simulated galaxies, with a 1σ scatter shown by the error bars. The cyan line shows a fit to SFR$-M_*$ for star-forming BzK galaxies from Daddi et al. (2007), with approximate 1σ error bars (± 0.3 dex) indicated by the dashed lines. *Top right:* Gas fraction $f_{\rm gas} \equiv M_{\rm gas}/(M_{\rm gas}+M_*)$ for simulated SMGs (green) and galaxies (red), plus a running median (red line). Black circles show gas fractions inferred for $z\sim 2$ BM/BX galaxies by Erb et al. (2006). Blue squares show more direct gas fractions from CO measurements by Tacconi et al. (2008). *Bottom left:* Local galaxy density smoothed over 1 Mpc spheres. SMGs tend to live in denser environments, but particularly at lower masses there is a substantial spread. *Bottom right:* Oxygen metallicity. Data points for BM/BX galaxies are shown from Erb et al. (2006). SMG metallicities tend to be higher than typical galaxies, following the mass-metallicity relation defined by lower-mass systems. Note that the lower-mass SMGs tend to have higher gas fractions, lower metallicities, and (by construction) higher star formation rates than other simulated galaxies of the same M_*.

low-mass systems would seem to require an implausibly top-heavy IMF to produce the SMG far-IR luminosities.

In short, our simulations broadly match the number densities and the stellar masses of SMGs but fail to reproduce the observed SFRs by a modest factor. Other popular scenarios fail to match different ones of these three quantities. It is not clear where the answer lies, but in §5 we will examine how the SFR discrepancy might be symptomatic of a more general problem with $z\sim 2$ galaxies. For now we will focus on examining other properties of our simulated SMGs to see how our scenario fares against other observational data, and to gain a greater physical insight into the nature of this population.

3.4 Gas fractions

The upper right panel of Figure 2 shows the gas fractions ($\equiv M_{\rm gas}/(M_{\rm gas}+M_*)$) of our simulated galaxies, with the subsample of SMGs indicated by the green points. Binned mean gas fractions from a sample of BM/BX galaxies (i.e. $z\approx 2$ photometrically-selected galaxies) are shown from Erb et al. (2006). It is worth cautioning that this comparison is fairly crude; first, the simulated gas masses are taken to be the mass of star-forming gas in each galaxy, which may not correspond directly to what would be inferred from molecular or H I emission. Furthermore, the Erb et al. (2006) data do not come from direct measurements of gas masses, but rather are gas masses inferred from the star formation rate surface density assuming the Kennicutt (1998) relation. Despite these caveats, the simulated galaxy population shows a general agreement with the trend of higher gas fractions in lower-mass systems. Note that this is critically dependent on our outflow model; other outflow models do not match as well (Davé, Finlator, & Oppenheimer 2007).

Direct measures of gas fractions at $z \sim 2-3$ are now becoming available thanks to improving millimetre interferometry. CO gas measures by Tacconi et al. (2008) are shown as blue squares in the figure. Unfortunately, once again the comparison is not straightforward, since the observations include only H_2+He, while the simulations include all the cold gas including H I. Also, the observed measurements depend on the famous X factor, the conversion factor from CO emission to molecular hydrogen mass; the data of Tacconi et al. (2008) is best fit by an X factor similar to that found in local ULIRGs, which is about 5× lower than that in the Milky Way disk. Still, the data generally lie in the range of the simulated galaxies. The one exception is the "Cosmic Eye" (Smail et al. 2007; Coppin et al. 2007) at $M_* = 1.5 \times 10^{10} M_\odot$, which is the blue point well below the relation at low masses; it could be a 2σ outlier, or its M_* or $f_{\rm gas}$ could be misestimated, or it may have a large H I reservoir. Even so, there are still simulated galaxies with similarly low $f_{\rm gas}$ at these stellar masses.

Although simulated SMGs broadly follow the $f_{\rm gas} - M_*$ anti-correlation seen in lower-mass systems, it is notable that at a given stellar mass, SMGs tend to be more gas-rich objects. This simply reflects the fact that SMGs are a SFR-selected sample, which in turn selects galaxies that have large gas reservoirs to fuel star formation. While the simulated galaxies are broadly in agreement with the data, more direct measures of gas mass, together with a better understanding of the relationship between H I and molecular gas, can potentially provide more robust and interesting constraints.

3.5 Metallicities

The bottom right panel of Figure 2 shows the metallicity of simulated galaxies versus M_*. The SMGs lie along a well-defined mass-metallicity relation that broadly matches an extension of the relation for $z \sim 2$ BM/BX galaxies (Erb et al. 2006; Finlator & Davé 2008). Because they are extremely massive, they also have quite high metallicities, typically solar or more. Note that the amplitude agreement is perhaps not so meaningful given the systematic uncertainties in metallicity measures of distant galaxies (e.g. Kewley & Ellison 2008), but the relative metallicities (and hence the trend with M_*) are likely more robust.

At a given M_*, the SMGs tend to have lower metallicities; this goes along with their gas richness and high star formation rate. In Finlator & Davé (2008) we pointed out that galaxy metallicities are set by a competition between accretion (which dilutes the metallicity) and star formation (which increases it), the balance of which is modulated by outflows. Hence, a galaxy that has recently acquired a large amount of gas through an infall event will have a lower metallicity, as well as a higher gas content and star formation rate. This predicted trend is observed in local galaxies (Ellison et al. 2008; Peeples et al. 2009). It will be interesting to see, as the data improves, whether this trend is also true in SMGs compared to similar mass-selected galaxy samples.

3.6 Environment and clustering

The bottom left panel of Figure 2 shows the local galaxy density of our simulated galaxy sample spherically averaged over 1 comoving Mpc, plotted versus stellar mass. The local density is computed using all the resolved galaxies ($M_* > 7.7 \times 10^9 M_\odot$). Our simulated SMGs clearly prefer to live in overdense environments. However, at a given stellar mass there is no particular trend; SMGs and non-SMGs are not obviously distinguished by environment. Hence the dense environs simply reflect the high degree of clustering expected for a massive galaxy population.

Observational estimates of SMG environments are difficult, owing to the relatively small and non-uniform coverages of existing surveys. Serjeant et al. (2008) found that SMGs tend to prefer dense environments (though not exclusively so), although the statistics were only definitive for $1 < z < 1.5$ systems. Tamura et al. (2009) studying the SSA22 protocluster regions at $z = 3.1$ also finds evidence that SMGs prefer to live in denser regions. Chapman et al. (2009) finds that SMGs appear to be more biased than Lyman break galaxies. The idea that SMGs tend to live in dense environments is qualitatively consistent with our model, but a quantitative comparison will have to await improved data sets, particularly over wider areas; SCUBA-2 will help in this effort.

Our large simulation volume allows us to make predictions for the clustering of SMGs. Figure 3 (top panel) shows the autocorrelation functions of simulated SMGs (solid black) at $z = 2$, along with that of our entire resolved galaxy sample (having a number density of 2.5×10^{-3} Mpc^{-3}, similar to that of bright Lyman break galaxies) and the dark matter. The autocorrelation of SMGs clearly shows a larger amplitude than the full galaxy sample, while its slope is fairly similar. The clustering length of simulated SMGs is $r_0 \approx 10h^{-1}$Mpc, compared to $5.2h^{-1}$Mpc for the full resolved galaxy sample.

In the bottom panel we show the bias of SMGs relative to all resolved galaxies (green) and to the dark matter (blue). We estimate the bias by taking the square root of the ratio of the correlation functions. Relative to the dark matter, the bias of SMGs is ≈ 6, which is about twice that of typical galaxies. In short, SMGs are highly biased and clustered objects in our simulation, as would be expected from their large stellar masses.

Observations of SMGs support the idea that they are highly clustered. Blain et al. (2005) found a correlation length of $r_0 \approx 7.5 \pm 2.6h^{-1}$Mpc for SMGs, suggesting that they are located in fairly massive halos. Farrah et al. (2006) determined $r_0 \approx 6 \pm 1h^{-1}$Mpc for ULIRGs at $1.5 < z < 3$, though many of these had IR luminosities below that of SMGs. These determinations are somewhat lower than we

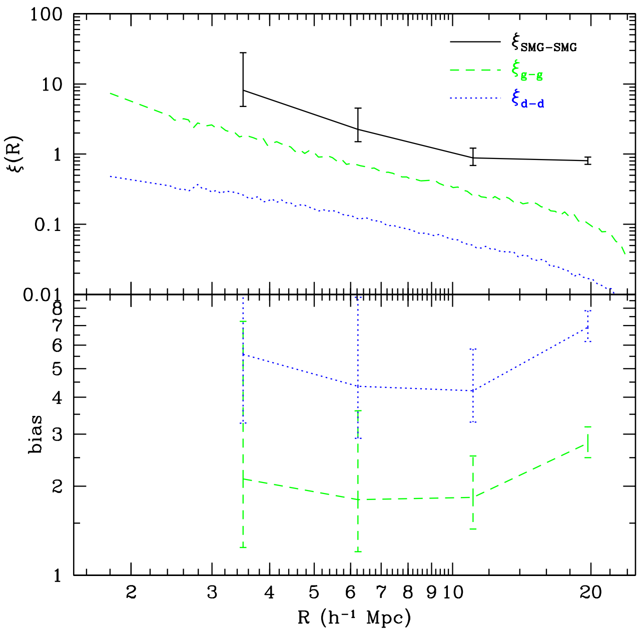

Figure 3. *Top:* Correlation function of our simulated SMGs (black solid), of our resolved galaxy sample (green dashed), and the dark matter distribution (blue dotted). Error bars on the SMG curve show Poisson errors in the pair counts; the Poisson errors for the other curves are negligibly small and are likely dominated by cosmic variance, which is not included here. *Bottom:* The bias of SMGs estimated from $\sqrt{\xi_{\rm SMG}/\xi}$ relative to the dark matter (blue dotted), and of all galaxies (green dashed). SMGs are a highly clustered population with $r_0 \sim 10h^{-1}$Mpc and a bias of ~ 6.

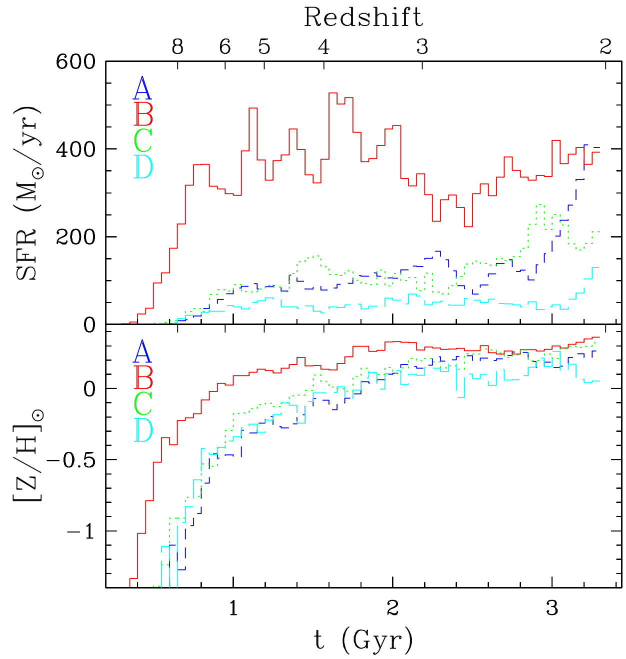

Figure 4. *Top:* Star formation histories in 50 Myr bins for the four galaxies described in text. The right edge of the histograms corresponds to $z = 2$, the adopted epoch of observation. *Bottom:* Mean metallicity of star formation as a function of time for the four chosen galaxies.

predict, although given the uncertainties, the agreement is not bad.

The general prediction that simulated SMGs live in fairly dense and clustered environments seems to be borne out, at least preliminarily, in available data. But a detailed comparison will have to await large uniform samples of SMGs as is anticipated from upcoming instruments. Clustering may provide a key discriminant of SMG scenarios, since if SMGs are mergers of more ordinary-sized galaxies, they will generally cluster as such, although a weak effect is expected from merger bias (i.e. that more massive galaxies have a higher merger rate; e.g. Guo & White 2008; Chapman et al. 2009). If SMGs are massive, they have little choice but to live in massive halos that cluster strongly.

4 EXAMPLE SIMULATED SMGS

We now concentrate on several individual simulated SMGs to study their properties in more detail. We choose four galaxies that span the range of SMGs from our $z = 2$ simulation output:

A. The highest SFR SMG ($M_* = 2.8 \times 10^{11} M_\odot$, SFR=$574 M_\odot$/yr);

B. The most massive SMG ($M_* = 7.9 \times 10^{11}$, SFR=$334 M_\odot$/yr);

C. The median M_* SMG ($M_* = 2.7 \times 10^{11}$, SFR=$224 M_\odot$/yr);

D. The least massive SMG ($M_* = 1.1 \times 10^{11}$, SFR=$216 M_\odot$/yr).

We also refer the reader to our website, `http://luca.as.arizona.edu/∼oppen/IGM/submm.html`, where we show images similar to Figure 5 for all of our simulated SMGs.

4.1 Star formation and enrichment histories

Figure 4, top panel, shows the star formation histories (SFHs) of these four galaxies. Overall, the SFHs are relatively constant since $z \sim 6$ ($t = 1$ Gyr), with the larger stellar masses simply owing to a higher rate of quiescent SF. Excursions at the $\sim \times 2$ level from the time-averaged SFR are not uncommon.

However, in their recent histories, i.e. in their last ~ 200 Myr, our SMGs divide into two types, ones whose current SFR is comparable to their recent average (B,C) and ones that are experiencing a current boost in their SFR (A,D). This is directly related to where they lie in the SFR$-M_*$ plane (Figure 2): A and D are clearly outliers above the median SFR, while B and C lie close to the median. Hence, we can generalise these trends by looking at where SMGs lie relative to other galaxies in the SFR$-M_*$ plane.

The careful reader will note that the final $z = 2$ SFRs in Figure 4 are not always identical to the SFRs listed for these objects in §4. The difference is that the plot shows 50 Myr-averaged star formation rates, while the numbers quoted above are instantaneous SFRs. For the more quiescent systems, B & C, the numbers are similar but for the bursting systems, A & D, the instantaneous rate is non-trivially higher than the past 50 Myr smoothed average.

While the scatter in SFR$-M_*$ is fairly small (0.3 dex), this is still comparable to the spread in SFRs for SMGs, which means that a SFR-selected sample like SMGs will preferentially pick out galaxies like A and D that are undergoing a boost. Therefore, despite an underlying trend in SFR$-M_*$, examining only SMGs in current samples would likely result in a scatter plot in this plane, as shown in Figure 2. As one probes to lower masses, SMGs more strongly select high-SFR outliers in SFR$-M_*$.

Figure 4, bottom panel, shows the growth of metallicity in these galaxies. All four galaxies enrich themselves to at least 50% solar by $z = 6$, showing that even with strong outflows that drive the majority of metals into the IGM, massive galaxies still enrich themselves quite rapidly. The most massive galaxy has the earliest formation epoch and hence the earliest metal growth, but by $z \sim 4$ all the galaxies have similar metallicities around solar. A consequence of rapid enrichment is that there is also expected to be large amounts of dust in these galaxies from a fairly early epoch (assuming that dust production tracks metallicity on a reasonably short timescale), providing the obscuration required to produce the large far-IR luminosities. We leave for future work an analysis of dust reprocessing in these systems to predict a detailed SED (as in Narayanan et al. 2009a); this will likely require substantially higher spatial resolution than we can currently achieve in representative cosmological volumes.

4.2 Morphologies and kinematics

One argument in favour of a merger origin for SMGs is their apparently compact and disturbed morphologies. Double nuclei, tidal tails, and kinematics that depart strongly from simple spiral or elliptical galaxies are seen in many cases (e.g. Tacconi et al. 2006, 2008). How can a model that postulates that these objects are oversized but otherwise normal star-forming galaxies be reconciled with such a scenario? The short answer is, at this epoch *most* star-forming galaxies are compact and disturbed (Giavalisco 2002), hence such traits are not necessarily indicative of an ongoing merger as would be the case locally (Law et al. 2007).

Figure 5 shows 50 × 50 kpc (physical; about 12" at $z = 2$) maps of our four example simulated SMGs, in various physical quantities. Galaxy A (left panels) is undergoing a merger at this epoch with a smaller object about one-eighth its mass, seen just to the lower left. This results in a more centrally-concentrated distribution of gas and stars compared to the other systems, as well as a fairly chaotic velocity field. We note that the smaller object was originally significantly larger, about twice its current mass, but was tidally disrupted to its current size during the merger.

The largest galaxy, B, appears the most quiescent and ordered of them all. It shows an extended gaseous star-forming centre with a large central galaxy showing ordered rotation. It is being fed by gas along various streams, but while some lumps are apparent, the majority comes in relatively smoothly. As argued in Kereš et al. (2009), that is typically the case for high-z galaxies.

The other two galaxies (C,D) show more typical examples of simulated SMGs. In both cases they show relatively extended gas and star-forming regions, at least compared to A. However, the velocity fields do not show any particular order, as there are a fair number of other small galaxies in the vicinity as well as infalling gas resulting in somewhat chaotic kinematics.

The actual appearance of these galaxies in observable bands depends on a number of other effects. CO traces neutral gas density to some extent, modulo variations in the molecular gas fraction and the ratio of molecular gas to CO. Ongoing star formation can be traced directly in the far-IR continuum, although the relationship of the reradiating dust to the star formation may not be trivial. Radio observations may provide a more direct constraint, assuming that any contribution from a central AGN can be resolved out. The stellar density can be most directly traced in the rest near-IR, but given the amount of dust in SMGs, even those wavelengths can be substantially affected by extinction and its associated patchiness. The velocity field traced in Hα with integral field units such as SINFONI (Förster Schreiber et al. 2009) provides a fairly direct measure of the star forming gas kinematics, if not extincted. All these observations are possible today, but their interpretation is complex. Dust and molecular radiative transfer models as in Narayanan et al. (2009b) are required for a proper interpretation; in a fully cosmological setting this is a strong challenge for numericists in the coming years.

Using millimetre interferometry plus other wavelength data, Tacconi et al. (2006) provide a variety of evidence that SMGs are scaled-up versions of local major mergers seen as ULIRGs. Many of the arguments involve the compactness of the star formation as seen in CO lines, typically $1-2$ kpc, although these were high-CO transitions that typically come from only the densest gas. On the other hand, there is good evidence from radio interferometry that the star formation in SMGs is extended over many kpc scales (as in our simulated SMGs in Figure 5) and not confined to the nucleus as in local ULIRGs (Chapman et al. 2004; Biggs & Ivison 2008). Also, SMGs appear significantly less reddened than nuclear starbursts, which further differentiates them from nearby ULIRGs (Hainline et al. 2009). This may argue against the major merger interpretation, since in mergers the star-forming gas is generally driven into a very compact and highly obscured nuclear starburst that in local ULIRGs are $\lesssim 1$ kpc, although simulations of SMGs from mergers do show larger extents of a few kpc (e.g. Narayanan et al. 2009b). Hence, current results on CO morphologies are not conclusive at to whether or not SMGs are major mergers or not, and it remains possible that SMGs could be a heterogeneous population. The kinematics are also not yet conclusive, as even our non-merging systems show disordered kinematics. A key advance in this area would be high-resolution imaging in the near-IR, with, e.g., *Hubble*/WFC3 or JWST, to probe the stellar distribution on sub-arcsec scales (modulo patchy extinction). We predict single smooth stellar distributions in most cases with perhaps small companions, whereas a pre-coalescence major merger would clearly show two distinct large concentrations.

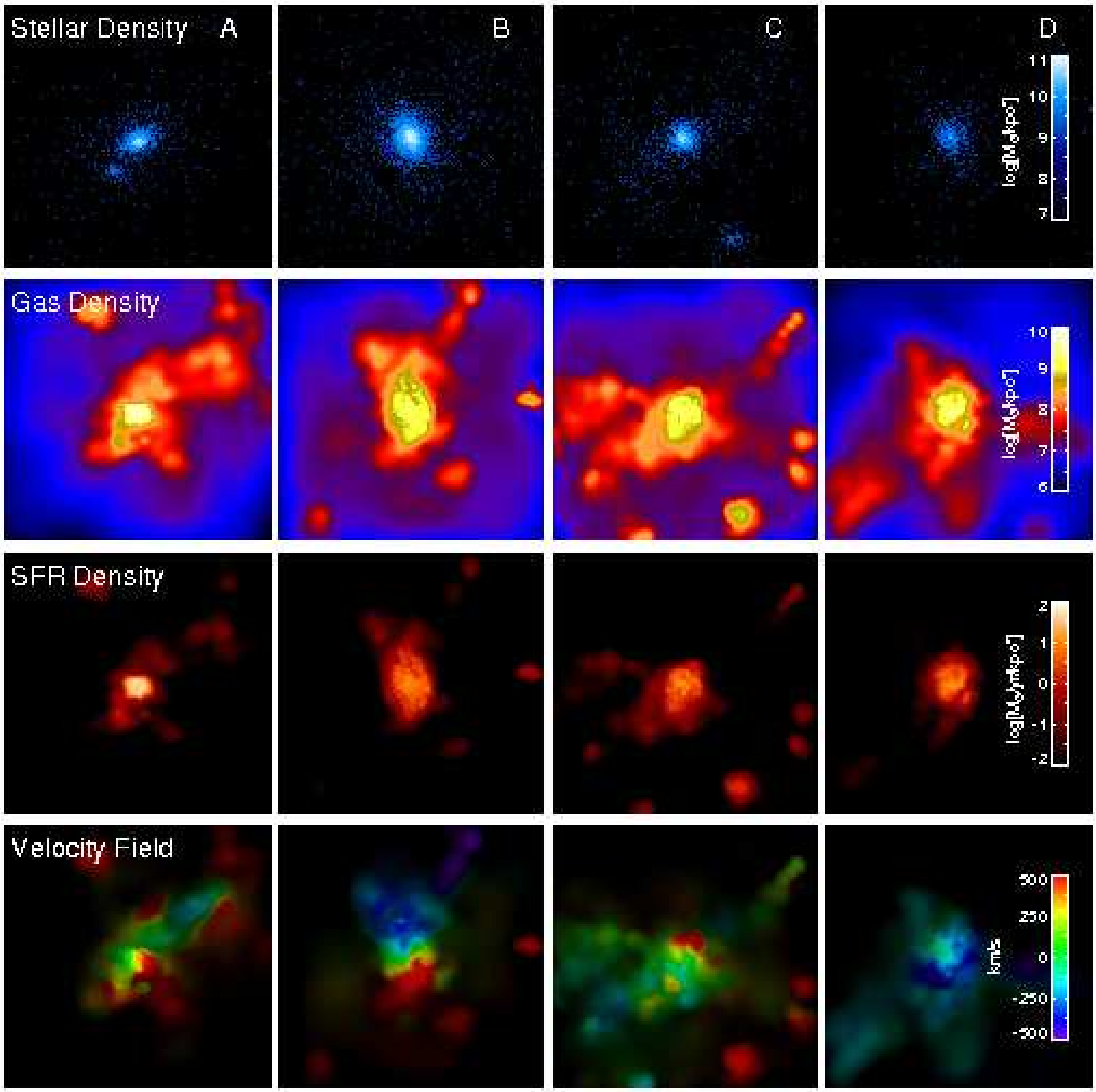

Figure 5. Simulated $z = 2$ SMGs A, B, C, D (left to right), in slices 50 kpc (physical; 6") across, showing from top to bottom the stellar density, gas density, star formation rate density, and line-of-sight velocity field.

5 RELATIONSHIP TO OTHER GALAXY POPULATIONS

5.1 Are the observed star formation rates overestimated?

The overall properties for SMGs derived from simulations broadly agree with the available observations of SMGs, including their stellar masses, gas fractions, morphologies, and clustering. However, there is still one clearly discrepant issue: the star formation rates in the simulated galaxies are a factor of a few below that inferred from far-IR measures of SMG SFRs. Is this discrepancy sufficiently serious to rule out our scenario for SMGs, or is there a plausible explanation?

To investigate this, we introduce the star formation activity parameter

$$\alpha_{\rm sf} \equiv (M_*/{\rm SFR})/(t_H - 1{\rm Gyr}) \qquad (1)$$

(Davé 2008). $\alpha_{\rm sf}$ measures the fraction of a Hubble time (minus the first Gyr in which little growth happens) that this galaxy must form stars at its current rate to produce its current stellar mass.

Figure 6 shows $\alpha_{\rm sf}$ for the simulated SMGs (green

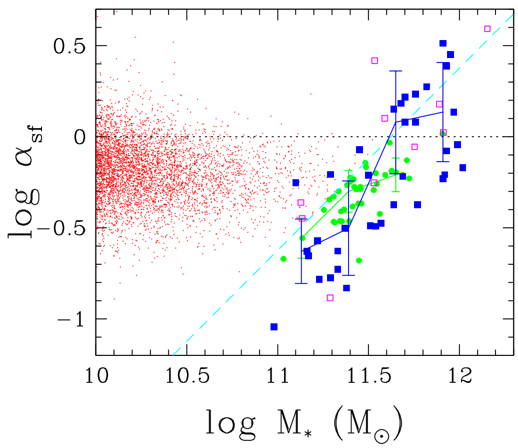

Figure 6. The star formation activity parameter $\alpha_{sf} \equiv (M_*/\mathrm{SFR})/(t_H - 1~\mathrm{Gyr})$ for the simulated SMGs (green) and all the simulated galaxies (red), with green solid lines showing the running median for the SMGs. The cyan dashed line shows a limit of SFR= 180 $M_\odot$/yr at $z = 2$. Observations of SMGs from Michalowski et al. (2009) and Dye et al. (2008) with the SFRs arbitrarily lowered (and thus α_{sf} raised) by a factor of 3 are plotted as blue triangles and magenta squares, respectively, with a running median shown for the Michalowski et al. (2009) sample. Such a rescaling places the median value of α_{sf} in line with simulated SMGs.

points), which indicates that $\alpha_{sf} \approx 0.8$ for simulated galaxies in this mass range. Taking the data of Dye et al. (2008) and Michalowski et al. (2009) at face value yields a typical $\alpha_{sf} \approx 0.2 - 0.3$. If we apply an ad hoc correction factor of $\times 3$ to their α_{sf}, then the results are as shown by the blue and magenta data points. This results in good agreement between the simulated and observed SMGs, with a median $\alpha_{sf} \approx 0.7 - 0.8$. This shows that to reconcile our model with data, M_*/SFR must be overestimated in the models or underestimated in the data by about a factor of three.

Let us first consider whether the simulations might underestimate the star formation rates by $\sim \times 3$, perhaps owing to some details of the subgrid star formation prescription. It turns out this is not viable in a cold mode accretion-driven scenario, where the star formation rate is strongly limited by the gas supply rate, which in turn is set predominantly by the gravitational accretion rate (Kereš et al. 2005; Dekel & Birnboim 2006; Kereš et al. 2009). That is the reason why $\alpha_{sf} \sim 1$ is a fairly generic result attained in both numerical and semi-analytic galaxy formation models (Davé 2008). Hence, the model galaxies cannot form stars faster unless gravity brings gas in faster. Alternatively, we argued in §3.3 that mergers are unlikely to be responsible for such an underestimate, since only a small fraction of galaxies are undergoing a merger at any given time.

One could equivalently match α_{sf} by claiming that the observed stellar masses are underestimated by $\sim \times 3$. However, this would then require galaxies with quite large stellar masses, which grossly exacerbates the problem of producing enough such systems by $z \sim 2$ in a hierarchical cosmology. Note that the recently discussed stellar population issue of thermally pulsating AGB stars (Maraston et al. 2005) would tend to lower, not raise, the inferred stellar masses, though it is not expected to be a large factor compared to the current systematic uncertainties.

Hence for our scenario to be viable, the observed star formation rates in SMGs must have been overestimated by a (modest) factor of 3. It seems rather presumptuous to claim based on our models that observations are wrong, but a factor of 3 does not seem out of the realm of possibility, given the current uncertainties involved in converting various fluxes to star formation rates in high-z galaxies.

As an aside, a subtle predicted trend is that α_{sf} is correlated with M_*. This is characteristic of a SFR-selected sample; the dashed cyan line in Figure 6 shows our adopted SFR limit of 180 $M_\odot$/yr. Smaller SMGs would be preferentially selected to have elevated SFRs (and hence lower α_{sf}), while more massive galaxies are more quiescent and so would have $\alpha_{sf} \sim 1$. This trend is also seen in the observed samples but only weakly, probably owing to the currently large systematic uncertainties in determining M_* and SFR.

There are other lines of evidence that suggest that SFRs in $z \sim 2$ galaxies of *all* types have been overestimated. As pointed out in Davé (2008), this would reconcile the observed values of α_{sf} in BzK galaxies (Daddi et al. 2007) with the simulated α_{sf}. More such evidence comes from examining the global cosmic star formation rate density evolution versus stellar mass growth (Wilkins et al. 2008); they showed that the time derivative of the cosmic stellar mass density at $z \sim 2$ is lower by $\sim \times 3$ compared to the star formation rate inferred from high-mass tracers such as Hα or UV (though see Reddy & Steidel 2009), suggesting that the true SFR is lower than that obtained using conversion factors from Kennicutt (1998a).

Possible physical reasons for such an overestimate are numerous. It could simply be a calibration issue; the locally-calibrated conversions between far-IR, UV or radio luminosities could be off by this factor in the case of high-z galaxies. Galaxies as active as SMGs do not exist in the local Universe, so it is difficult to test such calibrations in analogous systems nearby. One could imagine that the physical conditions in the ISM are systematically different, since high-z galaxies tend to have much higher star formation rate surface densities than typical galaxies today (Erb et al. 2006; Tacconi et al. 2008). It could also be an issue with dust temperatures, as the inferred SFR is highly sensitive to its assumed value (e.g. Fardal et al. 2001). Observations of 350μm and 850μm fluxes by Coppin et al. (2008) indicate a typical dust temperature of 28 K (with substantial scatter), which is lower than the canonically-assumed 35 K from local starbursts (Dunne et al. 2000); this will be better determined with upcoming *Herschel* data. The lower temperature could imply as much as $\times 2$ lower SFRs. There also may be some far-IR light from AGN, particularly for the most luminous sources, although direct estimates show that it is likely to be sub-dominant in SMGs. Finally, SED fitting itself can be uncertain at a factor of $\sim 2-3$ level in SFR when only broad-band data are employed (Muzzin et al. 2009), although it's not clear that this would provide a systematic shift. It is not a stretch to think that one or more of these factors could lead to a factor of 3 overestimate in the SFRs.

Another perhaps related possibility is that the IMF could be different in high-z galaxies. This has been offered as a solution to various nagging quandaries in galaxy and stellar evolution, such as the colour and luminosity evolution of early-type galaxies (van Dokkum 2008), the abundance of carbon enhanced metal-poor stars in the Milky Way (Tumlinson 2007), and the evolution of the cosmic stellar mass assembly (Fardal et al. 2007; Wilkins et al. 2008). One solution invoked to solve all these problems, as pointed out in Davé (2008), would be that the IMF is somewhat more top-heavy or bottom-light at higher redshifts, such that SFRs would be overestimated by $\sim \times 3$ at $z \sim 2$. Recently, Meurer et al. (2009) suggested that nearby galaxies with higher SFR surface densities have more top-heavy IMFs, which adds some local credibility (albeit controversial) to the idea of the IMF perhaps being more top-heavy (or bottom-light) at early epochs.

The level of IMF variation required in our scenario is far milder than that in the Baugh et al. (2005) semi-analytic models of SMGs, and it is not easy to constrain directly even in local galaxies let alone at $z \sim 2$. It is, for instance, quite consistent with direct constraints on the IMF of SMGs by Tacconi et al. (2008). IMF variations would also have other implications, such as more metals (and hence dust) being produced for a given stellar mass, which could have important effects on dust temperatures and inferred SFRs (see e.g. Baugh et al. 2005); a thorough analysis of all its effects is beyond the scope of this work. It must be pointed out that there is no clear evidence for IMF variations in any context, so this possibility should be considered with some skepticism.

For our scenario, it is irrelevant whether the cause of the purported SFR overestimates is a different IMF or some calibration effect. The main point is that if the SFRs have been systematically overestimated by a factor of 3, then this removes the main clearly discrepant aspect of our model when compared to current observations of SMGs. Such an overestimate may not be unique to SMGs, but may be reflective of a systematic difference in all $z \sim 2$ star-forming galaxies relative to the local ones.

5.2 Duration of the SMG phase

SMGs in our scenario are forming stars relatively quiescently, as seen in Figure 4. Hence one expects that SMGs remain identifiable as SMGs for a long time. This contrasts with the short duty cycle of SMGs in a merger-based scenario. Inferred duty cycles for SMGs tend to be short, but these are mostly based on gas consumption timescales. In our scenario, such timescales are not relevant because the IGM supplies gas at a rate comparable to the star formation rate. Therefore, our SMGs don't "use up" their gas but merely consume it at the rate at which it is being supplied. The key point is that simulations generically predict remarkably large gas supply rates in high-z galaxies.

To get a handle on the duration of the SMG phase, we identify the progenitors and descendants of $z = 2$ SMGs in our simulations at $z = 2.5$ and $z = 1.5$, i.e. 0.67 Gyr prior and 1 Gyr later. In Figure 7 we show the location in SFR$-M_*$ of $z = 2$ SMGs (green points) at these earlier and later epochs. For reference, the horizontal line demarcates the SFR threshold needed to maintain a number density of 1.5×10^{-5} Mpc^{-3}; the values are slightly different than at $z = 2$, namely 130 $M_\odot$/yr at $z = 2.5$ and 190 $M_\odot$/yr at $z = 1.5$.

At both $z = 2.5$ and $z = 1.5$, slightly more than half the $z = 2$ SMGs are among the galaxies that would be identified as SMGs based on an analogous SFR threshold. The remainder fall just below the SFR threshold. In general, the $z = 2$ SMGs at these other epochs are fairly randomly distributed in SFR amongst the general galaxy population at a given M_*. This is in line with our scenario that SMGs have a fairly constant SFR, with minor ($\sim \times 2$) excursions owing to stochastic accretion events.

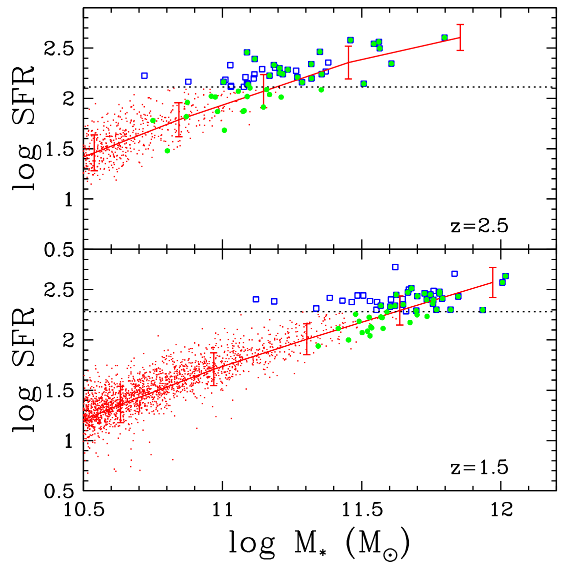

Figure 7. SFR vs. M_* at $z = 2.5$ (top panel) and $z = 1.5$ (bottom panel). Descendants/progenitors of $z = 2$ simulated SMGs are shown as green points. Blue squares denote SMGs that would be identified based on a SFR threshold at those redshifts; the SFR thresholds are indicated by the dotted lines. More than half the $z = 2$ SMGs are identified with similarly-selected SMGs at $z = 2.5$ and $z = 1.5$.

Expressed in terms of a duty cycle, one might say that the SMGs in our simulations have a duty cycle of $\sim 50\%$, since at any given epoch the high-SFR criterion picks out about half the massive galaxy population. This duty cycle depends on mass; the lower-mass SMGs tend to be greater outliers, and hence have smaller duty cycles. Of course, the concept of a duty cycle may not be exactly appropriate for these systems, given that they do not become dramatically less active when they are not in the SMG phase, but rather simply fall slightly below what would be identified in an SFR-selected sample.

One implication of this relatively high duty cycle is that the number density and clustering of SMGs should independently translate into roughly the same halo mass. This would indicate that a large fraction of halos at the high-mass end are occupied by SMGs. This is in contrast to a scenario where SMGs are major mergers, in which the small duty cycle of SMGs in a merger phase would imply a low fraction of massive halos containing an SMG. With wider and more uniform samples, this prediction can be tested relatively straightforwardly, which we expect will strongly discriminate between the different SMG scenarios.

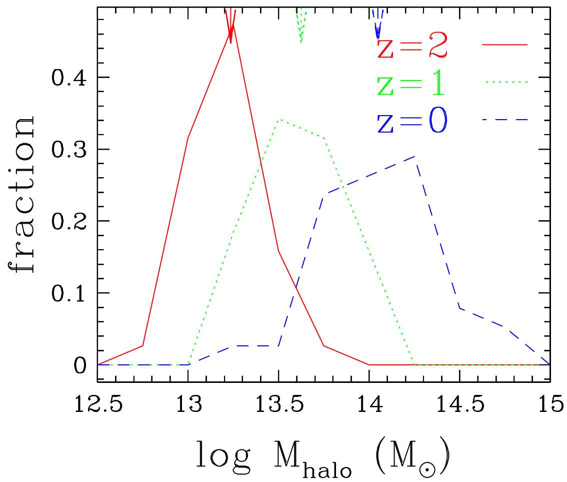

Figure 8. Histogram of halo masses of simulated SMGs at $z = 2$ (red solid line), and the halos in which their descendants live at $z = 1$ (green dotted) and $z = 0$ (blue dashed). The median values at each epoch are indicated at the top of the figure.

5.3 SMG descendants today

Where do the descendants of SMGs live today? In our simulation we can follow our simulated SMG sample to $z = 0$, where we can directly identify the halos in which they reside.

Figure 8 shows a histogram of the halo masses of simulated SMGs at $z = 2$ (red solid line), and the halos in which their descendants live at $z = 1$ (green dotted) and $z = 0$ (blue dashed). At each epoch, these are among the most massive halos in the simulation. From $z = 2 \rightarrow 0$, the typical halo mass grows from $1.7\times10^{13}M_\odot$ to $1.1\times10^{14}M_\odot$. The latter is a group-sized halo. Hence, we can infer that SMGs are typically the brightest group galaxies in the process of active formation at $z \sim 2$. This is also consistent with their number density and large clustering length.

Another issue is that SMGs cannot continue to form stars at their $z \sim 2$ rates all the way to $z = 0$, since no galaxies approaching those bolometric luminosities are seen locally, and their stellar masses would be far too large. Our simulated SMGs match the $z \sim 2$ observed stellar mass function (Figure 1). How much longer can they sustain these rates and still be consistent with lower-z mass functions?

To answer this, let us make the ansatz that SMGs turn into the most massive galaxies today. Clearly this is not strictly true, but given that the simulated SMGs are among the most massive galaxies at $z \sim 2$ living in the most massive halos, it may not be a bad approximation. In any case it provides a upper limit to how much SMGs can grow. Examining the stellar mass functions versus redshift of Marchesini et al. (2009), it is clear that there is not much room for growth at the massive end. For SMG number densities of 10^{-5} Mpc^{-3}, the stellar mass has grown by only 0.2 dex since $z \sim 2$. Hence even if one were to ignore dry merging, this only allows for a growth of 60% in stellar mass in the last 10 Gyr. If the typical stellar mass is $M_* = 10^{11.3}M_\odot$, then this is a growth of $\approx 1.2 \times 10^{11}M_\odot$. Taking a median SFR of $\approx 400M_\odot$/yr (Coppin et al. 2008), this means a typical SMG can only continue forming stars at this rate for at most 300 Myr, and perhaps much less given that massive galaxies also grow by dry merging. Therefore, one would be observing SMGs at a fairly special time, when the star formation has to shut off within $\ll 0.1t_H$. If, however, the SFRs were lowered by a factor of three, the SMGs could conceivably continue to form stars at their observed rates for the better part of a Gyr before quenching, and hence SMGs would not be being observed at a particularly special time. The latter interpretation is more consistent with our scenario that SMGs are not typically undergoing a spectacularly life-changing event. We note that there would still be some phenomenon required to quench star formation in massive galaxies to produce the red and dead systems seen today, but perhaps it does not have to be directly associated with the SMG phase.

6 CONCLUSIONS

We investigate the physical properties of the most rapidly star-forming galaxies at $z = 2$, constrained to match the observed number density of sub-millimetre galaxies, in a ΛCDM hydrodynamic simulation of galaxy formation. We examine their stellar masses, star formation rates, metallicities, environments, clustering, star formation histories, morphologies, and kinematics. We find that the simulated high-SFR galaxies are a good match to the observed SMGs in terms of their stellar masses, number densities, and clustering, which is a first for a cosmologically-situated galaxy formation model.

However, there is a significant discrepancy between the predicted and observed star formation rates: The simulated SMG's SFRs are lower by a factor of ~ 3 compared to that inferred for SMGs from their observed far-IR fluxes. We argue that it is plausible that the SFRs of SMGs have been overestimated by this factor. There is growing evidence that such a modest overestimate would reconcile various observations related to star formation and stellar mass growth at $z \sim 2$. Given that high-z galaxies are in many ways systematically different than present-day ones (e.g. they have much higher star formation rate surface densities), it is possible that the conversion factors calibrated to local galaxies may be incorrect at high-z. One way to alter such calibrations would be to invoke an IMF with more massive stars relative to low-mass ones. This IMF variation is within currently allowed constraints, and is far milder than the extremely top-heavy IMF proposed in the Baugh et al. (2005) semi-analytic models. However, there are many other possible reasons why the SFR calibration could be off for SMGs.

We note that the agreement with the observed stellar masses depends with which observational sample one compares. Most analyses seem to favour large stellar masses for the SMGs, typically $> 10^{11}M_\odot$, but some obtain significantly lower stellar masses, even using identical data. This illustrates the current uncertainties in determining stellar masses from photometric data, especially in the presence of large amounts of extinction and possible AGN contamination, in a regime that is poorly calibrated by local data. If the lower stellar masses as inferred by e.g. Hainline (2008) are confirmed, our model would be significantly less preferred, as it would require an order of magnitude overestimate of the observed star formation rates to reconcile our simulations with such data. Furthermore, it would alleviate one of the difficulties with the major merger model, namely that large major mergers are too rare, since these lower-mass systems are more common. However, it is still true that the merger model would have to explain the enormous far-IR fluxes, which seem to require quite massive gas-rich progenitors or else a dramatic change in the IMF.

If our scenario is correct, the most significant implication would be that SMGs are typically not large major mergers of gas-rich disks, as is canonically believed. Hence, they are in this sense not analogs of local ULIRGs, in spite of their high bolometric fluxes. They are instead, to first order, super-sized versions of ordinary star forming galaxies, sitting at the high-mass end of the star formation rate–stellar mass relation. They are being supplied with gas from minor mergers and smooth cold accretion at a rate comparable to their SFR. The SMG phase is, therefore, not a particularly dramatic event in the life of a massive galaxy, although their star formation must eventually be quenched by some mechanism for these systems to become brightest group ellipticals today.

It is worth noting that our simulations do not produce a population of passively evolving galaxies as observed, likely because we do not explicitly include any physical process that fully quenches star formation, such as AGN feedback (e.g. di Matteo et al. 2008). Passively evolving galaxies are seen at $z \sim 2$ (e.g. Kriek et al. 2008), and at the massive end perhaps as many as half the galaxies are passively evolving, or at least forming stars at a reduced rate for their mass (Papovich et al. 2006). If we declared half our massive galaxies to be passively evolving, then to reproduce the number density of SMGs, we would have to go to a somewhat lower SFR threshold of 120 $M_\odot$/yr (vs. 180 $M_\odot$/yr). Hence, to match the observed SFRs we would then require a reduction by a factor of ~ 4 in SFR instead by a factor of ~ 3 owing to some systematic, which is still not implausible. Of course a full galaxy formation model should account for passively evolving systems, but the fact that our current simulations do not is unlikely to affect our basic conclusions here.

Although SMGs are not particularly distinguished from the more typical galaxy population other than by their larger stellar masses, they are still effectively a star formation rate-selected sample. Therefore, we predict that there will be mild trends to higher SFRs, lower metallicities, and higher gas fractions than for non-SMGs at comparable stellar masses. In other words, the specific star formation rate of SMGs will be higher than the average at their stellar mass, and this will be particularly true for lower-mass SMGs owing to the scatter in the SFR$-M_*$ relation. Stated in terms of the star formation activity parameter $\alpha_{\rm sf} \equiv (M_*/{\rm SFR})/(t_H - 1~{\rm Gyr})$, one expects that SMGs at higher masses will have a higher $\alpha_{\rm sf}$, since they will be less likely to have a temporarily elevated SFR. If this trend is confirmed in future studies (which will require much-improved measures of SFR and M_*) it would provide further support for our overall scenario.

Our model predicts further trends that should become evident with larger and deeper SMG samples: (i) Lower-M_* SMGs will appear preferentially more disturbed or merger-like, while high-M_* systems will appear more quiescent; (ii) Going a factor of a few deeper in far-IR luminosity should start to suggest a trend in SFR$-M_*$ for SMGs; (iii) This trend should smoothly join onto the trend of SFR$-M_*$ seen in optically-selected galaxies; (iv) SMGs should be highly clustered, and the clustering strength should increase with SMG luminosity; (v) The occupancy fraction of SMGs within massive halos, as might be quantified by comparing the clustering and number densities of SMGs, should be fairly high. These trends are likely subtle, so testing them will require improved modeling along with improved data. We particularly emphasize the importance of accurate stellar mass and clustering measures to provide optimal discrimination between models. Naively, one might expect that the above trends would not exist or would be weaker in a major merger-dominated scenario for SMGs, but this must be assessed within a full hierarchical model.

All the current scenarios for SMGs, i.e. the large major merger scenario, the modest merger scenario with very top-heavy IMF, and our super-sized star-forming galaxy scenario, each have their own difficulties. Our main point is that the latter scenario is at least as consistent with the available observations of SMGs as all the others. Hence, there should be some doubt as to whether or not SMGs are systems caught in the act of a major merger. Even so, major mergers of large galaxies almost certainly occur, and based upon the simple number density estimates we presented earlier (§1), it might be expected that perhaps one or two in ten SMGs are indeed such systems. In fact, this may be the only way to produce the most extremely luminous SMGs, e.g. with $L_{IR} > 10^{13} L_\odot$. Therefore, we speculate that perhaps SMGs are a heterogeneous population, and that the very most extreme systems are indeed large major mergers, while the more common modestly-luminous SMGs are super-sized star formers.

SMGs are a key phase in the evolution of massive galaxies, possibly the most active phase of formation for present-day passive spheroids. Assembling a fully self-consistent cosmological framework for their formation and evolution will require much effort on both theoretical and observational fronts. Fortunately, there will be substantial observational advances forthcoming in long-wavelength capabilities to trace star formation, dust continuum emission, and molecular lines of SMGs out to high-z. These will be complemented by better multiwavelength data to constrain their stellar masses, AGN content, clustering, and metallicities. Together with rapidly improving models of SMGs within a cosmological framework, there is growing hope that the nature of these enigmatic systems and their importance in our overall picture of galaxy formation will soon be revealed.

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