MERGERS AND MASS ACCRETION RATES IN GALAXY ASSEMBLY: THE MILLENNIUM SIMULATION COMPARED TO OBSERVATIONS OF $z \approx 2$ GALAXIES

SHY GENEL$^1$, REINHARD GENZEL$^{1,2}$, NICOLAS BOUCHÉ$^3$, AMIEL STERNBERG$^3$, THORSTEN NAAB$^4$, NATASCHA M. FÖRSTER SCHREIBER$^1$, KRISTEN L. SHAPIRO$^5$, LINDA J. TACCONI$^1$, DIETER LUTZ$^5$, GIOVANNI CRESCI$^1$, PETER BUSCHKAMP$^5$, RICHARD I. DAVIES$^1$, ERIN K. S. HICKS$^1$

Accepted for publication in ApJ

ABSTRACT

Recent observations of UV-/optically selected, massive star forming galaxies at $z \approx 2$ indicate that the baryonic mass assembly and star formation history is dominated by continuous rapid accretion of gas and internal secular evolution, rather than by major mergers. We use the Millennium Simulation to build new halo merger trees, and extract halo merger fractions and mass accretion rates. We find that even for halos not undergoing major mergers the mass accretion rates are plausibly sufficient to account for the high star formation rates observed in $z \approx 2$ disks. On the other hand, the fraction of major mergers in the Millennium Simulation is sufficient to account for the number counts of submillimeter galaxies (SMGs), in support of observational evidence that these are major mergers. When following the fate of these two populations in the Millennium Simulation to $z = 0$, we find that subsequent mergers are not frequent enough to convert all $z \approx 2$ turbulent disks into elliptical galaxies at $z = 0$. Similarly, mergers cannot transform the compact SMGs/red sequence galaxies at $z = 0$. We argue therefore, that secular and internal evolution must play an important role in the evolution of a significant fraction of $z \approx 2$ UV-/optically and submillimeter selected galaxy populations.

Subject headings: galaxies: formation — galaxies: evolution — galaxies: high-redshift — cosmology: dark matter

1. INTRODUCTION

In the cold dark matter model of hierarchical structure formation (Blumenthal et al. 1984; Davis et al. 1985; Springel et al. 2006a), mergers are believed to play an important role in galaxy formation and evolution (Steinmetz & Navarro 2002). Mergers induce starbursts (Hernquist & Mihos 1995) and transform galactic morphology (Naab & Burkert 2003). Major mergers may drive the buildup of the red sequence (Toomre 1977; Hopkins et al. 2008b). Dark matter models and many observations show that mergers are more frequent at high redshift (Fakhouri & Ma 2008; Conselice 2003).

However, there is growing evidence that a smoother growth mode may be important for the baryonic mass assembly and star formation history at high redshift. For example, the tight correlation between star formation rate (SFR) and stellar mass in UV-/optically selected star forming galaxies is indicative of buildup by continuous gas inflow (Daddi et al. 2007; Noeske et al. 2007). As part of the SINS survey (Förster Schreiber et al. 2006; N. M. Förster Schreiber et al. 2008 in preparation), integral field spectroscopy of more than 50 UV-/optically selected $z \approx 2$ star forming galaxies show a preponderance of thick gas-rich rotating disks and only a minority of major mergers (Förster Schreiber et al. 2006; Genzel et al. 2006; Shapiro et al. 2008). In contrast, SMGs are probably short-lived maximum-starburst galaxies undergoing dissipative major mergers (Tacconi et al. 2006; Bouché et al. 2007; Tacconi et al. 2008). Table 1 summarizes key properties of these $z \approx 2$ galaxy samples.

How do these observations fit into the concordance cosmological model? Modern simulations of dark matter structure formation are robust and fixed by the cosmological parameters. However, complicated baryonic physics makes it difficult to model the evolution of galaxies and reproduce, for example, the high SFRs of these $z \approx 2$ galaxies (Daddi et al. 2007).

Galaxies at $z \approx 2$ differ significantly from local galaxies. The central mass densities of SMGs and of massive quiescent galaxies at the same redshift (van Dokkum et al. 2008 and references therein) are an order of magnitude greater than those of local spheroids and disks (Tacconi et al. 2008). Also, the $z \approx 2$ rotating disks are thick and turbulent, unlike local disk galaxies. These differences raise the question: what are the local Universe descendants of these $z \approx 2$ galaxies?

In this paper we use the cosmological dark matter Millennium Simulation (Springel et al. 2008) to investigate the possible role of major mergers in galaxy formation at $z \approx 2$ (§2), and to consider the evolution of the $z \approx 2$ galaxies to $z = 0$ (§4).

2. ANALYSIS OF THE MILLENNIUM SIMULATION

2.1. The Millennium Simulation and its merger trees

The Millennium Simulation is a cosmological N-body simulation. It follows 2160$^3$ dark matter particles of mass $8.6 \times 10^4 h^{-1} M_{\odot}$ in a box of $500 h^{-1}$ Mpc on a side from $z = 127$ to $z = 0$. There are 64 output times (“snapshots”), at $\approx 300$ Mpc intervals at $z \lesssim 3$. The cosmology is $\Lambda$CDM, with $\Omega_m = 0.25$, $\Omega_{\Lambda} = 0.75$, $\Omega_b = 0.045$, $h = 0.73$, $n = 1$ and $\sigma_8 = 0.9$. 

$^1$ Max Planck Institut für extraterrestrische Physik, Giessenbachstrasse, D-85748 Garching, Germany; shy@mpe.mpg.de; genzel@mpe.mpg.de; nbouche@mpe.mpg.de; forster@mpe.mpg.de; lindag@mpe.mpg.de; lutz@mpe.mpg.de; gcresci@mpe.mpg.de; buschkamp@mpe.mpg.de; davies@mpe.mpg.de; echicks@mpe.mpg.de. 

$^2$ Department of Physics, Le Conte Hall, University of California, Berkeley, CA 94720. 

$^3$ School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel; amiel@wise.tau.ac.il. 

$^4$ Universität-Sternwarte München, Scheinerstr. 1, D-81679 München, Germany; naab@usm.uni-muenchen.de. 

$^5$ Department of Astronomy, Campbell Hall, University of California, Berkeley, CA 94720; shapiro@astron.berkeley.edu.
### Table 1: Properties of Galaxy Samples at $z \approx 2$

| Galaxy sample | SFR $\left[ M_\odot \text{yr}^{-1} \right]$ | Halo mass $\left[ M_\odot \right]$ | Comoving number density $\left[ h_0^2 \text{Mpc}^{-2} \right]$ | Major merger fraction |
|---------------|---------------------------------|---------------------------------|---------------------------------|---------------------|
| SINS          | $\approx 30$–$300$               | $10^{11.5}$                    | $10^{-2}$                      | 0.03$^{\pm}$0.07    |
| SMGs$^{(d)}$  | $\approx 750$–$3000$            | $10^{12}$                      | $10^{-2}$                      | 0.05$^{\pm}$0.03    |

**Note.** — (a) N. M. Förster Schreiber et al. 2008 in preparation; (b) Förster Schreiber et al. 2008; (c) Tacconi et al. 2008 and references therein; (d) BXBM & SIRK galaxies with $K < 20$; (e) Shapiro et al. 2008; (f) S(850 μm) $> 5$ mJy; (g) Genzel, priv. comm.

In the Millennium Simulation, structures are identified in two steps. First, the Friends-of-Friends (FOF) algorithm (Davis et al. 1985) creates a catalogue of FOF groups at each snapshot. The FOF groups represent dark matter halos. Second, bound substructures are identified inside the FOF groups (SubFind; Springel et al. 2001), so that each halo contains at least one subhalo. The Millennium merger trees are constructed by finding a single descendant for each subhalo in the following snapshot, while the FOF groups themselves play no role in constructing the merger trees.

In traditional merger trees, mergers are instantaneous, i.e. there is no information on their durations. Therefore, the Millennium public merger trees$^6$ can be used to determine the merger rate, which is merely a count of the number of mergers per unit time (Fakhouri & Ma 2008, S. Genel et al. 2008 in preparation). However, they cannot be used to determine important quantities such as the major merger fraction, defined as the fraction of halos undergoing major mergers at a given time, or the mass growth rate of each halo.

#### 2.2. Constructing new merger trees

To derive merger fractions and mass growth rates, we must consider the finite physical durations of mergers. Therefore, start and end points must be defined. Also, to derive these quantities for entire dark matter halos rather than subhalos, new trees have to be constructed based on FOF groups. In our procedure, the main subhalo in each FOF group is identified and is then followed to its subhalo descendant, using the original subhalo-based trees. The FOF group to which the subhalo descendant belongs is defined as the FOF group descendant of the original FOF group. Thus, in our new trees each node is an entire FOF group, rather than a subhalo. If two subhalos merge while within a single FOF group we do not count this as a merger event.

We identify a merger whenever two or more FOF groups at snapshot $s$ have a common descendant at snapshot $s+1$. However, at this time the halos are not necessarily already physically merging, since they may still be well separated. To account for that, we track the distances between the subhalo descendants of the main subhalos of the original FOF groups. These subhalos represent, approximately, the centers of the entire halos. We then define the start point of the merger as the last snapshot at which this distance is still larger than the sum of the virial radii of the original halos (FOF groups). In some mergers the subhalos disappear before the distances become smaller than the sum of the original virial radii. When this happens the start point is defined as just one snapshot prior to the point where the subhalos merge and/or disappear.

After a merger begins, one of the halos becomes a substructure within the other. This substructure typically dissolves too quickly to be followed until the merger is physically complete. To overcome this problem we first estimate the duration of mergers $T_{\text{merger}}$, and define their end point as $T_{\text{merger}}$ after the start point. To estimate the durations, we considered the fitting functions of Boylan-Kolchin et al. (2008) and Jiang et al. (2008), which are based on simulations of mergers. Our results are qualitatively robust with respect to this choice.

We present quantitative results based on the orbit-averaged fitting function of Boylan-Kolchin et al. (2008) for the dynamical friction merger time: $T_{\text{merger}} = 0.05 \frac{3^{\frac{3}{2}}}{(m_1 + m_2) H(z)}$, where $r$ is the mass ratio and $H(z)$ is the Hubble constant at redshift $z$.

The accretion rate we associate with each merger equals the amount of accreted mass divided by the merger duration $T_{\text{merger}}$.

To summarise, we construct new FOF group-based merger trees, where each FOF group also holds information about internal on-going mergers. The accretion rates associated with those mergers are summed up to obtain the total accretion rate onto the FOF group in question. The merger mass ratio is determined by the masses of the FOF groups at snapshot $s$, just prior to the appearance of a common FOF group descendant at snapshot $s+1$. We define major mergers as those with mass ratios between $3 : 1$ and $1 : 1$ (with $1 : 1$ being the most “intense” type of merger). If the most intense merger associated with a halo lies between $3 : 1$ and $1 : 1$, the halo is labelled as undergoing a major merger.

#### 3. Galaxies at $z \approx 2$

Fig. 1 shows halo number densities (shaded contours) and major merger fractions (red contours) as functions of halo mass and dark matter accretion rate for $z \approx 2.2$. It shows that the major merger fraction is an increasing function of specific dark matter accretion rate ($\dot{M}_{DM}$), as both quantities increase towards the upper-left direction of the plane. This trend holds at all redshifts.

The mean accretion rate scales with halo mass and redshift as

$$\langle \dot{M}_{DM} \rangle \approx 35 M_\odot \text{yr}^{-1} (1+z)^{2} M_{12}^{0.37}$$

(1)

(1) (where $M_{12} \equiv M / 10^{12} M_\odot$). The $1\sigma$ scatter equals $\langle \dot{M}_{DM} \rangle \times (\frac{2}{3})^{0.5}$, which reflects more the upwards scatter, although negative accretion rates do exist for some halos (because of tidal stripping or fluctuations related to the FOF algorithm).

Our numerical results are in good agreement with the analytic approximation for the accretion rate presented by Neistein et al. (2006), which is based on the extended Press-Schechter (EPS) model (Press & Schechter 1974, Bond et al. 1991, Bower 1991). The Neistein et al. (2006) approximation has a somewhat stronger mass and redshift dependence compared to our results. For example, at $z = 0$ and $M = 10^{12} M_\odot$, their accretion rate is $\approx 10\%$ higher, and at $z = 3$ and $M = 10^{14} M_\odot$, it is a factor of $\approx 2$ higher. For halos of particular interest for this paper, i.e. of $M \approx 10^{12} M_\odot$ at $z \approx 2$, the Neistein et al. (2006) approximation exceeds our eq. $(1)$ by $\approx 30\%$.

To compare our results to observed galaxies, we assume that the galaxies are the central galaxies of their halos. We convert dark matter accretion rate ($\dot{M}_{DM}$) into SFR ($\dot{M}_s$) using

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$^6$ The Structure catalogues and derived merger trees have been made public by the Virgo Consortium: [http://www.mpa-garching.mpg.de/millennium](http://www.mpa-garching.mpg.de/millennium)
The baryonic fraction $\eta_B = 0.18$ and an effective star formation efficiency $\epsilon$, which is a free parameter used to interpret the results:

$$M_\epsilon = \eta_B \times \epsilon \times M_{DM}. \tag{2}$$

In the "cold flow" regime ($M_{\text{halo}} \lesssim 10^{12} M_\odot$; Birnboim & Dekel 2003; Kereš et al. 2005; Östvirk et al. 2008) eq. (2) is a plausible measure of the baryonic accretion rate. At larger masses the accretion rate is lower and is controlled by the cooling time in the hot virialised baryonic gas. At much smaller masses it is strongly reduced by outflows generated by supernovae feedback. In the cold flow regime, the cold gas (which may be clumpy) is fed at approximately virial velocity via filaments directly into the flow regime, the cold gas (which may be clumpy) is fed at

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3.1. SINS galaxies

On Fig. 1 we overplot the SINS galaxies. Their SFRs are based on their $H\alpha$ fluxes corrected for extinction using $A_{H\alpha} = 0.8$, and their halo masses were estimated by assuming that the observed disk maximum rotation velocity is equal to the circular velocity of the halo (Forster Schreiber et al. 2006). Fig. 1 shows that if $\epsilon \gtrsim 0.5$ is assumed, the host halos of SINS galaxies with $M_{\text{halo}} > 10^{11.25} M_\odot$ lie in the region where most halos of their mass are expected to be concentrated. Furthermore, for $\epsilon \gtrsim 0.5$ the expected mass accretion rates are sufficient to account for the observed SFRs. Also, the predicted major merger fraction is small ($\lesssim 0.5$), consistent with observations. Although the statistics are still small, we notice that the confirmed SINS mergers (Shapiro et al. 2008; stars) have higher specific dark matter accretion rates than the confirmed disks (open circles), and therefore come from a region where the halo major merger fraction is higher.

The computed number density of halos with $M \approx 10^{11.5} - 10^{12} M_\odot$ is a few times higher than the observed number density of the galaxies the SINS sample is drawn from (Table I). Possibly, the observed galaxies have typically high $M_{\text{gal}}/M_{\text{halo}}$, with other halos of comparable mass hosting fainter undetected galaxies. Also, some of the halos in this mass range may have already developed virial shocks that quench star formation.

In should be noted that our estimated major merger duration $T_{\text{merger}}$ equals $350 - 1000$ Myr at $z \approx 2.2$, depending on the mass ratio. This is very similar to the "observable" galaxy merger timescale often found in the literature (e.g. Conselice 2006; Lotz et al. 2008). Therefore, the approximation taken here, i.e. considering directly the halo merger fraction and inferring the galaxy merger fraction from it, is probably a reasonable one with respect to the deduced merger fraction of the SINS galaxies.

Genzel et al. (2006) studied BzK-15504 with high resolution using adaptive optics, and concluded that it was a large proto-disk with no sign of a recent/ongoing major merger, and a SFR of $140(-80,+110) M_\odot$ yr$^{-1}$. Förster Schreiber et al. (2006), Law et al. (2007), Genzel et al. (2008), G. Cresci et al. (2008, in preparation), Bournaud et al. (2008) and van Starkenburg et al. (2008) have found similar systems. Fig. 2 shows that for halos not undergoing major mergers, and
with masses equal to the halo mass of BzK-15504, the typical dark matter accretion rate is \( \approx 450 \, M_\odot \, \text{yr}^{-1} \), i.e. the typical SFR assuming \( \epsilon = 1 \) is \( \approx 80 \, M_\odot \, \text{yr}^{-1} \). About 15% of such halos have SFRs exceeding the 140 \( M_\odot \, \text{yr}^{-1} \) observed in BzK-15504 (again assuming \( \epsilon = 1 \)). Thus, the implied dark matter accretion rate in BzK-15504 may be quite typical. Considering the uncertainty in the measured SFR, the implied dark matter accretion rate is consistent with theoretical expectations for \( \epsilon \) as low as \( \approx 0.5 \).

We conclude that high star formation rates and large abundances of non-major merger, massive disks at \( z \approx 2 \) are consistent with expectations from \( \Lambda \) CDM simulations if accretion is in the ’cold flow’ regime and the star formation efficiency is high.

### 3.2. SMGs

For \( \epsilon \approx 1 \), the observed SFRs of the SMGs imply dark matter accretion rates of \( \approx 2500 - 6000 \, M_\odot \, \text{yr}^{-1} \) (Fig. 1). When examining halos with accretion rates in this range that are undergoing major mergers, we find that their masses lie mostly in the range \( (2-6) \times 10^{12} M_\odot \) and obey a log-normal distribution with a mean \( \approx 3 \times 10^{12} M_\odot \) and \( \sigma \approx 0.25 \, \text{dex} \). We also find that their number density is \( \approx 5 \times 10^{-3} \, \text{Mpc}^{-3} \). This is only slightly larger than the observed SMG density (Table 1), and supports the conclusions of Tacconi et al. (2006, 2008) that the SMGs represent major mergers. If the SMG phase is shorter than the halo merger duration, such that \( \epsilon > 1 \), the implied number density is much altered, but lower halo masses are found. E.g., if the SMG phase lasts only 100 Myr, the mean halo mass is \( \approx 10^{12} M_\odot \), in which case SMGs could be members of the UV-optically selected galaxy populations that have recently experienced a dissipative major merger. The observed rotation velocities of SMGs are larger than the expected circular velocities of halos with these inferred masses. This is consistent with the SMGs being concentrated major mergers where the rotation velocities peak close to the center.

### 4. FATE AT \( z = 0 \)

#### 4.1. Fate of SINS galaxies

Fig. 3 summarizes the major merger history of halos from \( z \approx 2.2 \) to \( z = 0 \). For halos with initial masses typical of the SINS galaxies’ halos, \( \approx 40\% \) will be accreted via minor mergers by more massive halos (representing groups or clusters) with final masses \( 10^{13} M_\odot \lesssim M \lesssim 10^{15} M_\odot \) at \( z = 0 \). Around one half of those halos will merge fully with the central subhalo of the group/cluster, and the other half will remain satellite subhalos. The other \( \approx 60\% \) remain “main branch” halos to \( z = 0 \). Of these, \( \approx 2/3 \) undergo at least one major merger during their evolution to \( z = 0 \). Their final halo masses are \( 10^{12.3} M_\odot \lesssim M \lesssim 10^{13.3} M_\odot \), so their associated galaxies may become massive ellipticals (cf. Conroy et al. (2008)). The other \( \approx 1/3 \) do not undergo any future major mergers, and grow to a mass \( 10^{11.8} M_\odot \lesssim M \lesssim 10^{12.5} M_\odot \) at \( z = 0 \). Thus, these may evolve via secular evolution into bulges and later possibly grow a new disk.

#### 4.2. Fate of SMGs

A popular scenario is that the large central mass densities of SMGs and of \( z \approx 2 \) compact red sequence galaxies are reduced by \( z = 0 \) via dry dissipationless mergers (van Dokkum 2005, Bell et al. 2006, Naab et al. 2006, Tacconi et al. 2008) show (in their Fig. 5) that this requires that the SMG masses grow by about an order of magnitude by \( z = 0 \), assuming dry mergers with structurally similar systems, following Nipoti et al. (2003). We find that of the halos we have identified with the SMGs in \( \approx 70\% \) remain “main branch” halos to \( z = 0 \) (Fig. 3), and that their masses grow by factors of \( \approx 3 - 30 \). This mass growth appears consistent with the requirement of the dry merger hypothesis. However, most of the mass growth does not occur via major mergers, since typically only \( \approx 1 \) major merger occurs per halo to \( z = 0 \), as shown by Fig. 3.

Moreover, we show in Fig. 4 that most of the mass growth is achieved via mergers less intense than \( 10 : 1 \), which is qualitatively consistent with the idea that the growth of massive galaxies is not dominated by major mergers (e.g. Hausman & Ostriker 1978, Maller et al. 2006, Masjedi et al. 2008). This is especially true for the halos that do not undergo further major mergers until \( z = 0 \). Such halos tend to grow in mass only by a factor of \( \approx 3 \), and gain \( \gtrsim 0.7 \) of their new mass via mergers less intense than \( 10 : 1 \). Also, the galaxies themselves probably grow even less than their dark matter halos. It seems unlikely that the mass accreted via such small halos can be sufficiently gas poor for minor dry mergers (e.g. Burkert et al. 2007) to be an important growth mechanism (unless the galaxies are effectively stripped of their gas before merging with the descendant of the SMG (Naab et al. 2007)).

A simpler and more likely explanation (Tacconi et al. 2008) is that the high SMG densities trace only the central starburst region, and exclude more extended fainter envelopes of pre-merger stars. At lower redshifts these stars would become visible and be of greater relative importance as the starburst
halos with no future major mergers
halos with at least 1 future major merger

Fig. 4.— Mass growth to $z=0$ of halos with initial ($z\approx 2.2$) masses $10^{12.1}-10^{12.8} M_{\odot}$ that remain "main branch" halos (filled blue columns in the bottom Panel of Fig. 2). The plot displays the relative number of halos versus the fraction of the total mass added from $z=2.2$ to $z=0$ that is accreted via mergers more intense than $10:1$. Results are shown for halos that undergo no major mergers to $z=0$ (green) and halos that undergo at least one major merger to $z=0$ (filled red). The results do not depend on whether the halo at $z\approx 2.2$ is undergoing a major merger or on its accretion rate.

fades, giving rise to larger half-light radii and smaller inferred densities (cf. simulations by Hopkins et al. [2008b]).

5. SUMMARY

We have constructed new halo merger trees from the $\Lambda$CDM Millennium Simulation. Our trees account for merger durations, and we use them to identify halos that are undergoing mergers and to extract dark matter accretion rates. We show that the high star formation rates observed in rotating disks at $z\approx 2$ are plausibly consistent with the dark matter accretion rates expected for halos not undergoing major mergers. Given the measured star formation rates of SMGs, and the observationally supported assumption that they are undergoing major mergers, we infer their likely halo masses. Major mergers can neither lead to the complete transformation of the $z\approx 2$ disks to $z=0$ ellipticals, nor to the disappearance of the very high density SMGs from $z\approx 2$ to $z=0$. Therefore, secular/internal processes are likely important in the evolution of these high-redshift populations to present time.

We thank Gabriella De Lucia, Mike Boylan-Kolchin and Volker Springel for useful discussions, and the anonymous referee for valuable comments. The Millennium Simulation databases used in this paper and the web application providing online access to them were constructed as part of the activities of the German Astrophysical Virtual Observatory. We are grateful to Gerard Lemson who devotedly helped us to use the public databases. SG acknowledges the PhD fellowship of the International Max Planck Research School in Astrophysics, and the support received from a Marie Curie Host Fellowship for Early Stage Research Training.

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We thank Gabriella De Lucia, Mike Boylan-Kolchin and Volker Springel for useful discussions, and the anonymous referee for valuable comments. The Millennium Simulation databases used in this paper and the web application providing online access to them were constructed as part of the activities of the German Astrophysical Virtual Observatory. We are grateful to Gerard Lemson who devotedly helped us to use the public databases. SG acknowledges the PhD fellowship of the International Max Planck Research School in Astrophysics, and the support received from a Marie Curie Host Fellowship for Early Stage Research Training.