Submitted to ApJ on January 27th, 2009
Preprint typeset using LaTeX style emulateapj v. 10/09/06

SLAC-PUB-13715
July 2009

# GAS-RICH MERGERS IN LCDM: DISK SURVIVABILITY AND THE BARYONIC ASSEMBLY OF GALAXIES

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*Submitted to ApJ on January 27th, 2009*

## ABSTRACT

We use $N$-body simulations and observationally-normalized relations between dark matter halo mass, stellar mass, and cold gas mass to derive robust expectations about the baryonic content of major mergers out to redshift $z \sim 2$. First, we find that the majority of major mergers ($m/M > 0.3$) experienced by Milky Way size dark matter halos should have been gas-rich, and that gas-rich mergers are increasingly common at high redshift. Though the frequency of major mergers into galaxy halos in our simulations greatly exceeds the observed late-type galaxy fraction, the frequency of *gas-poor* major mergers is consistent with the observed fraction of bulge-dominated galaxies across the halo mass range $M_{\rm DM} \sim 10^{11} - 10^{13} M_\odot$. These results lend support to the conjecture that mergers with high baryonic gas fractions play an important role in building and/or preserving disk galaxies in the universe. Secondly, we find that there is a transition mass below which a galaxy's past major mergers were primarily gas-rich and above which they were gas poor. The associated stellar mass scale corresponds closely to that marking the observed bimodal division between blue, star-forming, disk-dominated systems and red, bulge-dominated systems with old populations. Finally, we find that the overall fraction of a galaxy's cold baryons deposited directly via major mergers is substantial. Approximately $\sim 30\%$ of the cold baryonic material in $M_{\rm star} \sim 10^{10} M_\odot$ ($M_{\rm DM} \sim 10^{11.5} M_\odot$) galaxies is accreted as cold gas in major mergers. For more massive galaxies with $M_{\rm star} \sim 10^{11} M_\odot$ ($M_{\rm DM} \sim 10^{13} M_\odot$) the fraction of baryons amassed in mergers is even higher, $\sim 50\%$, but most of these accreted baryons are delivered directly in the form of stars. This baryonic mass deposition is almost unavoidable, and provides a limit on the fraction of a galaxy's cold baryons that can originate in cold flows or from hot halo cooling.

*Subject headings:* cosmology: theory — dark matter — galaxies: formation — galaxies: halos — methods: $N$-body simulations

## 1. INTRODUCTION

In the cold dark matter (CDM) model of structure formation, major galaxy mergers are believed to play an important role in determining a galaxy's morphology (e.g. Toomre & Toomre 1972; Barnes & Hernquist 1996; Robertson et al. 2006a,b; Burkert et al. 2008), as well as triggering star formation and AGN activity (e.g. Mihos & Hernquist 1996; Heckman et al. 1986; Springel et al. 2005; Cox et al. 2008), while minor mergers may help explain the origin of thick disks and extended diffuse light components around galaxies (Barnes & Hernquist 1996; Kazantzidis et al. 2008a; Purcell et al. 2007; Younger et al. 2007; Purcell et al. 2008a; Villalobos & Helmi 2008; Kazantzidis et al. 2008b). More than simply triggering star formation in existing gas and altering existing galaxy morphologies, mergers deliver new stars and additional fuel for star formation, and thereby contribute to baryonic acquisition of galaxies over their histories. That mergers contribute significantly to many aspects of galaxy formation is now fairly well accepted, however there are lingering concerns that mergers are too common in CDM to explain the prominence of thin disk-dominated galaxies in the local universe (e.g. Toth & Ostriker 1992; Walker et al. 1996; Stewart et al. 2008; Purcell et al. 2009; Bullock et al. 2008, and references therein). Here we explore the baryonic content of these predicted mergers and the potential ramifications of gas-rich and gas-poor mergers on galactic morphological evolution.

The baryonic delivery of material into galaxies via major mergers touches on a broader question in galaxy formation: how do galaxies get their baryons? In recent years, studies motivated by hydrodynamic simulations have placed a growing emphasis on the importance of smooth gas accretion via "cold flows." These cold flows constitute streams of cold gas flowing along filamentary structures (particularly at high redshift) with sufficiently high densities to penetrate into a halo's central region without heating the gas to the virial temperature (e.g. Birnboim & Dekel 2003; Kereš et al. 2005; Dekel & Birnboim 2006; Keres et al. 2008; Dekel et al. 2008; Brooks et al. 2008; Agertz et al. 2009). These simulations demonstrate a characteristic halo mass scale ($\sim 10^{12} M_\odot$) below which cold streams are the dominant mode of gas accretion, and above which gas cooling directly from shock-heated (hot mode) material dominates.

Though there has yet to be any observational evidence that cold flows actually occur in nature, the possibility is well motivated by theory and is suggestive of a number of interesting scenarios for galaxy assembly. One particularly interesting idea is that flows of cold gas are vital to the formation of disk galaxies at high redshift $z \gtrsim 1$ (Dekel et al. 2008). Still, even if disks were built at high redshift via streams of cold gas, we can return to the issue of disk *survival* raised above. How do observed populations of disk galaxies at high redshift (e.g. Wright et al. 2008, at $z \sim 1.6$) survive subsequent mergers and remain disk-dominated by $z = 0$?

In a previous paper (Stewart et al. 2008) we studied the merger histories of Milky Way-size dark matter halos within a cosmological $N$-body simulation and found

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*Submitted to the Astrophysical Journal*

Work supported in part by US Department of Energy contract DE-AC02-76SF00515

that approximately 70% should have accreted an object with more than twice the mass of the Milky Way disk ($m > 10^{11} M_{\odot}$) in the last 10 Gyr. In order to achieve the $\sim 70\%$ disk-dominated fraction that has been observed in Milky Way-sized halos (Weinmann et al. 2006; Park et al. 2007; Choi et al. 2007), mergers involving $> 1/3$ mass-ratio events must *not always* destroy disks. Adding to the associated concern, Purcell, Kazantzidis, and Bullock (2008b) performed focused numerical experiments to study the impact of $m = 10^{11} M_{\odot}$ encounters onto fully-formed Milky-Way type thin *stellar* disks and concluded that *thin* ($\sim$ 400 pc) dissipationless stellar disks do not survive these (presumably common) encounters.

One possible solution appeals to the role of cold gas in mergers. Focused merger simulations in the past few years have begun to suggest that sufficiently gas-rich mergers may help build angular momentum in the central galaxy, while feedback physics prevents the gas from forming stars too quickly, resulting in a disk-dominated merger remnant (Barnes 2002; Springel & Hernquist 2005; Robertson et al. 2006a; Brook et al. 2007b; Hopkins et al. 2008; Robertson & Bullock 2008). Encouragingly, cosmological simulations that have been successful in reproducing disk galaxies have also shown that gas-rich mergers have played an important role in the disk's creation (e.g. Brook et al. 2004; Governato et al. 2007, 2008). Robertson & Bullock (2008) also showed that the disk-like merger remnants from gas-rich mergers are similar to the kinematically hot disks that have been observed at $z \sim 2$ (Förster Schreiber et al. 2006; Genzel et al. 2006; Shapiro et al. 2008).

Our goal in this work is to provide an empirically-motivated accounting for the expected gas and stellar content of mergers by relying on robustly determined dark matter halo merger rates. We aim first to determine whether gas-rich mergers are common enough to significantly alleviate the disk formation problem (a necessary but not sufficient condition in evaluating this scenario). We also aim to investigate the overall importance that mergers play in the acquisition of a galaxy's cold baryons.

While the merger histories of the dark matter halos are predicted accurately in dissipationless $N$-body simulations, the baryonic content of these mergers are much more difficult to predict from first principles. Indeed, an accurate *ab initio* accounting of the baryonic content of dark matter halos would require an overarching theory that solved all of the major problems in galaxy formation, including star formation, feedback, and the complicated interplay between mergers and galaxy assembly. In this work we chose to avoid the issues of galaxy formation physics entirely. Instead we adopt a semi-emperical approach that forces our model to match observations at various redshifts. First, we adopt the technique of monotonic abundance matching to assign stellar masses to dark matter halos (specifically following Conroy & Wechsler 2008). Second, we use observational relations between stellar mass and gas mass (e.g. McGaugh 2005; Erb et al. 2006) to assign gas masses to our halos. We then combine these relations with the $N$-body halo merger histories described in Stewart et al. (2008) and Stewart et al. (2009a) in order to determine the baryonic properties of mergers back to redshift $z \sim 2$. In §2 we discuss the details of our method. We present our primary results and discuss the implications for disk survival and the baryonic assembly of galaxies via mergers in §3. We summarize our main conclusions in §4.

## 2. METHOD

### 2.1. *The Simulation*

Our simulation contains $512^3$ particles, each with mass $m_p = 3.16 \times 10^8 M_{\odot}$, evolved within a comoving cubic volume of $80h^{-1}$ Mpc on a side using the Adaptive Refinement Tree (ART) $N$-body code (Kravtsov et al. 1997, 2004). We assume LCDM cosmological parameters: $\Omega_M = 1 - \Omega_\Lambda = 0.3$, $h = 0.7$, and $\sigma_8 = 0.9$. The simulation root computational grid consists of $512^3$ cells, which are adaptively refined to a maximum of eight levels, resulting in a peak spatial resolution of $1.2h^{-1}$ kpc (comoving). We give only a brief overview of the simulation here, as it has been reviewed more extensively in previous works. We refer the reader to Stewart et al. (2008), and reference therein, for a more complete discussion.

Field dark matter halos and subhalos are identified using a variant of the bound density maxima algorithm (Klypin et al. 1999). A *subhalo* is defined as a dark matter halo whose center is positioned within the virial radius of a more massive halo, whereas a *field halo* does not. The virial radius is defined as the radius of a collapsed self gravitating dark matter halo within which the average density is $\Delta_{\rm vir}$ times the mean density of the universe. Under comparison to constructed mass functions, we have determined that our halo catalogs are complete to a minimum mass of $10^{10} M_{\odot}$, and our sample includes $\sim 17,000$ field halos at $z = 0$ in the mass range $M = 10^{11.2-13.2} M_{\odot}$. We use the same merger trees described in Stewart et al. (2008), constructed using the techniques described in Wechsler et al. (2002, 2006).

We present our results primarily in terms of the dark matter mass ratio between the two halos that are undergoing a merger, $(m/M)_{\rm DM}$, where we always define $m_{\rm DM}$ as the mass of the smaller dark matter halo (which we will sometimes refer to as the *satellite* halo) just *prior* to entering the virial radius of the larger one, and $M_{\rm DM}$ is the mass of the larger dark matter halo (also referred to as the *host* halo) at this infall epoch. Thus, $M_{\rm DM}$ does not incorporate the mass $m_{\rm DM}$, and $(m/M)_{\rm DM}$ has a maximum value of 1.0. However, we also present results in terms of the *stellar* mass ratio of the central galaxies within merging halos, or the mass ratio between the *total* baryonic mass of these central galaxies (stellar mass plus gas mass). We refer to the dark matter, stellar, and galaxy (baryonic) mass ratios as $(m/M)_{\rm DM}, (m/M)_{\rm star}, (m/M)_{\rm gal}$, respectively. Independent of the mass ratio definitions above, we always refer to a merger ratio of $m/M > 0.3$ as a *major merger*. For the sake of comparison to our past work, we emphasize that in Stewart et al. (2008), we considered two definitions of merger ratio. The first (written as $m/M_0$ in that paper) referred to the ratio of the satellite mass at infall $m$ to the final dark matter halo mass $M_0$ at $z = 0$. This is *not* the ratio we are using here. The mass ratio definition we adopt here is more standard and refers always to the mass ratio at the redshift $z$ of accretion ($m/M_z$ in the notation of Stewart et al. 2008a).

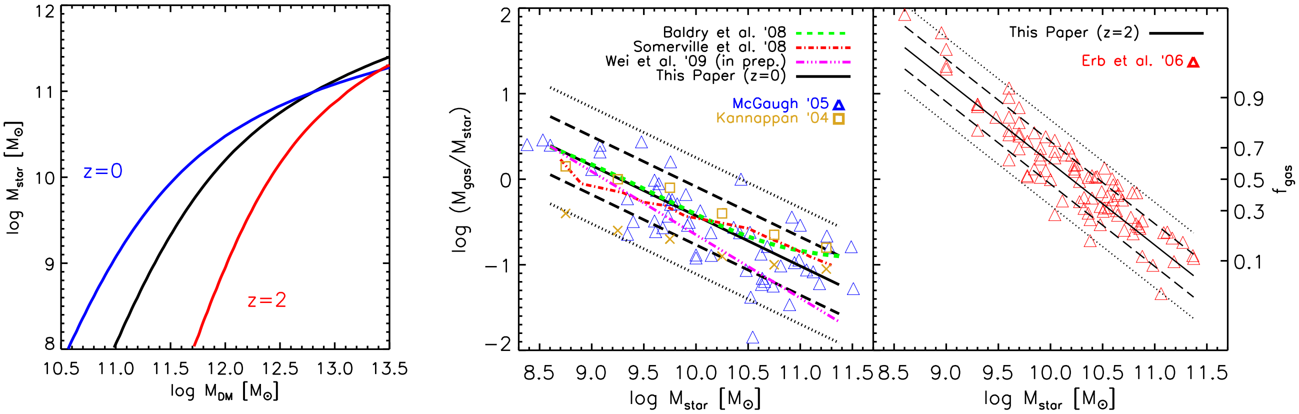

FIG. 1.— Two step method for assigning baryons to dark matter halos. *Left:* Stellar mass $M_{\rm star}$ versus dark matter halo mass $M_{\rm DM}$, for $z = 0, 1, 2$, based on abundance matching (Conroy & Wechsler 2008). *Middle(Right):* Power law fits to $M_{\rm gas}/M_{\rm star}$ as a function of stellar mass at $z = 0(2)$, with the corresponding gas fraction $f_{\rm gas} = M_{\rm gas}/(M_{\rm gas} + M_{\rm star})$ shown on the right axis. The symbols represent observational estimates from McGaugh 2005 (entire sample: blue triangles), Kannappan 2004 (average of blue galaxy sample, gold squares; average of red galaxy sample, gold X's), Baldry et al. 2008 (average: green short-dashed line), Somerville et al. 2008 (average: red dot-dashed line), Wei et al. 2009 (best fit to total sample: magenta dot-dot-dot-dashed line) and Erb et al. 2006 (entire sample: red triangles). The solid (black) line in each panel is the best-fit relation (Equation 1), while the long-dashed and dotted (black) lines represent the $1\sigma$ and $2\sigma$ scatter, respectively.

In order to provide robust results, we define a merger to occur once the smaller halo crosses within the virial radius of the larger halo and becomes a subhalo, as the subsequent orbital evolution of each subhalo will depend on the baryonic distribution within both halos. We emphasize that for the major mergers we consider in this paper, the dynamical friction decay timescales are expected to be short (comparable to the halo dynamical timescale) for typical orbital parameters (Boylan-Kolchin et al. 2008). Since only $\sim 5\%$ of $10^{12} M_\odot$ halos have experienced a major merger in the past halo dynamical time at $z = 0$ (see Figure 4), most of these major mergers into the virial radius have had adequate time to impact the central galaxy and do not survive as distinct substructure by $z = 0$. For a more in-depth comparison between merger rates into the virial radius and the rate at which accreted satellites are "destroyed" in this simulation (i.e. once they lose 90% of their infall mass) we refer the reader to Stewart et al. (2009a).

## 2.2. *Assigning Stars*

One particularly simple, yet surprisingly successful approach for assigning galaxies to dark matter halos is to assume a monotonic mapping between dark matter halo mass $M_{\rm DM}$ and galaxy luminosity $L$ (Kravtsov et al. 2004; Tasitsiomi et al. 2004; Vale & Ostriker 2004; Conroy et al. 2006; Berrier et al. 2006; Purcell et al. 2007; Marín et al. 2008). Using this technique, provided we know $n_g(> L)$ (the cumulative number density of galaxies brighter than $L$) we may determine the associated dark matter halo population by finding the halo mass above which the number density of halos (including subhalos) matches that of the galaxy population, $n_h(> M_{\rm DM}) = n_g(> L)$.

We use a similar approach, and instead assume a monotonic relationship between halo mass and stellar mass $M_{\rm star}$. Specifically, we adopt the relation found by Conroy & Wechsler (2008) (hereafter CW08; interpolated from their data as shown in their Figure 2). Figure 1 (left panel) shows the resulting relation between stellar mass and dark matter halo mass for $z = 0, 1, 2$ (upper blue, middle black, lower red curves respectively) where $M_{\rm star}$ is the stellar mass of the central galaxy residing within a dark matter halo of mass $M_{\rm DM}$. We ignore scatter in this relationship for the results that follow, but we find that including a Gaussian scatter of 0.1 dex has no substantive effect our results.

Of course, a simple relation of this kind cannot be correct in detail, however, in an average sense, it provides a good characterization of the relationship between halo mass and galaxy stellar mass that must hold in order for LCDM to reproduce the observed universe. Moreover, by adopting it we insure that our model self-consistently reproduces the observed stellar mass function of galaxies out to $z \sim 2$. We cannot use this method to explore merger rates as a function of stellar mass beyond $z \sim 2$ because the stellar mass function is poorly constrained at higher redshifts. We refer the reader to Marchesini et al. (2008) for a detailed investigation of random and systematic uncertainties in computing the stellar mass function at $1.3 < z < 4.0$ (e.g. the impact of different SED-modeling assumptions, cosmic variance, and photometric redshift errors).

## 2.3. *Assigning Gas*

In order to reasonably assign gas to the central galaxies within our halos, we quantify observationally-inferred relations between the ratio of cold gas mass to stellar mass ($M_{\rm gas}/M_{\rm star}$) as a function of stellar mass using the empirical results of McGaugh 2005 (blue triangles, for disk-dominated galaxies at $z = 0$) and Erb et al. 2006 (red triangles, for UV-selected galaxies at $z \sim 2$), as shown in the middle and right panels of Figure 1. Though both of these samples are biased with respect to blue (gas-rich) galaxies, we argue below that by adopting these relations we are not strongly biasing our overall results.

As shown by the black solid lines in the right panels of Figure 1, the $z \sim 0$ and $z \sim 2$ cold gas fraction data can be characterized by a relatively simple function of stellar mass and redshift:

$$\frac{M_{\rm gas}}{M_{\rm star}} = 0.04 \left(\frac{M_{\rm star}}{4.5 \times 10^{11} M_{\odot}}\right)^{-\alpha(z)}, \qquad (1)$$

where the gas fraction relation evolves and steepens with redshift as $\alpha(z) = 0.59(1+z)^{0.45}$. Assuming a Gaussian scatter about the best-fit lines (independent of mass), we find that the scatter evolves with redshift as $\log_{10}[\sigma(z)] = 0.34 - 0.19 \log_{10}(1+z)$, such that the correlation between the cold gas fraction and stellar mass is tighter at $z \sim 2$ than it is at $z = 0$. The black long-dashed and dotted lines in the right panels of Figure 1 demonstrate the $1\sigma$ and $2\sigma$ scatter, respectively. In order to assign gas content to our halos as a function of stellar mass, we draw randomly from a Gaussian distribution with the average value and standard deviation given by the above analytic characterizations of $M_{\rm star}(M_{\rm gas})$.

For comparison, the middle panel of Figure 1 also shows several additional observational estimates for the gas-fraction relation as a function of stellar mass. The gold squares and gold X's present the average relation measured by Kannappan (2004) for blue galaxies and red galaxies, respectively. The green short-dashed line shows the average (statistical) relation derived using a combination of published galaxy stellar mass functions and the observed stellar mass-metallicity relation by Baldry et al. (2008), who used robust chemical evolution arguments to derive implied gas fractions as a function of stellar mass. Finally, the average results from direct measurements by (Wei et al. 2009, in preparation) are shown by the magenta dot-dot-dot-dashed line. For the sake of comparison, we show the *predicted* relation from the semi-analytic model of Somerville et al. 2008 (red dot-dashed line). While we do not utilize these additional data sets in *constructing* our fitting function, they conform well to our average relation and certainly lie within the $1\sigma$ scatter of our fit to the McGaugh (2005) data (with the exception of low-mass red galaxies from Kannappan 2004; see discussion below). We also note that the cold gas fractions derived by Wright et al. (2008) for six galaxies at $z \sim 1.6$ are also consistent with the evolution in our fit, with every galaxy in their sample falling within our $2\sigma$ scatter. Their sample does have a slightly higher average gas fractions at fixed $M_{\rm star}$ than our adopted relation, but the discrepancy is not significant given the small-number statistics.

The fact that we have fit our $z = 0$ relation to disk-dominated galaxies introduces a potential worry about applying the relation to every galaxy halo in our simulation, including ones that presumably host massive (spheroidal) galaxies. However, it is unlikely that this bias will drastically affect our results, primarily because the gas fractions in the adopted relation are only appreciable ($\gtrsim 0.5$), in the smallest galaxies (at $z = 0$) with $M_{\rm star} \lesssim 10^{10.5} M_{\odot}$ – the stellar mass regime that is known to be dominated by disk-dominated galaxies (see, e.g., the left panel of Figure 2). For larger galaxies, it is reassuring to note that the average relation for the red galaxy sample from Kannappan (2004) lies within our adopted $\sigma$ scatter and is in relatively good agreement with the other (disk-selected) observations. It is only for *less* massive galaxies (a regime where blue disk galaxies dominate the total population anyway) where the red galaxy sample of Kannappan (2004) becomes significantly discrepant from our fiducial relation. Finally, even if our fiducial relation is biased to be slightly high for massive galaxies, the gas fractions are already small enough that we would never classify them as "gas-rich" in our discussions below.

A similar point of concern may be applied to the Erb et al. (2006) data at $z \sim 2$. These galaxies were selected based on UV luminosity and thus constitute an actively star-forming population. However, there is a good deal of evidence that UV luminosity is tightly correlated with total stellar mass (or halo mass) at $z \gtrsim 2$ (see e.g., discussion in Conroy et al. 2008, and references therein). For example, galaxies with higher UV luminosities at $z \sim 2$ are more strongly clustered (Adelberger et al. 2005), suggesting that they reside within more massive dark matter halos. In addition, the UV and V-band luminosity functions of galaxies at $z \sim 3$ are in relative agreement, producing similar number densities for $\sim L^*$ galaxies (Shapley et al. 2001; Sawicki & Thompson 2006; also see Table 2, and discussion, in Stewart et al. 2009a). As such, it is reasonable to consider a galaxy sample selected on UV luminosity to contain a fairly representative sample of bright galaxies at $z \sim 2$.

We also note that the gas estimates we adopt from Erb et al. (2006) assume the global Schmidt law of Kennicutt (1998): $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{1.4}$. Both observations and recent hydrodynamic simulations have suggested that while this relation is tightly correlated for *molecular* gas, it may underestimate the *total* gas content, especially for galaxies where the fraction of gas in molecular form is not uniform (e.g. Wong & Blitz 2002; Robertson & Kravtsov 2008; Gnedin et al. 2008). As a consequence, the gas fraction estimates from Erb et al. (2006) may represent a lower limit, such that the evolution of gas fraction with redshift may actually be *steeper* than our adopted relation. Insofar as issues of gas accretion and disk survival are concerned, our relation may be considered a conservative lower limit on the estimated gas content of our galaxies.

Finally, there has been some discussion in the literature that the stellar initial mass function (IMF) may evolve systematically to become more top heavy at high redshift in galaxies with extremely low metallicities (e.g. Lucatello et al. 2005; Tumlinson 2007; van Dokkum 2008; Komiya et al. 2008). This evolution in the IMF has not been corrected for in our adopted mapping between halo mass and stellar mass. While we do not expect this to significantly affect our results, including this evolution of the IMF would decrease our stellar mass estimates at fixed halo mass—which would, in turn, *increase* our estimated gas fractions. As such, so far as issues of gas accretion and disk survival are concerned, the results we present are a conservative lower limit.

With the above qualifications in mind, we now turn to the implications of this empirically-motivated stellar mass and gas mass assignment prescription.

## 3. RESULTS AND IMPLICATIONS

### 3.1. *Galaxy Morphology*

We start by investigating the merger histories of $z = 0$ dark matter halos. The solid black line in the left panel of Figure 2 shows the fraction of dark matter halos that have experienced at least one major dark matter merger with $(m/M)_{\rm DM} > 0.3$ since $z = 2$ as a function of dark

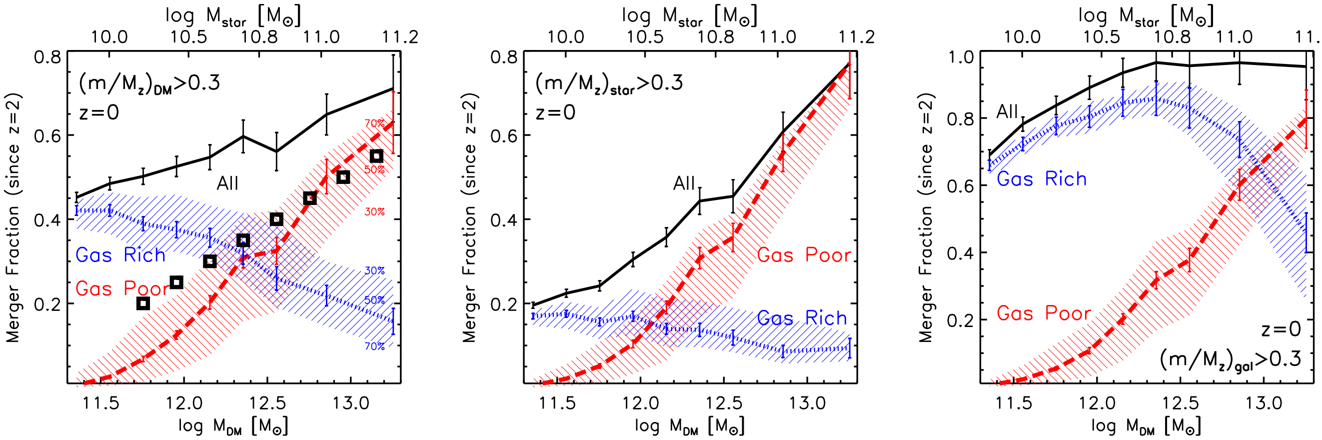

FIG. 2.— Fraction of dark matter halos with at least one major merger since $z = 2$, as a function of host halo mass $M_{\rm DM}$ (lower axis) and stellar mass $M_{\rm star}$(upper axis), for varying definitions of 'major merger.' *Left:* Major merger defined by the ratio of dark matter halo masses, $(m/M)_{\rm DM}$. The black squares in this figure show the observed early-type fraction as a function of halo mass from Weinmann et al. (2006). *Middle:* Major merger defined by the ratio of the stellar masses in each central galaxy, $(m/M)_{\rm star}$. *Right:* Major merger defined by ratio of the total baryonic mass of the central galaxies, $(m/M)_{\rm gal}$. In each panel, the solid (black) line shows the total merger fraction. The dashed (red) line shows the merger fraction while *only* considering mergers between two halos that *both* contain gas-poor central galaxies ($f_g < 50\%$). The dotted (blue) line shows only mergers for which both galaxies are gas-rich ($f_g > 50\%$). The shaded regions surrounding the red and blue lines represent the impact of varying our distinction between gas-rich and gas-poor from 30% to 70%. The bottom axis shows the same range in halo mass in each panel, while the corresponding stellar (or baryonic) mass of the central galaxy is shown on the top axis. Note that the range in y-values in the right panel is larger than the left and middle panels. Error bars are Poissonian based on the number of host halos and the total number of mergers, and do not include possible errors in assigning stars and gas to halos (though we do account for *scatter* in the $M_{\rm star}(M_{\rm gas})$ relation, see §2.2,2.3).

matter halo mass (lower axis label). Equivalently, the merger fraction as a function of galaxy stellar mass can be seen by focusing on the upper axis label. Compare this result to the black squares, which show the early-type fraction for SDSS galaxies as a function of central halo mass as derived by Weinmann et al. (2006; henceforth W06) [4]. Clearly the fraction of halos with major mergers greatly exceeds the late-type fraction at low masses.

Consider now the likely baryonic makeup of these mergers. The (blue) dotted line shows the fraction of halos that have experienced a *gas-rich* major merger and the (red) dashed line shows the fraction of halos with at least one *gas-poor* merger. In our fiducial case, we define a merger to be gas-rich if both the central galaxy *and* the infalling satellite galaxy have more baryonic mass in the form of gas than in stars: $f_g \equiv M_{\rm gas}/(M_{\rm gas} + M_{\rm star}) > 50\%$. Similarly, gas-poor mergers are defined such that each of the progenitors has $f_g < 50\%$. The shading of the red and blue bands correspond to varying the definition of gas-rich from $f_g > 30\%$ to $f_g > 70\%$. [5]

Remarkably, if one makes the simplistic assumption that only gas-poor mergers generate early-type galaxies (red dashed line) and gas-rich mergers preserve disks, then the observed SDSS relation from W06 is reproduced fairly well. Specifically, we find that the fraction of halos with a disk-destructive merger increases from only $\sim 15\%$ at $10^{12}M_\odot$ to $\sim 55\%$ at $10^{13}M_\odot$, in remarkably good agreement with W06. Not only does this agreement provide a possible solution to disk survivability within Milky Way-sized halos, but it also implies that the gas-poor merger history of a dark matter halo may be closely tied to the halo mass–morphology relation (across this range in halo mass). Although halo merger rates have been shown to depend strongly on environment (Fakhouri & Ma 2009), suggesting a possible connection to the morphology–density relation of galaxies, we see in Figure 2 that the overall halo major merger rate (solid black line) is *not* steep enough to account for the observed change in morphological fraction with halo mass.

It is also worth mentioning that the implied transition between mostly gas-rich and mostly gas-poor mergers occurs at a characteristic mass $M_{\rm star} \simeq 5 \times 10^{10} M_\odot$ (or equivalently $M_{\rm DM} \simeq 2 \times 10^{12} M_\odot$), which is close to the characteristic bimodality scale that separates blue, star-forming, disk-dominated systems and red, bulge-dominated systems with old populations typically occurring at a characteristic stellar mass (typically $M_{\rm star} \sim 3 \times 10^{10} M_\odot$, see e.g. Kauffmann et al. 2003; Baldry et al. 2004; Kannappan 2004; Baldry et al. 2006; Cattaneo et al. 2006; Dekel & Birnboim 2006).

## 3.2. *Alternative definitions for major merger*

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[4] Note that in W06, they divide galaxies into three categories instead of two; early-type, late-type and intermediate-type. In order to compare our simple bimodal model to their findings, we have forced half of their intermediate-types to be counted as early-type, and half as late-type.

[5] Because the morphological impact of a mixed merger (where one galaxy is gas-rich and one is gas-poor) is largely unclear, we choose to focus on the extreme cases where both are either gas-rich or gas poor, and to leave a more detailed exploration of mixed mergers for future work. This means that the combined gas-rich fractions and gas-poor fractions in Figure 2 need *not* equal the total merger fraction, which includes all major mergers regardless of baryonic content. However, because a galaxy's gas fraction is a strong function of halo mass at fixed redshift (and because we define a strict cutoff between gas-rich and gas-poor based on gas fraction) we find that mixed mergers are less frequent than mergers between two gas-poor or two gas-rich systems. If the larger galaxy in a major merger is gas-rich (by our definition), then the smaller galaxy is most likely gas-rich as well. Conversely, if the smaller galaxy in a major merger is gas-poor, then the larger galaxy is most likely also gas-poor. While there does exist a characteristic mass scale for which mixed mergers become a significant portion of the overall merger fraction, even at this special mass scale they still only constitute about half of all mergers (see Figure 4, discussion in §3.3).

The middle and right panels of Figure 2 explore how the implied merger fraction trends change when one choses to define major mergers using the stellar-mass ratio, $(m/M)_{\rm star} > 0.3$, and total baryonic galaxy mass ratio, $(m/M)_{\rm gal} > 0.3$, respectively, rather than the total mass ratio in dark matter. Clearly, the implied trends between merger fraction and galaxy halo mass depend sensitively on whether dark matter mass ratios, stellar mass ratios, or baryonic galaxy mass ratios are considered (also see Maller 2008). As seen by the solid black line in the middle panel, high stellar-mass ratio events are rare in small galaxy halos and common in high mass halos. This follows directly from the fact that low-mass halos tend to have a higher stellar-mass to dark matter mass ratios (see Figure 1). The trend changes dramatically when the full baryonic mass of the galaxy is considered in the ratio (right panel). In this case, even small galaxy halos are expected to have had common mergers with galaxies of a comparable total baryonic mass (note that the range of the vertical axis has changed in the right-hand panel). It is clear from this comparison alone that most of the major mergers experienced by small galaxies must be gas-rich.

We note that the fraction of systems that have experienced at least one gas-rich merger (and consequently, the total merger fractions as well) show qualitatively different behavior depending on these definitions. Gas-rich *halo* mergers ($(m/M)_{\rm DM} > 0.3$) are relatively frequent for $M_{\rm DM} = 10^{11.5} M_\odot$ systems (40% since $z = 2$), with a smoothly declining merger fraction for increasing halo mass (roughly linear in $\log M_{\rm DM}$), while the gas-rich *stellar* merger fractions decline in a qualitatively similar fashion but are universally less common, with merger fractions $< 20\%$ for $M_{\rm DM} = 10^{11.5} M_\odot$. In contrast, the fraction of halos with at least one major *galaxy* merger ($(m/M)_{\rm gal} > 0.3$) shows completely different behavior, with extremely high fractions ($40 - 90\%$) and non-monotonic evolution with $\log M_{\rm DM}$ (with a maximum value at $M_{\rm DM} \sim 10^{12.2} M_\odot$).

The behavior of *gas-poor* merger fractions, on the other hand, remains remarkably similar in each case. Regardless of these three merger ratio definitions, the fraction of halos which have experienced a gas-poor major merger is negligible at small halos masses ($M_{\rm DM} \sim 10^{11.5} M_\odot$) and increases roughly linearly with $\log M_{\rm DM}$ to a fraction of $65 - 75\%$ at $M_{\rm DM} = 10^{13.2} M_\odot$. Because these gas-poor merger fractions appear somewhat independent of the merger ratio definition used (and they remain consistent with observed morphological fractions as a function of halo mass) we again suggest that a dark matter halo's gas-poor merger history may be a particularly useful tracer of galaxy morphology—more so than the merger history of all mergers.

One might be tempted to conclude that the total major merger rate in the middle panel (major stellar mergers) is sufficiently steep to account for the change in morphological fraction with halo mass reported by W06. Encouragingly, only $\sim 30\%$ of $10^{12} M_\odot$ halos have experienced a $(m/M)_{\rm star} > 0.3$ merger since $z = 2$. However, it is important to note that even relatively minor, $(m/M)_{\rm DM} = 0.1$ dark matter halo mergers with *negligible* stellar content $(m/M)_{\rm star} \sim 0.03$ are capable of heating and thickening a galactic disk beyond the properties of the Milky Way (Purcell et al. 2009). Larger dark matter mergers (which do not necessarily correspond to major stellar mergers) are expected to easily be capable of destroying disk morphologies. Thus, the major stellar merger fractions in this panel likely present an incomplete picture of possible means of disk destruction.

### 3.3. *Gas Delivery Via Mergers*

In Stewart et al. (2009a), we discuss the observational implications of two well-known consequences of galaxy halo mergers: merger-induced starbursts and morphological disturbance. A third potentially important consequence of mergers is the direct, cumulative deposition of cold baryons (gas and stars) onto galaxies.

The solid black line in Figure 3 shows the fraction of a central galaxy's current ($z = 0$) baryonic mass ($M_{\rm gal} = M_{\rm gas} + M_{\rm star}$) acquired directly via major mergers as a function of halo mass $f_{\rm merged} \equiv M_{\rm merged}/M_{\rm gal}(z = 0)$. Specifically, $M_{\rm merge}$ includes all of the baryonic mass in mergers obeying $(m/M)_{\rm DM} > 0.3$ since $z = 2$. The first clear result is that the merged baryonic fraction is significant: from $\sim 30 - 60\%$ of the final galaxy mass is accreted directly in the form of major mergers. Given the effectiveness of dynamical friction in major mergers, we expect the majority of the accreted baryonic material in these events to be deposited in the central galaxy itself. In principle, this limits the fraction of a galaxy's baryons that can be acquired by direct hot halo cooling, cold flows, or minor mergers to $40 - 70\%$. Of course, (gaseous) baryons deposited via major mergers could in principle be blown out by energetic feedback, but all in all, this result on major merger deposition (much like known results on cold flows) would seem to make the 'overcooling' problem in galaxy formation more difficult. Interestingly, there also a demonstrated minimum in merged baryon fraction at the $M_{\rm DM} \sim 10^{12} M_\odot$ scale, which corresponds closely to the well-known mass scale of maximum galaxy formation efficiency (corresponding to $\sim L_*$ in the galaxy luminosity funciton).

The dotted (blue) and dashed (red) lines in Figure 3 separate the total baryonic accretion fraction from major mergers into contributions from gas and stars, respectively (this is not a division between gas-rich and gas-poor mergers as before, but rather an integrated accounting of all material regardless of the makeup of the merged progenitors). We see that the baryonic accretion onto smaller halos ($M_{\rm DM} \lesssim 10^{12.3} M_\odot$) is typically dominated by the gas content of the infalling galaxies, while the baryonic makeup of merged material into more massive systems is dominated by the infalling galaxies' *stellar* content. For Milky Way-size systems ($M_{\rm DM} = 10^{12} M_\odot$), we find that typically $\sim 20\%(10\%)$ of a galaxy's baryonic content was accreted in the form of gas (stars) directly via major mergers. More massive systems ($M_{\rm DM} = 10^{13} M_\odot$) typically accrete $30\%(13\%)$ of their baryons as gas (stars) via major mergers. Though not shown, we find that most ($70 - 80\%$) of the *stellar* accretion from major mergers occurred at late times ($z < 1$) while most ($60 - 70\%$) of the *gas* accretion took place earlier ($z > 1$).

How do our results change if we include more minor mergers in our accounting? If we count up all of the baryonic acquisition in mergers larger than $(m/M)_{\rm DM} > 0.1$ we find that the mass fraction accreted as stars remains relatively unchanged (boosted from the dashed line in

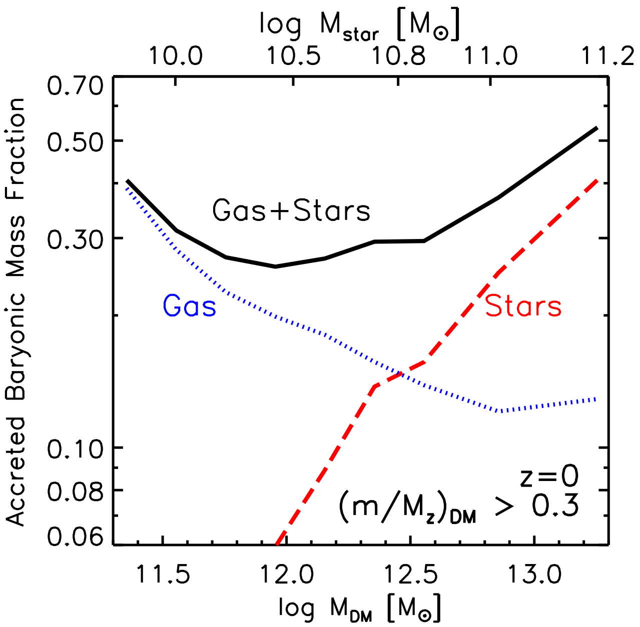

FIG. 3.— The fraction of a $z = 0$ galaxy's total baryonic mass that was accreted directly via major mergers ($(m/M)_{\rm DM} > 0.3$) since $z = 2$, as a function of halo mass. The dotted (blue) and dashed (red) lines show the accreted baryonic mass fraction from gas and stars, respectively, while the solid (black) line shows the total.

Figure 3 by a factor of $1.1 - 1.5$, with a slightly larger increase for more massive halos), but we find a considerable enhancement in the accreted gas mass (boosted by a factor of $\sim 1.7$ from the dotted line in Figure 3, roughly independent of halo mass).

We caution, however, that the importance of minor mergers in delivering baryons to central galaxies is significantly less clear than it is with major mergers. While the baryons associated with major mergers almost certainly become deposited directly onto the central galaxy (see e.g. the simulations of Purcell et al. 2008b) the ultimate fate of the baryons in minor mergers will depend sensitively on the orbital properties of the secondary and on the potential presence of hot gas halo around the primary galaxy. Past work has demonstrated that the *stellar* material in minor mergers will likely contribute to extended diffuse light components like stellar halos or intracluster light (e.g., Bullock & Johnston 2005; Purcell et al. 2007; Conroy et al. 2007; Purcell et al. 2008a), but the destiny of *accreted gas* (which is the dominant component for galaxy halos) in these minor mergers is relatively unexplored. One possibility is that the gas in minor mergers is quickly liberated via ram pressure stripping (see, e.g. Grcevich et al. 2008) and that it either evaporates into the hot halo itself or eventually rains down onto the galaxy, possibly in the form of high-velocity clouds. These interesting possibilities are clearly beyond the scope of the present work but provide important avenues for future investigation.

### 3.4. *Redshift Evolution*

While the cumulative fraction of halos that have *ever* experienced a gas-rich or gas-poor major merger (since $z = 2$) is the most pertinent question for morphological evolution and disk survivability (see §3.1), another point of interest is the redshift evolution of a more instantaneous measure of the merger rate of gas-poor and gas-rich mergers. Figure 4 shows the fraction of halos that have experienced at least one major merger with $(m/M)_{\rm DM} > 0.3$ in the past halo dynamical time, $\tau$ [6]. As in Figure 2, the solid (black) line shows the total merger fraction for dark matter halos, while the dotted (blue) and dashed (red) lines show the major merger fraction for gas-poor ($f_g < 50\%$) and gas-rich ($f_g > 50\%$) mergers, respectively. Because the quantitative values of these merger fractions depend sensitively on the merger timescale in question at each redshift, we choose to focus on two important *qualitative* results from this figure. We refer the reader to Stewart et al. (2009a) for a more detailed discussion of the evolution of the halo merger rate (and merger fractions) with redshift, halo mass, and merger mass ratio (see also Fakhouri & Ma 2009, for the effects of halo environment on the merger rate).

The first feature of note in this figure is the presence of a typical transition mass, $(M_t)_{\rm DM}$, such that most of the recent major mergers into halos less massive than $(M_t)_{\rm DM}$ are gas-rich, while most of the recent major mergers into halos more massive than $(M_t)_{\rm DM}$ are gas-poor. The existence of this transition mass is primarily due to the strong dependence of galaxy gas fractions on stellar mass (and thus, halo mass) at fixed redshift. In addition to creating this transition mass, the dependence of gas fraction on halo mass also results in a very limited mass range for which mixed mergers (where one galaxy is gas-poor and the other is gas-rich) constitute a significant portion of all mergers (at most $\sim 50\%$). This effect is apparent in Figure 4 where the combined total of the gas-poor and gas-rich merger fractions fall significantly short of the total. Not unexpectedly, this range of importance for mixed mergers is centered on $(M_t)_{\rm DM}$.

The other important result from Figure 4 is that $(M_t)_{\rm DM}$ is more massive at higher redshifts, with $(M_t)_{\rm DM} \simeq 10^{11.4}, 10^{11.9}, 10^{12.8} M_\odot$ at $z = 0.0, 0.5, 1.0$, respectively. This arises naturally from the strong increase in galaxy gas fractions to higher redshift. The corresponding galaxy stellar mass transitions at $z = 0.0, 0.5,$ and $1.0$, are $(M_t)_{\rm star} \sim 10^{9.7}, 10^{10.3}, 10^{11.0} M_\odot$ (upper horizontal axis in Figure 4). Of course, the precise value of $M_t$ at each redshift will depend to some degree on our definitions of "gas-rich" and "gas-poor," but the *existence* of this transition mass, and its qualitative evolution with redshift should be robust to changes in these definitions.

Consider recent major mergers into Milky-Way size $10^{12} M_\odot$ halos. At $z = 0$, mergers of this kind are very uncommon. Only $\sim 5\%$ of Milky-Way size halos should have experienced a major dark matter accretion event with $(m/M)_{\rm DM} > 0.3$ in the last $\tau \sim 2$ Gyr. However, when these major mergers do occur at $z = 0$ they are very likely gas-poor ($\sim 0.04/0.05 = 80\%$ of the time). On the other hand major mergers are fairly common in $10^{12} M_\odot$ halos at $z \sim 1$, with $\sim 15\%$ experiencing such a merger in the last $\tau \sim 1$ Gyr. Nevertheless, these higher redshift mergers are almost universally gas-rich. Under the pre-

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[6] As in Stewart et al. (2009a), in which we studied the evolution of the halo merger rate with redshift, we again adopt $\tau(z) = R/V \propto (\Delta_v(z)\,\rho_u(z))^{-1/2}$, such that the halo dynamical time evolves with redshift, but is independent of halo mass.

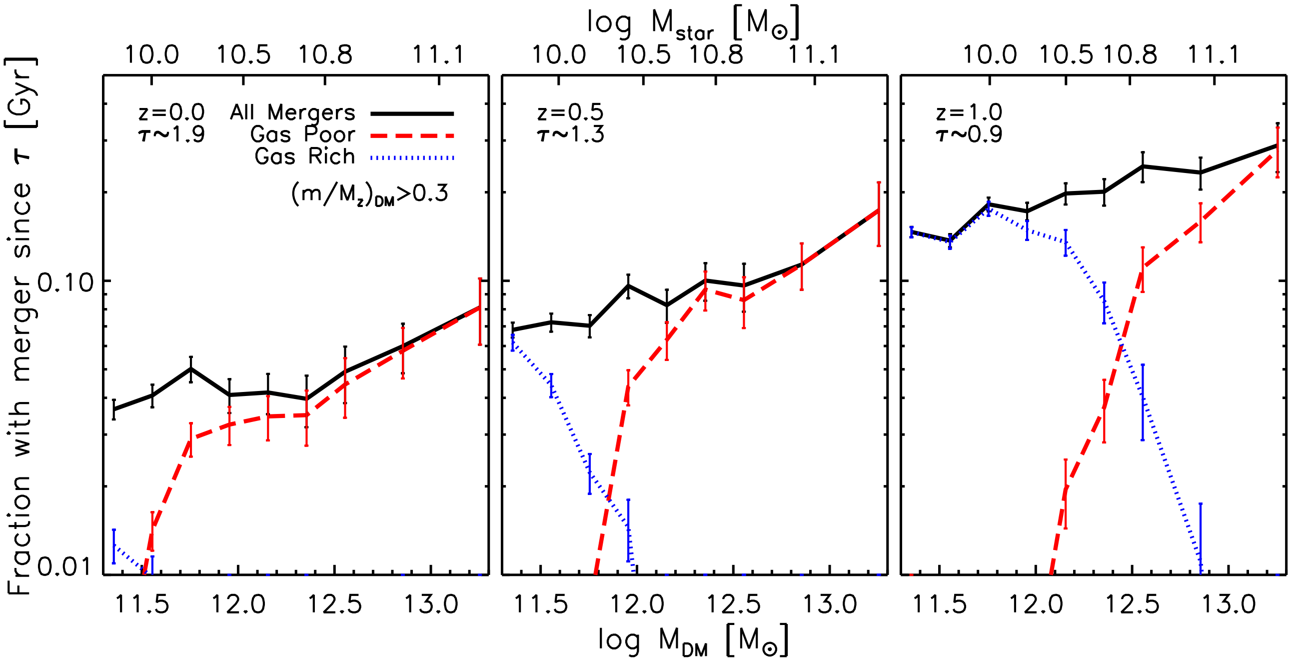

Fig. 4.— Major merger fraction within the past dynamical time of the halo, $\tau$, as a function of halo mass. The solid (black) line shows the total merger fraction for dark matter halos (no baryons included). The dashed (red) line shows the merger fraction while only considering gas poor mergers ($f_g < 50\%$). The dotted (blue) line shows only gas-rich mergers ($f_g > 50\%$). The three panels show results for $z = 0$, $z = 0.5$, and $z = 1$, for which the halo dynamical time, $\tau \simeq 1.9, 1.3, 0.9$ Gyr, respectively. We primarily focus on the decomposition of these merger fractions into gas-rich and gas-poor mergers. We refer the reader to Stewart et al. (2009a) for a detailed analysis of the dependence of dark matter of merger rates and merger fractions on redshift, halo mass, and mass ratio.

sumption that gas-rich mergers do not destroy disk morphologies, the evolution of the merger rate with redshift and in the associated gas-rich transition mass makes it increasingly likely that major mergers *build* disk galaxies at high redshift rather than destroy them (c.f. Robertson et al. 2006a, Robertson & Bullock 2008). If we were to boldly extrapolate our trends to higher redshift, we would expect that nearly *all* major mergers into halos with $M_{\rm DM} < 10^{12} M_\odot$ should be gas-rich ($f_g > 50\%$) at $z > 1$.

Encouragingly, Lin et al. (2008) observe a similar redshift evolution between gas-rich and gas-poor mergers by studying the close-pair counts of galaxies from the DEEP2 Redshift Survey. While our definitions vary in detail from theirs (they divide galaxy pairs into wet and dry mergers based on galaxy colors, and bin their sample by total galaxy luminosity, while we use galaxy gas fractions to define gas-poor versus gas-rich mergers, and bin by galaxy stellar mass) they also find that at fixed luminosity (stellar mass) the percentage of major mergers that are dry (gas-poor) should decrease with increasing redshift, while the percentage of major mergers that are wet (gas-rich) should increase. We reserve a more detailed comparison to their results for a future study, but we find the qualitative agreement encouraging.

### 3.5. *Comparison to Previous Work*

Recent studies of galaxy formation at high redshift using hydrodynamic simulations have stressed the importance of smooth accretion of cold gas from filamentary streams. For example, Keres et al. (2008) compared the accretion rate of gas onto galaxies via cold flows and via mergers, and found that at $z = 1 - 2$, only about half of all gas accretion (onto galaxies corresponding to $M_{\rm DM} \gtrsim 10^{11.3} M_\odot$) is in the form of mergers, (where gas from mergers was defined as any gas that was added to galaxies in dense baryonic clumps). Similarly, Dekel et al. (2008) found that half of cold gas infall onto massive $z = 2$ galaxies is aquired via mergers with $(m/M)_{\rm DM} > 0.1$, and the other acquired from cold flows. Indeed, even studies that focus primarily on the importance of galaxy mergers also note that smooth gas accretion is at least as dominant as galaxy mergers in the mass buildup of galaxies (e.g. Maller et al. 2006). Our results do not contradict these expectations. As demonstrated in Figure 3, we expect that $\sim 30 - 40\%$ of a typical galaxy's baryons should have been accreted directly via major mergers with $(m/M)_{\rm DM} > 0.3$. This leaves significant room for cold-flow gas to contribute to the baryonic assembly of small galaxies and for cooling to contribute to the buildup of larger galaxies. Though, as mentioned above, we do expect that the percentage of merger-delivered baryons could rise to as much as $\sim 60\%$ if all of the baryonic material from $(m/M)_{\rm DM} > 0.1$ mergers is able to find its way into the central galaxy.

Brooks et al. (2008) used a high-resolution cosmological hydrodynamic simulation to study the gas accretion onto four disk galaxies within halos of masses $10^{10.7-12.7} M_\odot$, and also found that accretion of unshocked gas via cold flows dominates the mass buildup of their galaxies. When comparing smooth gas accretion to gas infall from mergers (using a generous definition of what qualifies as a merger) they found that $\sim 25\%$ of the total gas infall into their Milky Way-size galaxy derives from mergers, with $\sim 10\%$ of the final stellar content at $z = 0$ being accreted directly as stars from mergers. While their detailed results (and definitions) differ slightly from our own, the rough consistency between their simulation and our own semi-empirical approach is quite encouraging.

One point of caution associated with the discussion of cold flows is that these predictions are based entirely on simulations that do not generally reproduce the observed baryonic mass function and stellar mass function of galaxies. It is possible that the cold flows are somehow restricted in the real universe in a way that solves the well-known over-cooling problem in galaxy formation. Due to the inherent difficulties in detecting cold filaments of gas locally and at high redshift, there has yet to be an observational confirmation of a star forming galaxy fueled by the smooth accretion of cold gas along filaments, as seen in hydrodynamic simulations. In contrast, our predictions for the accretion of stars and gas via major mergers is solidly normalized against observations, and is arguably inevitable in the context of LCDM merger histories. Of course, baryonic material (especially gas) that is delivered via major mergers need not remain in the central galaxy indefinitely. Gas accreted either along cold flows or through major mergers may be subsequently expelled via supernovae or AGN feedback (e.g. Benson et al. 2003; Di Matteo et al. 2005; Springel et al. 2005; Somerville et al. 2008). In this respect, Figure 4 represents an upper limit on the baryonic contribution from major mergers, with respect to the total amount of barons *currently* exist in the galaxy.

## 4. CONCLUSION

We have used dark matter halo merger trees from a large cosmology $N$-body simulation together with observationally-normalized relationships between dark matter halo mass, galaxy stellar mass, and galaxy gas mass to explore the baryonic content of galaxy mergers back to redshift $z = 2$. Though our adopted associations between halo mass and the baryonic content of galaxies cannot be precisely correct, it is almost certainly accurate in its scalings with halo mass and redshift, and has the added advantage that it is *independent of any uncertain galaxy formation physics*. Indeed, any self-consistent galaxy formation model that is set within the LCDM framework would certainly need to reproduce our gross baryonic assignments in order to reproduce the observed universe. Our main results based on this methodology may be summarized as follows:

1. The vast majority ($\sim$ 85%) of the major mergers experienced by Milky-Way size galaxies since $z = 2$ should have been gas-rich, and this fraction drops significantly towards higher mass systems (see Figure 2). Remarkably, the fraction of galaxies with gas-poor major mergers matches well to the observed fraction of bulge-dominated galaxies as a function of halo mass from $M_{\rm DM} = 10^{11}$ to $10^{13} M_\odot$.

2. Though *recent* major mergers are expected to be rare for small galaxies in the local universe, the recent mergers that do occur should typically be gas poor. At higher redshift, recent mergers become more common and the probability that such a merger is gas-rich also increases (see Figure 4). One can define a transition dark matter halo mass $M_t$, below which most of the recent major mergers are gas-rich and above which they are gas poor, and this transition mass increases with redshift: $(M_t)_{\rm DM} \sim 10^{11.4}, 10^{11.9}, 10^{12.8} M_\odot$ at $z = 0.0, 0.5, 1.0$. As a result, the vast majority of recent major mergers into galaxy-size $M_{\rm DM} < 10^{12} M_\odot$ dark matter halos are expected to be gas-rich at $z < 1$.

3. A significant fraction ($30 - 50\%$) of the baryonic mass in field galaxies at $z = 0$ should have been deposited directly via major mergers. For less massive galaxies, $M_{\rm DM} \sim 10^{11.5} M_\odot$, most of the merger-acquired baryons are initially gaseous, while in more massive galaxies $M_{\rm DM} \sim 10^{13} M_\odot$, major mergers typically bring in stars (see Figure 3). For Milky Way-size systems, major mergers bring in $\sim$ 30% of the galaxy's $z = 0$ baryonic mass, with $\sim$ 20% of that acquired mass in the form of gas.

Many of these conclusions lend support to the conjecture of Robertson et al. (2006a) and Brook et al. (2007a), who were the first to forcefully suggested a scenario where gas-rich mergers play an important role in building and stabilizing disk galaxies at high redshift. Though our conclusions are far from a sufficient test of this idea, we have demonstrated that gas-rich mergers should be common enough to make it viable for serious consideration.

Among our most interesting results is the similarity between our predicted gas-poor merger fraction with halo mass and the observed late-type galaxy fraction with halo mass (Figure 2, left panel). Of course, even if gas-rich mergers do preserve disks, there are many openings for concern. For example, the current presentation leaves little room for the production of bulge-dominated systems by means *other* than major mergers. In an extreme yet illustrative example, Bournaud et al. (2007) used a suite of focused simulations to show that bulge-dominated galaxies may be formed by successive minor mergers. Disk galaxies can also grow massive bulges by secular processes (typically bulges formed in this way show kinematically distinct properties from classical bulges, and are referred to as "pseudobulges") (e.g. Courteau et al. 1996; Kormendy & Kennicutt 2004; Kormendy & Fisher 2005, 2008).

An interesting possibility in this context of disk survival and secular evolution is that we have been too conservative in our classification of 'gas-rich'. Our fiducial division between gas-rich and gas poor at $f_g = 50\%$ was motivated by the idealized simulations studied by Robertson et al. (2006a) and Hopkins et al. (2008). However Governato et al. (2008) used a cosmologically self-consistent hydrodynamic simulation to demonstrate the creation of spiral galaxy at $z = 0$ within a system that experienced a very major ($(m/M)_{\rm DM} > 0.8$) merger at $z = 0.8$. The two progenitor galaxies in this case were only moderately gas-rich ($f_g \sim 20\%$). Despite these relatively low gas fractions, the merger remnant was able to quickly reform a disk via the cooling of gas from the hot phase. If we use this result as motivation to focus on the more lenient ($f_g > 30\%$) definition of gas-rich in Figure 2, our gas-poor merger fractions drop to $10 - 20\%$ smaller than the observed bulge-dominated fractions, leaving room for processes other than gas-poor major mergers to cause a significant portion of morphological transformations.

The general semi-empirical findings we have presented here may be regarded as accurate (not precise) predictions based on merger histories of LCDM halos and observed relations. As such, it is reassuring that our almost unavoidable qualitative trends are consistent with a growing body of work that stresses the importance of gas-richness in preserving disk morphologies during mergers (Barnes 2002; Brook et al. 2004; Springel & Hernquist 2005; Robertson et al. 2006a; Brook et al. 2007b,a; Governato et al. 2007, 2008; Hopkins et al. 2008; Robertson & Bullock 2008). Although we have focused primarily on issues of morphological transformation, disk survival, and baryonic accretion via mergers in this paper, we believe that in future work, the semi-empirical approach we have used here may provide a useful tool in exploring a vast array of galaxy properties and evolutionary mechanisms.

The simulation used in this paper was run on the Columbia machine at NASA Ames. We would like to thank Anatoly Klypin for running the simulation and making it available to us. We are also indebted to Brandon Allgood for providing the merger trees. We thank Charlie Conroy for sharing his abundance matching data so we could assign stellar masses to dark matter halos, and Lisa Wei (and collaborators) for sharing gas fraction data from an upcoming paper. JSB and KRS are supported by NSF grant AST 05-07916. RHW was supported in part by the U.S. Department of Energy under contract number DE-AC02-76SF00515 and by a Terman Fellowship from Stanford University. AHM acknowledges partial support from a CUNY GRTI-ROUND 9 grant and from an ROA supplement to NSF grant AST 05-07916. JSB and KRS are supported by the Center for Cosmology at the University of California, Irvine.

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