1. INTRODUCTION

The simplest semianalytic model (SAM) for galaxy formation might assume that the nature of a galaxy is determined solely by the mass and merging history of the dark matter halo or subhalo within which it resides. However, correlations between the observed properties of galaxies and their environments have been known for many years now. An increased fraction of early-type galaxies have been observed toward the centers of clusters (Dressler 1980; Dressler & Gunn 1982; Smith et al. 2005), and an increased fraction of blue, star-forming galaxies have been observed in clusters at high redshift compared to their low-redshift counterparts (Butcher & Oemler 1978, 1984). Massive elliptical galaxies in clusters are, on average, older than comparable ellipticals in the field (Thomas et al. 2005), and the interaction rate of galaxies in clusters increases with redshift much more rapidly than in the field (van Dokkum et al. 1999), indicating accelerated galaxy transformation in dense environments. Recent studies of, e.g., the Sloan Digital Sky Survey (SDSS) and the DEEP2 survey, show that the fraction of galaxies of a given mass populating the red sequence is a strong function of the environment (Baldry et al. 2006), and that massive dark halos will have a larger fraction of their final mass in progenitors at earlier times compared to low-mass halos (e.g., Neistein et al. 2006), resulting in an increased merger fraction of galaxies at larger redshifts in high-density environments (Khochfar & Burkert 2001). Furthermore, galaxies falling into dense environments are subject to interaction between the hot intracluster medium (ICM) and the interstellar medium (ISM) in the form of ram pressure stripping (Gunn & Gott 1972; Farouki & Shapiro 1980; Abadi et al. 1999; Mori & Burkert 2000) and shock heating (e.g., Frenk et al. 1999), which can allow for morphological transformation of galaxies by depriving them of gas (Quilis et al. 2000) and inducing star formation (Marcicic et al. 2007). The interplay between these processes will influence galaxies within a dark matter halo and should account for many observations in a natural way. Models that are based on a phenomenological approach and that stop cooling flows in halos above a critical mass (e.g. Kauffmann et al. 1999; Binney 2004), and hence in dense environments, are promising in that they are able to reproduce the luminosity function and color bimodality of the local galaxy population (e.g. Cattaneo et al. 2006). Many of these effects are already seen in hydrodynamic simulations (Blanton et al. 1999, 2000).

The purpose of this paper is to illustrate the consequences that result from environmental effects that are usually omitted in SAMs. These effects are real and are automatically included in hydrodynamical simulations of sufficient resolution (see, e.g.,...
Naab et al. 2007), but we do not intend to claim that the implementation attempted in this paper is definitive, or even necessarily a substantial improvement over current modeling methods. Rather, we intend to show the sign of the effects and the rough order of magnitude of the effects produced. In many cases, these physical effects produce consequences that seem at variance (or even in opposition in some cases) to overly naive interpretations of the hierarchical scenario that is consequent to gravitational interactions alone. Also, we wish to make clear at the outset that the physical effects described in this paper are independent of “feedback,” a concept we define to be related to the return of energy, momentum, and mass from evolving stars and central black holes to the environment. These feedback effects are also real, but they should not be confused with the gas physics effects that would necessarily occur even if there were neither stars nor AGNs. If the effects that we are adding to the SAM prescription are found to be useful, the correct way to implement them will be to use comparisons with detailed high-resolution numerical hydrodynamical simulations, which are just now becoming available; of course, feedback effects from central black holes (Ciotti & Ostriker 2001, 2007; Springel et al. 2005; Croton et al. 2006; Bower et al. 2006; Kang et al. 2006) must also be added to a comprehensive treatment for the most accurate results.

Here, we briefly summarize the additional gas physics that we have included in our basic model (introduced in § 2), which made the most important differences in the model predictions; later, we show the details of the implementation (§ 3) and first results (§§ 4–8). For individual satellite galaxies, we relaxed the generally assumed assumption of instantaneous shock heating of hot gas when those galaxies fall into dense environments (§ 3.1) and added a prescription for ram pressure stripping of gas (§ 3.2) while they orbit in a dense environment. We modify cooling flows for central galaxies, generally the most massive galaxies within a dark matter halo, by taking into account the heating of the ICM by gravitational heating from potential energy released by stripped gas from satellites (§ 3.3). This additional energy source, which is not usually included in SAM treatments (but automatically allowed for in hydrodynamical treatments) adds energy to the gas in amounts comparable to the energy added by feedback processes.

2. THE SEMIANALYTIC MODEL

The main strategy behind our modeling approach is first to calculate the collapse and merging history of individual dark matter halos, which is governed purely by gravitational interactions, and second to estimate the more complex physics of the baryons inside these dark matter halos, including, e.g., radiative cooling of the gas, star formation, and feedback from supernovae by simplified prescriptions on top of the dark matter evolution (e.g., Silk 1977; White & Rees 1978; White & Frenk 1991, hereafter WF91; Kauffmann et al. 1999; Somerville & Primack 1999; Cole et al. 2000; Hatton et al. 2003; Cattaneo et al. 2006; Croton et al. 2006; Bower et al. 2006; De Lucia & Blaizot 2007). Each of the dark matter halos will consist of three main components that are distributed among individual galaxies inside them: a stellar, a cold, and a hot gas component, where the last of these is only attributed to central galaxies, which are the most massive galaxies inside individual halos and are typically observed to reside in extended X-ray-emitting coronal gas. In the following sections, we will briefly describe the recipes used to calculate these different components, which are mainly based on recipes presented in, e.g., Kauffmann et al. (1999, hereafter K99), Cole et al. (2000, hereafter C00), and Springel et al. (2001, hereafter S01); for more details on the basic model implementations, we refer readers to their work and to the references therein. In the remainder of this paper, we refer to the model implementation presented in Khochfar & Burkert (2003, 2005) as the standard/old SAM, which is summarized in this section. The new additional environmental physics is presented in § 3. Throughout this paper, we use the following set of cosmological parameters, motivated by the three-year results of WMAP (Spergel et al. 2007): $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$, $\Omega_b/\Omega_{Q} = 0.17$, $\sigma_8 = 0.77$, and $h = 0.71$.

2.1. Dark Matter Evolution

We calculate the merging history of dark matter halos according to the prescription presented in Somerville & Kolatt (1999). This approach has been shown to produce merging histories and progenitor distributions in reasonable agreement with results from N-body simulations of cold dark matter structure formation in a cosmological context (Somerville et al. 2000). The merging history of dark matter halos is reconstructed by breaking each halo up into progenitors above a limiting minimum progenitor mass $M_{\text{min}}$. This mass cut needs to be chosen carefully, as it ensures that the right galaxy population and merging histories are produced within the model. Progenitor halos with masses below $M_{\text{min}}$ are declared as accretion events, and their histories are not followed farther back in time. Progenitors labeled as accretion events should ideally not host any significant galaxies and be composed mainly of primordial hot gas at the progenitor halo’s virial temperature. The mass scale at which this is the case can, in principle, be estimated from the prescriptions of supernova feedback and reionization presented in § 2.2.1. However, to achieve a good compromise between accuracy and computational time, we instead estimated $M_{\text{min}}$ by running several simulations with different resolutions and choosing the resolution for which results in the galaxy mass range of interest were independent of the specific choice of $M_{\text{min}}$. Changing the mass resolution mainly affects our results at low-galaxy-mass scales, leaving massive galaxies nearly unaffected. Throughout this paper, we will use $M_{\text{min}} = 10^{10} M_\odot$, which produces numerically stable results for galaxies with stellar masses greater than a few $\times 10^{10} M_\odot$.

2.2. Baryonic Physics

As mentioned above, once the merging history of the dark matter component has been calculated, it is possible to follow the evolution of the baryonic content in these halos forward in time. We assume that each halo consists of three components: hot gas, cold gas, and stars, where the last two components can be distributed among individual galaxies inside a single dark matter halo. The stellar components of each galaxy are additionally divided into bulge and disk to allow morphological classifications of model galaxies. In the following, we describe how the evolution of each component is calculated.

2.2.1. Gas Cooling and Reionization

Each branch of the merger tree starts at a progenitor mass of $M_{\text{min}}$ and ends at a redshift of $z = 0$. Initially, each halo is occupied by hot primordial gas that was captured in the potential well of the halo and shock heated to its virial temperature $T_{\text{vir}} = 35.9 (V_c/\text{km s}^{-1})^2 K$, where $V_c$ is the circular velocity of the halo (WF91; K99). Subsequently, this hot gas component is allowed to radiatively cool and settle down into a rotationally supported gas disk at the center of the halo, which we identify as the central galaxy (e.g. Silk 1977; White & Rees 1978; WF91). The rate at which hot gas cools down is estimated by calculating the cooling radius inside the halo using the cooling functions provided by Sutherland & Dopita (1993) and the prescription in S01. In the case of a merger between halos, we assume that all
of the hot gas present in the progenitors is shock heated to the virial temperature of the remnant halo (we will relax this assumption in our new model that includes environmental effects; see § 3.1), and that gas can only cool down onto the new central galaxy, which is the central galaxy of the most massive progenitor halo. The central galaxy of the less massive halo will become a satellite galaxy orbiting inside the remnant halo. In this way, a halo can host multiple satellite galaxies, depending on the merging history of the halo, but will always host only one central galaxy onto which gas can cool. The cold gas content in satellite galaxies is determined by the amount present when they first become satellite galaxies, and does not increase (this will again be modified in our new environmental prescription; see § 3.1); instead, it decreases due to ongoing star formation and supernova feedback.

In the simplified picture adopted above, the amount of gas available to cool down is limited only by the universal baryon fraction Ωbh2 = 0.023 (Spergel et al. 2007). However, in the presence of a photoionizing background, the fraction of baryons captured in halos is reduced (e.g., Gnedin 2000; Benson et al. 2002), and we use the method of Somerville (2002), which is based on a fitting formula derived from hydrodynamical simulations by Gnedin (2000) to estimate the amount of baryons in each halo. For the epoch of reionization, we assume that \( z_{\text{reion}} = 7 \), which is in agreement with observations of the temperature-polarization correlation of the cosmic microwave background by Spergel et al. (2007).

2.2.2. Star Formation in Disks and Supernova Feedback

Once cooled gas has settled down in a disk, we allow for fragmentation and subsequent star formation according to a parameterized global Schmidt-Kennicutt-type law (Kennicutt 1998) of the form \( M_\text{*,cold} = \alpha M_\text{cold}/t_{\text{dyn},\text{gal}} \), where \( \alpha \) is a free parameter describing the efficiency of the conversion of cold gas into stars, and \( t_{\text{dyn},\text{gal}} \) is assumed to be the dynamical time of the galaxy, approximated to be 40 times shorter than the dynamical time of the dark matter halo (Naab & Ostriker 2006).

Feedback from supernovae plays an important role in regulating star formation in small-mass halos and in preventing too-massive satellite galaxies from forming (Dekel & Silk 1986). We implement feedback based on the prescription presented in K99 with

\[
\Delta M_{\text{reheat}} = \frac{4}{3} \epsilon \frac{\eta_{\text{SN}}E_{\text{SN}}}{V_c^2} \Delta M_\text{vir}.
\]

Here, we introduce a second free parameter, \( \epsilon \), which represents our lack of knowledge about the efficiency with which the energy from supernovae reheats the cold gas. The expected number of supernovae per solar mass of stars formed for a typical IMF is \( \eta_{\text{SN}} = 5 \times 10^{-2} \), and \( E_{\text{SN}} = 10^{51} \) ergs is the energy output from each supernova. We take \( V_c \) as the circular velocity of the halo in which the galaxy was last present as a central galaxy.

2.2.3. Galaxy Mergers

We allow for mergers between galaxies residing in a single halo. As mentioned earlier, each halo is occupied by one central galaxy and a number of satellite galaxies, depending on the past merging history of the halo. Whenever two halos merge, the galaxies inside them will merge on a timescale that we calculate by estimating the time it would take the satellite to reach the center of the halo under the effects of dynamical friction. Satellites are assumed to merge only with central galaxies, and we set up their orbits in the halo according to the prescription of K99, modified to use the Coulomb logarithm approximation of S01.

If the mass ratio between the two merging galaxies is \( M_{\text{gal,1}}/M_{\text{gal,2}} \leq 3.5 \) (\( M_{\text{gal,1}} \geq M_{\text{gal,2}} \)), we declare the event as a major merger, and the remnant will be an elliptical galaxy. We assume that the stellar components of the progenitors add up to form a spheroid, that the cold gas present in the progenitors ignites in a central starburst, and that the hot gas components add up. In the case of a minor merger (\( M_{\text{gal,1}}/M_{\text{gal,2}} > 3.5 \)) we assume that the stellar component of the smaller progenitor adds to the bulge of the larger progenitor and that the cold gas in the disk of the smaller progenitor settles down into the disk of the larger progenitor.

3. ENVIRONMENTAL EFFECTS

The basic model introduced in the previous section already includes several environmental dependencies. For example, the merger rate of galaxies increases more steeply with redshift in high-density environments such as clusters (Kochfar & Burkert 2001), a feature also seen in observations (van Dokkum et al. 1999). In this section, we intend to incorporate further physical effects that are important to model the evolution of the galaxy population and that are already self-consistently included in hydrodynamical simulations (e.g., Frenk et al. 1999). Of these effects, some were already implemented in similar ways in previous models by other authors, e.g., ram pressure stripping and shock heating (e.g., Lanzoni et al. 2005). Some of the effects of gravitational heating have been discussed recently by Wang & Abel (2008) but have not yet been implemented within the context of a SAM.

The main difference between our SAM implementation and that of the previous section is that we explicitly follow the heating of the hot gas phase by the conversion of gravitational potential energy. To avoid adding liberate energy twice to the hot gas phase, we adopt the following prescription. Initially, when the dark matter halo becomes more massive than \( M_{\text{min},\text{gas}} \), we set the temperature of the hot gas to \( T_{\text{vir}} \). During the subsequent growth of the dark matter halo, however, we do not automatically increase the temperature of the hot gas in the host to the new virial temperature of the host dark matter halo (by host dark matter halo we always refer to the dark matter halo mass including all substructure). Instead, we only let it increase by the energy gained from the potential energy of the gas that is stripped from the substructure (see §§ 3.3 and 3.4). At each step in our simulation, we keep track of the specific energy of the hot gas component, and thus are able to calculate its temperature \( T_{\text{gas}} \). This allows us to define the parameter \( f_c = 1 + (T_{\text{vir}} - T_{\text{gas}})/T_{\text{vir}} \) to calculate the energy needed to remove gas from a halo. We assume here that the cold gas phase has \( T_{\text{gas}} = 0 \), which sets \( f_c = 2 \) for cold gas and \( f_c = 1 \) for gas at the virial temperature of the halo. In general, the liberated potential energy is sufficient to raise the temperature of the hot gas to the new virial temperature on a short timescale. Another main difference from the old SAM is that we allow satellites to have hot gas that is able to cool according to the prescription in § 2.2.1 and to subsequently form stars in the disk of the satellite galaxy. We remove hot gas from the satellites using the prescriptions laid out in §§ 3.1 and 3.2.

The following sections are structured as follows. First, we introduce our prescriptions for the stripping of gas from orbiting satellites by ram pressure and shock heating. This is necessary to help us approximate the rate at which potential energy is released at each individual time step within our simulation. In the following two sections, we introduce the actual prescriptions for gravitational heating and its implementation within our SAM.
3.1. Shock Heating of Gas

During the infall of satellite galaxies into dense environments, shock heating of satellite gas occurs, with the gas being removed from the satellite on timescales much shorter than the Hubble time (e.g., Metzler & Evrard 1994; Frenk et al. 1999). Generally, this process is implemented within SAMs by assuming that it is very efficient and quasi-instantaneous, thus depriving satellite galaxies of any reservoir of hot virialized gas (e.g., WF91; K99; C00). In the following, we will relax this assumption and investigate its effects on the galaxy population.

Gas removal from the satellite occurs efficiently when the shock deposits enough energy to heat the gas in the satellite above its virial temperature (e.g., Metzler & Evrard 1994; Bimboim & Dekel 2003). This condition can be expressed in terms of the adiabatic sound speed in the host halo, $c_{\text{gas}}^2 = \gamma V_{\text{max}}^2/\beta$, where $\gamma = 5/3$ and $\beta \sim 1.25$ (Bryan & Norman 1998), and the satellite’s maximum circular velocity $V_{\text{max, sat}}$ is

$$c_{\text{gas}}^2 \geq \zeta V_{\text{max, sat}}^2. \quad (2)$$

Here, we introduce a free model parameter $\zeta$, which in effect regulates the mass ratio between the infalling satellite and the host halo at which shock heating will occur. As we will show below, the specific choice of $\zeta$ does not change the properties of the overall galaxy population significantly and only has influence on satellite galaxies. The gas fraction of galaxies within clusters is an increasing function of radius (Dressler 1986), which supports the assumption that whatever reduces the gas fraction must work on a timescale comparable to the dynamical time within the cluster. Once the condition in equation (2) is satisfied, we therefore allow for gas removal from the satellite on some fraction 1/6 of the host halo’s dynamical time. In general, we find that the gas in our simulations will be completely shock heated on timescales less than 1 Gyr, with a tendency for faster heating in low-mass satellites, as shown by the conditional probability distribution $p(t_{\text{dyn}}\mid M_{\text{hot}})$ of infalling satellite galaxies in Figure 1.

Shocks will not only heat the hot gas phase, but also penetrate deep within the satellite and heat the cold gas phase (T. Naab 2007, private communication). We include this effect, sometimes neglected within SAMs, in the same manner as that described above. In consequence, at each time step within the simulation we have the following mass loss from each satellite due to shock heating, which will be added to the hot gas content of the host central galaxy:

$$\frac{dM_{\text{hot, sat}}}{dt} = -\delta M_{\text{hot, sat}}/t_{\text{dyn, halo}}. \quad (3)$$

$$\frac{dM_{\text{cold, sat}}}{dt} = -\delta M_{\text{cold, sat}}/t_{\text{dyn, halo}}. \quad (4)$$

A first comparison between our initial model (labeled “old SAM”; see Fig. 2), which includes instantaneous shock heating of only hot gas, does not show any significant difference in the cold and hot gas mass functions of central galaxies. On the contrary, Figure 3 shows that satellites tend to retain more cold and hot gas when the condition for shock heating, as laid out by equation (2), requires them to fall into a much more massive host (larger $\zeta$) and when the timescale for shock heating is longer (smaller $\delta$). In all cases, the amount of gas that has been shock heated is negligible compared to the hot gas content of the host central galaxy, which explains the lack of change in the gas mass function. The overall galaxy population at the intermediate-to-

massive end is dominated by central galaxies, which are unaffected by the specific choices of the shock heating parameters, and we choose to omit these parameters for the remainder of this paper; i.e., we set them to $\zeta = 1$ and $\delta = 1$.

3.2. Ram Pressure Stripping

Individual late-type galaxies within clusters show perturbed H I disks that are reduced in size with respect to their stellar disks (for a review, see van Gorkom 2004) and are H I deficient with respect to field late-type galaxies, a fact generally attributed to ram pressure stripping caused by the interactions between the hot ICM and the ISM of the satellite (Gunn & Gott 1972; Giovanelli & Haynes 1983; Quilis et al. 2000). The timescale for this process must be less than 1 Gyr, as indicated by the abrupt truncation of star formation in passive cluster spirals (Moran et al. 2006). However, it is very likely that ram pressure stripping alone is not sufficient to cause the observed H I deficit in satellite galaxies (Abadi et al. 1999) and that other processes such as shock heating play an important role. Furthermore, SAMs that include ram pressure stripping alone only report negligible changes in galaxy properties such as colors and star formation rates (Okamoto & Nagashima 2003; Lanzoni et al. 2005).

Following Gunn & Gott (1972), we assume that gas is stripped from the satellite once the dynamical pressure is able to overcome the gravitational force binding the gas to the satellite. In terms of energy deposited within the satellite gas, this can be approximated by

$$E_{\text{ram}} = \mu \rho_{\text{hot}} v_{\perp}^3 \pi R_{\text{h}}^2. \quad (5)$$

Here, we take $v_{\perp}$ as the velocity of the satellite perpendicular to its disk orientation and assume that the orbital velocity of the satellite is comparable to the sound speed $c_{\text{gas}}$ of the hot gas. The efficiency of this process for a face-on disk should be maximal, and the efficiency for an edge-on disk should be minimal; we take this into account by assuming that the disk orientation is random with respect to the infall direction. This is in good agreement
with cosmological dark matter simulations that show that the spin vectors of merging dark matter halos are randomly aligned to each other (Khochfar & Burkert 2006). We assign a random angle $\alpha_\perp$ between the disk plane and the velocity vector of the satellite and calculate $v_\perp$ by $c_{\text{gas}} \sin \alpha_\perp$ (Lanzoni et al. 2005). For simplicity, we calculate the density $\rho_{\text{hot}}$ by taking the average density of hot gas within the host halo's virial radius, and take $r_h$ to be the characteristic half-mass radius of the gas within the satellite. We introduce a free parameter $\mu$, which allows us to investigate the importance of this process. As we will show below, the efficiency parameter $\mu$ does not significantly influence general galaxy properties. Equation (5) is an upper limit to the expected ram pressure heating of the gas in the satellite, as we neglect tidal stripping and the change in the velocity of the satellite while it orbits through the host halo (see, e.g., Taylor & Babul 2001).

The amount of cold disk gas stripped from the satellite can be calculated by

$$\frac{dM_{\text{ram,c}}}{dt} = -\frac{4}{3} \frac{E_{\text{ram,c}}}{a_{\text{max,sat}}}.$$

Here, we use in equation (5) the observed mean size-mass relation reported for disk galaxies from the SDDS (Shen et al. 2003). We note that this might be an overestimate, as disk galaxies tend to be smaller by a factor of up to 1.5 at $z = 2.5$ (Trujillo et al. 2006).

Not only cold gas in disks is subject to ram pressure stripping, but also diffuse hot halo gas (e.g., Machacek et al. 2006), and we model this process in the same way as we do for the cold gas case, with the exception that $r_h = r_{\text{vir,sat}}/2$ in equation (5), and that the energy needed to heat a unit mass to the virial temperature of the host halo is less, since the hot gas in the satellite is already at some temperature $T_{\text{gas}}$. The hot gas mass stripped from the satellite is

$$\frac{dM_{\text{ram,h}}}{dt} = -\frac{4}{3} \frac{E_{\text{ram,h}}}{a_{\text{max,sat}}}.$$

The rate at which material is stripped in our implementation of ram pressure differs from earlier approaches. For example, Okamoto & Nagashima (2003) assume instantaneous stripping of all gas once the ram pressure overcomes a characteristic restoring force per unit area in the galactic disk, calculated using the surface mass density at the half-mass radius. Other implementations have a more gradual stripping rate, assuming an exponential profile for the surface mass density of material in the satellite disk (Lanzoni et al. 2005). Common to both of these implementations is that they assume a radial profile for the gas density in the host halo.

![Figure 2](image-url)
and that the time dependence of the stripping is driven basically by the physical location of the satellite within the halo. In our implementation, the time dependency is due to the continued transfer of energy to the gaseous disk of the satellite. For a host halo that is not significantly changing its average gas density with time, we deposit a constant amount of energy per unit time within the gaseous disk of the satellite. The stripping rate we calculate in this way is initially larger than that from gradual models like the one of Lanzoni et al. (2005). Such models, however, predict an increase in the stripping rate with time, due to the increasing ambient gas density encountered while the satellite orbits toward the center of the host halo. The effect of these different implementations on the galaxy populations is very mild. In our model, the cold and hot gas mass functions of central galaxies are mostly unaffected by ram pressure stripping from satellite galaxies in comparison to our initial SAM, shown in Figure 4 (top) and in agreement with previous work (Okamoto & Nagashima 2003; Lanzoni et al. 2005). The reason we do not find significant changes in the overall galaxy population is that central galaxies dominate the mass range studied here and that the gas fraction of satellites is much less than that of centrals. Increasing the efficiency \( \mu \) by 2 orders of magnitude only marginally reduces the amount of hot and cold gas in satellites. Therefore, we again omit this free parameter; i.e., we set it to \( \mu = 1 \).

3.3. Gravitational Heating

The energy used to expel gas from satellites is contributed by the gravitational potential energy that is gained when a satellite becomes bound in the potential of the primary halo. The majority of dark halos are initially on parabolic orbits with \( E_{\text{tot}} = 0 \) (Khochfar & Burkert 2006) before they become bound and merge. According to the virial theorem, at most half of the potential energy gained could be used to heat the ICM. Here, we take into account the energy gained by each infalling mass unit of gas and subtract from it the energy necessary to expel it from the potential of the satellite and to heat it to the virial temperature of the host.

The rate at which energy is gained is connected to the rate at which gas is expelled from satellites \( \dot{m}_{\text{gas}} \) according to the prescriptions in §3.1 and 3.2. At each time step within our simulation, we calculate

\[
\dot{E}_{\text{grav}} = \sum_{i=1}^{n_{\text{sat}}} \dot{m}_{\text{gas},i} \left( \Delta \phi - b \frac{3}{4} \frac{v_{\text{max},i}^2}{v_{\text{max},\text{cen}}} - \frac{3}{4} \frac{v_{\text{max},\text{cen}}^2}{v_{\text{max},\text{cen}}} \right),
\]

where \( b = 2 \) for cold gas and \( b = f_c \) for hot gas that is stripped from the satellites. Please note that equation (8) is the actual surplus of energy available to heat the ICM once the stripped gas
of the satellite is heated to the virial temperature of the host. We model the dark matter halo of the host as a truncated isothermal sphere with core radius \( r_0 \) and calculate the amount of potential energy gained by the satellite when it reaches the virial radius \( r_{\text{vir,cen}} \) of the host halo. For the halo, we assume a characteristic value \( r_{\text{vir,cen}} / r_0 = 25 \) (Shapiro et al. 1999; Mayer et al. 2002). It should be noted that in general, the concentration of dark matter halos is a function of mass and redshift (e.g., Bullock et al. 2001; Dolag et al. 2004) and that we omit this dependency for the sake of simplicity at this stage. The gain in potential energy is then calculated as

\[
\Delta \phi = -\ln \left( r_{\text{vir,cen}} / r_0 \right).
\]

Within the simulation, we will use the energy surplus calculated from equation (8) to heat and to counter cooling within the hot gas of the host halo. Equation (8) is generally not included in SAMs, although it appears to be necessary in order to conserve energy.

The time integral of equation (8) can be quite substantial and, if expressed in terms of \( E_{\text{grav, tot}} = \epsilon_{\text{grav}} m_p c^2 \), we find values in Figure 5 for \( \epsilon_{\text{grav}} \) ranging from a few \( \times 10^{-8} \) to a few \( \times 10^{-4} \) in galaxies of \( \sim 10^{10} \) and \( \sim 5 \times 10^{12} \) \( M_\odot \), respectively. That this increase is driven by the environment becomes most evident when considering the dependence of \( \epsilon_{\text{grav}} \) on the dark matter halo mass in Figure 6. Above a halo mass of \( 10^{11} M_\odot \), \( \epsilon_{\text{grav}} \) increases steadily. However, it appears that this increase is steeper at larger redshifts. We find that the upper limit for \( \epsilon_{\text{grav}} \) lies around \( \sim 5 \times 10^{-4} \), and that in general the most massive halos present at a given redshift tend to take on this value. One can understand this behavior by considering the accretion of satellites onto halos. In general, the most massive halos at any redshift had the largest accretion rates in the past, which explains the large amount of gravitational heating.

It is worth comparing gravitational heating to other common heating mechanisms such as supernovae and AGNs. Comparing \( \epsilon_{\text{grav}} \) to \( \epsilon_{\text{SN}} \sim 2.8 \times 10^{-6} \) and \( \epsilon_{\text{BH}} \) with values between \( \sim 6.5 \times 10^{-6} \) (Springel et al. 2005) and \( \sim 6.5 \times 10^{-7} \) (Ciotti & Ostriker 2007) shows that in general, gravitational heating is more efficient than supernova feedback only in galaxies larger than a few \( \times 10^{11} M_\odot \) and in halos more massive than \( 5 \times 10^{12} M_\odot \) at \( z = 0 \). This regime corresponds to massive field galaxies and extends into grouplike environments. For even more massive galaxies and dark halo masses larger than \( 10^{13} M_\odot \), gravitational heating starts dominating over proposed AGN feedback rates. This is very interesting, as one is dealing with mostly rich group and cluster environments that are subject to a very substantial gravitational heating generally neglected within SAMs. Furthermore, the most massive galaxies will have another large source of heating in addition to AGN feedback that will prevent ongoing star formation and will naturally reduce the overproduction of galaxies at the bright end of the luminosity function (Benson et al. 2003). Again, it is important to understand at which mass scales gravitational feedback operates at different times. At large redshifts, it will become more important than supernova and AGN

![Fig. 4.—Same as Fig. 3, but in this simulation we only included ram pressure stripping of satellite gas with different stripping efficiencies \( \mu \).](image-url)
feedback in smaller halos and galaxies. As a consequence, gravitational feedback can match AGN feedback at the epoch of peak QSO activity in the most massive halos and galaxies.

When considering the mass dependence of $\varepsilon_{\text{grav}}$, we find that over a wide range of masses it is roughly $\propto M_{\text{DM}}^{1.1}$. It is worth noting that from simple scaling arguments, one would expect that $\varepsilon_{\text{grav}} \propto M_{\text{DM}}^{2.3} m_{\text{gas}}/m_*$, where $m_{\text{gas}}$ is the total amount of gas expelled from satellite galaxies, which would indicate that the fraction of expelled gas to the stellar mass of central galaxies scales as $\propto M_{\text{DM}}^{0.43}$. Going to smaller masses, there is a distinctive break at a stellar mass of a few $\times 10^{10} M_\odot$, which coincides with the break in properties of the galaxy population found in the SDSS (Kauffmann et al. 2003). Our results suggest that this break could be the consequence of the accretion rate, and hence the amount of gravitational energy that is released.

### 3.4. Implementation

At the beginning of our merger tree, i.e., when the dark matter halo first crosses $M_{\text{min}}$, we set the temperature of the hot gas to the virial temperature $T_{\text{vir}}$ of the halo and allow it to cool as described in § 2.2.1. Once satellites fall onto the main halo, we calculate the amount of gas stripped from each individual orbiting satellite, $\dot{m}_{\text{gas}}$, using equations (2), (3), (5), and (7), plus the contribution from gas that leaves the satellite halo because of supernova feedback. This $\dot{m}_{\text{gas}}$ is then used in equation (8) to calculate the amount of gravitational heating energy added to the ICM. Please note that in practice, we use equation (8) without the last term, $\frac{1}{2} v_{\text{max},\text{cen}}^2$, because the hot gas of the host might not be at $T_{\text{vir}}$ but at some lower temperature $T_{\text{gas}}$, and therefore the stripped gas will not automatically be heated to $T_{\text{vir}}$, as assumed in equation (8). The energy contribution calculated in this way is then used to heat the host hot gas to $T_{\text{vir}}$. If the gas is already at $T_{\text{vir}}$, or if energy is left after elevating it to $T_{\text{vir}}$, we allow the surplus energy to be used to counter the energy losses due to our cooling prescription in § 2.2.1 and to reduce the amount of cooling gas. If there is still energy left after countering all the energy losses due to cooling, we use it to increase the energy of the host hot gas. We do not take into account the possibility of gas leaving the

![Fig. 5.—Gravitational heating efficiency $\varepsilon_{\text{grav}}$ as a function of stellar mass for different redshifts. The cross-hatched region shows the region where AGN and supernova feedback operate. Estimates for supernova feedback limit it mainly to below the dashed line, while estimates for AGN feedback cover the whole region. The solid line shows a fit of the form $\propto M_*^{1.2}$.](image-url)
host halo and getting lost once its energy becomes too large to be bound, but instead assume that it is marginally bound in a hot atmosphere. If two host halos merge, we assume that the smaller one becomes a satellite, calculate \( f_e \) according to its specific energy, and use it in equations (2), (3), (5), and (7). The satellites within this halo will now be considered satellites of the new host halo and contribute their potential energy to the new host.

4. GENERAL RESULTS

To illustrate the contribution from gravitational heating, we display the contours of the conditional probability for the ratio of heating to cooling that individual galaxies experience in a given environment. The top panel in Figure 7 shows the probability contours for central galaxies at \( z = 0.1 \) in our simulations. We translate the deposited energy per unit time into a heating rate, labeled \( heat \) in Figure 7, by calculating the amount of cold gas that can be heated to the virial temperature of the dark matter halo in which the galaxy resides. The cooling rate for central galaxies is calculated using the prescription outlined in § 2.2.1 and is labeled \( cool \) in Figure 7.

The left panel shows the contribution from gravitational heating to the hot gas of central galaxies as gas is stripped from satellites. The heating rate for the central galaxies is up to \( 10^2 \) times larger than the cooling rate, and in the most dense environments the heating rate becomes \( 10^4 \, M_\odot \, \text{yr}^{-1} \). The heating rate shows a clear environmental dependence that reflects the higher abundance of satellites that contribute to gravitational heating. From these results, one expects that star formation will be terminated in central galaxies of dense environments.

The importance of several physical processes that depend on environment and redshift is shown in Figure 8. The top left panel shows the average cooling rate in systems for which the cooling time is shorter than the dynamical time of the halo. This "cold accretion" mode occurs in halos with masses below \( \sim 10^{11} - 10^{12} \, M_\odot \) and is most efficient at high redshifts, in agreement with SPH simulations by Kereš et al. (2005) and earlier analytic models.
calculations (Binney 1977; Silk 1977; Rees & Ostriker 1977).
The solid line in the same figure is the maximum halo mass that shows cold accretion at each redshift. The average amount of cold gas in the ISM reheated by supernovae is shown in the top right panel. Supernovae are able to heat gas efficiently in small halos with masses below $\sim 10^{12} M_\odot$ and are responsible for shaping the low-mass tail of the luminosity function (Dekel & Silk 1986). The results in the two top panels are usually incorporated in all semianalytic models. The additional physics that we have included is shown in the lower panel of the same figure. It appears that the heating rate of the ICM by gravitational heating is always very efficient in the most massive halos found at each redshift, with several thousand solar masses per year, and not very efficient in low-mass halos. This is not too surprising, considering that low-mass halos have less infalling substructure than cluster-sized halos.

To illustrate how the new environmental effect operates, we followed the "$\epsilon$-trajectory" of a random central and satellite galaxy back in time. This trajectory is calculated as in Khochfar & Silk (2006a, 2006b) by summing up the $\epsilon$ from all the progenitors present at a given redshift. The results are shown in the left panel of Figure 9. The mass on the $x$-axes of the right panels is the sum of the stellar mass of all progenitors present at that redshift. We distinguish between field and cluster environment by associating the field with a dark matter halo of $10^{12} M_\odot$ and the cluster with a dark matter halo of $10^{15} M_\odot$ at $z = 0$.

For field galaxies at early times ($z > 5$), when the mass in progenitors is still small ($< 10^{10} M_\odot$), gravitational heating is not important. Heating/feedback will mostly be provided by supernovae and some (if any exist) AGNs in massive galaxies. At late times, gravitational heating begins catching up with supernovae. Central and satellite galaxies in the field are very unlikely to develop strong gravitational heating at any time during their evolution; as a consequence, it might be justified in a first approximation to neglect these effects when modeling their evolution. However, the situation is dramatically different for cluster galaxies. The central galaxies in these environments, which later become the first brightest cluster galaxies, generally have gravitational heating that surpasses supernova feedback at redshifts around $z = 5$. Present-day cluster member galaxies on the other hand, depending on their mass, will surpass supernova feedback at later times when their mass is large enough ($> 10^{11} M_\odot$) and stop increasing in $\epsilon$ once they become cluster members. It is interesting to note that for the first brightest cluster galaxies, gravitational heating steadily increases and continues to become very important at late times, and that the overall energy released will exceed that of the AGN, but only later, when the main AGN activity is already over.

5. COSMIC STAR FORMATION RATE

The observed average cosmic star formation rate (Lilly et al. 1996; Madau et al. 1996) shows a strong decline at redshifts less than $z \sim 2$ and a modest decline at $z > 3$ (e.g., Giavalisco et al. 2004), a trend generally recovered by semianalytic models with varying accuracy (e.g., Cole et al. 2000; Giavalisco et al. 2004). One of the problems occurring in these models is the steep decline of the star formation rate at low redshifts even as they reproduce star formation rates at high redshifts. Different approaches have shown some progress in this area by, e.g., including feedback from supermassive black holes (e.g., Bower et al. 2006; Croton et al. 2006b), which helps to reduce star formation in early-type galaxies at late times, or by shutting off star formation in halos above a critical mass (Cattaneo et al. 2006).

The environmental effects introduced in the previous sections start operating effectively in high-density environments such as clusters of galaxies and are able to prevent cooling of gas and associated star formation. In that sense, the average cosmic star formation rate (Lilly et al. 1996; Madau et al. 1996) provides an ideal way to compare our model predictions and to judge the importance of the effects we have added. Our model prediction, shown as the solid line in Figure 10, is in quite good agreement with the observations summarized by Hopkins (2004). However, our new model differs from the best-fit initial SAM (dashed line) in one very important point: we find higher star formation rates at $z > 3$ and significantly lower ones at $z < 2$. Furthermore, we have to reduce the energy deposited in the ISM by supernovae, as we have additional environmental heating sources that counter the cooling rate and regulate star formation. The reason for the change in shape of the cosmic star formation is that the environmental effects do not operate like supernova feedback, which is essentially proportional to the star formation rate, but rather are dependent on the mass of the halo and its assembly time. We find that many galaxies that dominate the star formation rate at redshifts $z > 4$ and that end up in dense environments at $z = 0$ will not yet have assembled in groups, and hence gravitational heating will not be significant. Once the assembly starts taking place during the peak of the merger epoch around $z \sim 2$ (Khochfar & Burkert 2001), the environmental effects start to operate and to provide more feedback than the supernovae; as a consequence, the star formation rate declines more steeply than in a model with only supernova feedback.

In Figure 11, we split the contribution to the cosmic star formation rate into different environments according to the host
dark matter halo mass. The top panel nicely illustrates the steep decline of the star formation rate in cluster environments compared to field environments, a signature of downsizing by environment and in agreement with recent observations by Finn et al. (2008). In the lower panel, we show how the new environmental prescriptions relate to the old SAM prescription with the same $\sigma$. As we mentioned above, at low redshifts the star formation is heavily suppressed by up to a factor of 6 in cluster environments due to our implementation of gravitational heating, while in field environments not much changes. Most of the star formation at late times occurs in low-mass systems in moderate-density environments.

6. DOWNSIZING

Growing observational evidence suggests that the main sites of star formation activity have changed from massive systems at early times to low-mass systems at late times (e.g., Juneau et al. 2005; Thomas et al. 2005; Zheng et al. 2007). A possible explanation for “downsizing” from the point of hierarchical modeling is that heating overcomes cooling at late times in massive systems (Naab et al. 2007). One approach to try to address this problem is, e.g., the use of AGN feedback (Scannapieco et al. 2005; Croton et al. 2006; Bower et al. 2006). Here, we investigate how environmental effects influence downsizing. As shown in Figures 6 and 8, environmental heating is very important for the most massive galaxies and halos. In addition, the mass scale affected by environmental heating decreases with larger redshifts, which shows downsizing. It is important to note that we do not claim that these effects are solely responsible for causing downsizing, but that we do investigate their contribution to downsizing. In Figures 12 and 13, we show the specific star formation rate $\frac{\dot{M}_*}{M_\odot}$ in units of Gyr$^{-1}$ as a function of the look-back time for galaxies with different present-day masses. In addition, we split the sample into galaxies residing in massive group/cluster
and field/small group ($M_{DM} < 10^{13} M_{\odot}$) environments. The results for the best-fit old SAM without environmental effects show a long extended tail to low redshifts even for the most massive galaxies, and no strong difference between massive $\log M_*>11.4$ and low-mass galaxies with $\log M_* < 11.4$ (Fig. 12). In addition, there is no strong environmental dependence in the specific star formation rate. The new SAM, including environmental effects, differs in several fundamental ways that are important with respect to downsizing. First, massive galaxies with $\log M_*>11.4$ have a strongly peaked star formation epoch at look-back times around 11 Gyr, with a strong decline to smaller look-back times; low-mass galaxies with $\log M_* < 11.4$ have only a modest decline, which shows the same trend as that expected from downsizing. Second, we find a strong environmental dependency that manifests itself through galaxies more massive than $\log M_* \sim 11.4$, which are extremely rare in the field, and low-mass galaxies that show more star formation at late times in low-density environments. It is interesting to note that we do not find that galaxies of the same mass are significantly older in high-density environments.

7. LUMINOSITY FUNCTION

One attractive point of AGN feedback is that it helps with the overcooling problem in SAMs and at the same time helps in fitting the luminosity function at the bright end by limiting the mass of the most massive galaxies in the simulations. Here, we compare the prediction of our low-redshift luminosity function with the SDSS $r$-band luminosity function of Blanton et al. (2003). As shown in Figure 14, the agreement between the model and the observations is very good over a wide range of luminosities. We slightly overpredict the abundance of very luminous galaxies compared to the SDSS luminosity function, which might not be a problem, as neither first brightest cluster galaxies nor starburst galaxies (ULIRGs), which have most of their energy output in the far-infrared part of the spectrum, are properly covered by SDSS photometry. However, in a direct comparison to our old SAM,
we significantly reduce the number density of very luminous galaxies. Another reason for finding a few too many luminous galaxies is that we follow the merging of galaxies using a simplified model based on dynamical friction, which is likely to overpredict the number of mergers for massive galaxies. It has been shown by Springel et al. (2001) that in these cases, the luminosity function in clusters shows too many luminous galaxies compared to high-resolution simulations that follow the orbits of galaxies in clusters.

Fig. 10.—Modeled vs. observed star formation history. We show the best-fit initial SAM (dashed line) and the best-fit new model including all environmental effects (solid line). The observed data are the compilation from Hopkins (2004).

Fig. 12.—Specific star formation rate in units of Gyr$^{-1}$ for galaxies of different present-day masses in the old SAM. The upper panel shows only galaxies in cluster environments with $M_{DM} > 10^{14} M_\odot$, and the lower panel only galaxies in field and small group environments with $M_{DM} < 10^{14} M_\odot$. The lines are fits to the simulation data.

8. COLOR BIMODALITY

The results by the SDSS (Baldry et al. 2006) or surveys like COMBO-17 (Bell et al. 2004) show that the galaxy population can be divided according to, e.g., its $u - r$ color into two separate regions with a so-called red sequence of mostly early-type old non-star-forming galaxies and a blue cloud of mainly late-type star-forming galaxies. Until recently, SAMs have had problems in recovering a strong pronounced bimodality, and only with the inclusion of feedback processes or other cooling shutoff mechanisms could a good agreement on the data be achieved (Cattaneo et al. 2006; Croton et al. 2006; Bower et al. 2006). Although these models are successful in reproducing the overall distribution of color in the galaxy population, they find different galaxies

Fig. 13.—Same as Fig. 12, but for a SAM including environmental effects. Note the degree to which low-density environments dominate at late times.
populating their red sequences and blue clouds. We predict the color distribution of our model galaxies based on the inclusion of environmental effects. The effect of dust on galaxy colors is estimated using the plane-parallel slab model of Kauffmann et al. (1999). For details of this model, we refer the reader to Kauffmann et al. (1999, and references therein). Figure 15 shows the color-mass diagram, and it is very clear to see that we produce a very pronounced bimodality. The low-mass part of our red sequence is dominated by satellite galaxies, which are part of a massive group or cluster environment. This is in agreement with the recent findings of Haines et al. (2006). The blue sequence at the low-mass end, on the other hand, is dominated by star-forming central galaxies in field environments. At mass $\log M_*/M_\odot > 10.2$, central galaxies start to leave the blue sequence and occupy the red sequence with $u-r > 2.5$. A detailed comparison to the data of Baldry et al. (2006) will be presented in a later paper in which we combine our SAM with a large-scale $N$-body simulation.

9. DISCUSSION AND CONCLUSIONS

In this paper, we have presented a first step in including in a SAM the physical effects that are connected to the environment in which galaxies reside. Our approach is novel in that we consider how much gravitational potential energy can be released by gas that is stripped from satellite galaxies once one takes into account the energy needed to strip it. It turns out that this source of gravitational heating is very dependent on the environment,
as the amount of potential energy gained for a unit mass coming from infinity increases with the mass of the dark matter halo, which is a good proxy for the density of the environment; we find a scaling with dark matter mass of $\propto M_{\text{DM}}^{1.1}$.

Gravitational heating, in general, is more important for galaxies that reside in environments that can secure a steady infall of gas-rich satellite galaxies, whose stripped gas contributes potential energy. This is naturally the case for present-day clusters and massive groups, and we indeed find in our simulations most of the gravitational heating occurring in these environments. At earlier times, the sites of gravitational heating turn to somewhat smaller dark matter halos and hence less dense environments. This is not surprising considering that the mass of $\sigma$ halos, which is the mass that we can associate with massive groups and clusters today, decreases at earlier times. The build up of dark matter on the scales we consider here is approximately self-similar, and one would expect roughly as much substructure falling into a $\sigma$ halo at early times as onto a $\sigma$ halo at late times. The main difference will be the higher gas fraction of the infalling satellites at earlier times. The higher gas fraction almost compensates for the lower potential energy per unit mass in the $\sigma$ halos at earlier times, causing them to have $\epsilon_{\text{grav}}$ similar to their counterparts at low redshifts. In this respect, our environmental effects are driven purely by the dark matter formation path.

One of the natural outcomes of including gravitational heating is downsizing (Zheng et al. 2007) in the star formation rate of massive galaxies. Central galaxies residing in the most dense environments generally have a very significant contribution by gravitational heating with $\epsilon_{\text{grav}} \sim 3 \times 10^{-4}$, which is greater than or comparable to the amount of feedback from AGNs (Springel et al. 2005; Ciotti & Ostriker 2007). However, the ways in which these two heating sources operate are very different. While luminous AGNs heat most efficiently during a QSO phase that takes place at redshifts $z > 3$ (Hasinger et al. 2005), gravitational heating will start heating more efficiently than AGNs at redshifts $z < 2$. This is connected to the epoch when most massive environments assemble by merging of groups. Besides being effective at late times, gravitational heating has the additional feature of showing a strong mass dependence that can produce the right trend of downsizing in the star formation rate of galaxies. Low-mass galaxies around $10^{11} M_{\odot}$ generally have $\epsilon_{\text{grav}} \leq \epsilon_{\text{SN}}$, and star formation is regulated mainly by supernova feedback, which by itself will not produce downsizing. Galaxies more massive than that have $\epsilon_{\text{grav}} > \epsilon_{\text{SN}}$, and star formation will be regulated by gravitational heating. In summary, the following picture emerges. At large redshifts, a first episode of strong heating occurs when AGNs have their peak activity. During that phase, a great deal of energy will be deposited within the ISM/ICM. After that, gravitational heating will start kicking in, mainly in the most massive systems, and will regulate the cooling rate of gas, and hence the star formation rate. We thus argue that downsizing at low redshifts is a consequence of the redshift and mass dependence of gravitational heating, which is driven by the environment.

In a study of galaxy properties within the SDSS, Kauffmann et al. (2003) found that galaxy properties show a bimodal distribution around $M_{\text{crit}} = 3 \times 10^{10} M_{\odot}$. Galaxies more massive than this generally have older stellar populations than less massive ones. It is intriguing to ask what the origin for this abrupt transition could be (see, e.g., Dekel & Birnboim 2006). The reason for the transition must be closely related to the ability to make stars. One natural suspect in this respect is feedback. The usual prime suspects for feedback, supernovae and AGNs, do not show a characteristic mass scale at which their actions occur. The energy output per unit stellar mass is independent of the mass of the galaxy for both AGN and supernova feedback, but increases as $M_{\text{crit}}^{1.2}$ for gravitational heating. However, it should be noted that the effects of a given amount of heating can be scale dependent, and hence can introduce a characteristic mass scale for supernova and AGN feedback as well. In addition, we find that gravitational heating shows a distinctive transition at a mass scale of $\sim 3 \times 10^{10} M_{\odot}$, from being roughly constant at smaller masses to increasing steadily at higher masses. Galaxies below $M_{\text{crit}}$ in our simulation are mostly unaffected by gravitational heating, and hence their star formation is regulated by supernova feedback. Above $M_{\text{crit}}$, the situation changes when gravitational heating starts to become more important and able to influence star formation by contributing significant amounts of feedback. Even when $\epsilon_{\text{grav}} < \epsilon_{\text{SN}}$, it will be important as a source of feedback and as a regulator for star formation, because unlike supernova feedback it operates independently of star formation and will contribute significant amounts of heating energy at late times. Again, just as in the case of downsizing, the feature that could cause the transition mass scale $M_{\text{crit}}$ is the specific mass dependency and epoch when gravitational heating kicks in.

It is interesting to make the connection between our work and previous work by Blanton et al. (1999), who suggest a scale-dependent bias for the galaxy population, in the sense that massive, red galaxies reside within high-density environments. Combining this with the results of Nagamine et al. (2006) suggests that one should expect a drop in the star formation rate for present-day massive red galaxies that reside in massive environments, just as we predicted with our model.

In this paper, we have included gravitational heating effects in our SAM based on simplified physical models and made some first predictions/comparisons. The results so far seem very promising, and we will present more detailed comparisons to observations in a follow-up paper. It is clear that this can only be viewed as a first step in trying to include environmental effects and that further comparisons to high-resolution hydrodynamical simulations will be necessary to improve on this effort.

We would like to thank the anonymous referee for comments and suggestions that helped to significantly improve the paper. We would also like to thank Rachel Somerville, Thorsten Naab, Andi Burkert, and Joe Silk for useful comments.

REFERENCES

Abadi, M. G., Moore, B., & Bower, R. G. 1999, MNRAS, 308, 947
Baldry, I. K., Balogh, M. L., Bower, R. G., Glazebrook, K., Nichol, R. C., Bamford, S. P., & Budavari, T. 2006, MNRAS, 373, 469
Bell, E. F., et al. 2004, ApJ, 608, 752
Benson, A. J., Bower, R. G., Frenk, C. S., Lacey, C. G., Baugh, C. M., & Cole, S. 2003, ApJ, 599, 38
Benson, A. J., Lacey, C. G., Baugh, C. M., Cole, S., & Frenk, C. S. 2002, MNRAS, 333, 156
Binney, J. 1977, ApJ, 215, 483
———. 2004, MNRAS, 347, 1093
Birnboim, Y., & Dekel, A. 2003, MNRAS, 345, 349
Blanton, M., Cen, R., Ostriker, J. P., & Strauss, M. A. 1999, ApJ, 522, 590
Blanton, M., Cen, R., Ostriker, J. P., Strauss, M. A., & Tegmark, M. 2000, ApJ, 531, 1
Blanton, M., et al. 2003, ApJ, 592, 819
Bower, R. G., Benson, A. J., Malbon, R., Helly, J. C., Frenk, C. S., Baugh, C. M., Cole, S., & Lacey, C. G. 2006, MNRAS, 370, 645
Bryan, G. L., & Norman, M. L. 1998, ApJ, 495, 80
Bullock, J. S., Kolatt, T. S., Sigad, Y., Somerville, R. S., Kravtsov, A. V., Klypin, A. A., Primack, J. R., & Dekel, A. 2001, MNRAS, 321, 559
