ON THE ORIGIN OF THE HUBBLE SEQUENCE: I. INSIGHTS ON GALAXY COLOR MIGRATION FROM COSMOLOGICAL SIMULATIONS

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ABSTRACT
An analysis of more than 3000 galaxies resolved at better than 114 h⁻¹ pc at z = 0.62 in a “LAOZI” cosmological adaptive mesh refinement hydrodynamic simulation is performed and insights are gained on star formation quenching and color migration. The vast majority of red galaxies are found to be within three virial radii of a larger galaxy at the onset of quenching, when the specific star formation rate experiences the sharpest decline to fall below ∼10⁻²−10⁻¹ Gyr⁻¹ (depending on the redshift). Thus, we shall call this mechanism “environment quenching,” which encompasses satellite quenching. Two physical processes are largely responsible: Ram pressure stripping first disconnects the galaxy from the cold gas supply on large scales, followed by a longer period of cold gas starvation taking place in a high velocity-dispersion environment, in which during the early part of the process, the existing dense cold gas in the central region (≤10 kpc) is consumed by in situ star formation. On average, quenching is found to be more efficient (i.e., a larger fraction of galaxies being quenched) but not faster (i.e., the duration being weakly dependent on the environment) in a denser environment. Throughout this quenching period and the ensuing one in the red sequence, galaxies follow nearly vertical tracks in the color–stellar mass diagram. In contrast, individual galaxies of all masses grow most of their stellar masses in the blue cloud, prior to the onset of quenching, and progressively more massive blue galaxies with already relatively older mean stellar ages continue to enter the red sequence. Consequently, correlations among observables of red galaxies—such as the age–mass relation—are largely inherited from their blue progenitors at the onset of quenching. While the color makeup of the entire galaxy population strongly depends on the environment, which is a direct result of environment quenching, physical properties of blue galaxies as a subpopulation show little dependence on the environment. A variety of predictions from the simulation are shown to be in accordance with extant observations.

Key words: galaxies: evolution – galaxies: formation – galaxies: interactions – intergalactic medium – methods: numerical

Online-only material: color figures

1. INTRODUCTION

The bimodal distribution of galaxy colors at low redshift is well established (e.g., Strateva et al. 2001; Blanton et al. 2003a; Kauffmann et al. 2003; Baldry et al. 2004). The “blue cloud,” sometimes referred to as the “star formation sequence” (Salim et al. 2007), is occupied by star-forming galaxies, while the “red sequence” galaxies appear to have little ongoing star formation (SF). It has been argued that this bimodality suggests that SF of the blue cloud galaxies en route to the red sequence must be turned off promptly to prevent them from lingering in the green valley between the blue and red peaks. A number of physical mechanisms have been proposed to cause this apparent “quenching” of SF. Galaxy mergers have been suggested to trigger strong and rapid SF that subsequently drives gas away and shuts down further SF activities in a sudden fashion. However, recent observations show that galaxies in the green valley do not show merger signatures, perhaps disfavoring the merger scenario (e.g., Mendez et al. 2011). Feedback from active galactic nuclei (AGNs) has also been suggested to provide quenching, but observational evidence for this scenario has been either inconclusive or at best circumstantial (e.g., Bundy et al. 2008; Santini et al. 2012; Bongiorno et al. 2012; Rosario et al. 2013). Some recent studies based on large data sets do not find evidence for AGN feedback playing a role in galaxy color migration (e.g., Zheng et al. 2007; Xue et al. 2010; Aird et al. 2012; Harrison et al. 2012; Swinbank et al. 2012; Mendel et al. 2013).

External environmental effects may have played an important role in shaping galaxy colors. High-density environments are observed to be occupied primarily by early type (elliptical and S0) red galaxies—the “density–morphology relation” (e.g., Oemler 1974; Dressler 1980; Postman & Geller 1984)—with giant elliptical galaxies anchoring the centers of rich clusters of galaxies (e.g., Kormendy et al. 2009). This relation is consistent with the larger trend of the galaxy population appearing bluer in more underdense regions in the local universe (e.g., Goto et al. 2003; Gómez et al. 2003; Tanaka et al. 2004; Rojas et al. 2004). Different types of galaxies are seen to cluster differently and have different Environmental dependencies, in the same sense as the density–morphology relation (e.g., Davis & Geller 1976; Hogg et al. 2003; Balogh et al. 2004; Kauffmann et al. 2004; Park et al. 2007; Coil et al. 2008; Zehavi et al. 2011).

Recent quantitative studies have yielded richer details on SF dependence on halo mass and environment, probing their relationships at higher redshifts. For example, using a large group catalog from the Sloan Digital Sky Survey (SDSS) Data Release 2, Weinmann et al. (2006) find that at fixed luminosity the fraction of early-type galaxies increases with increasing halo mass and this mass dependence is smooth and persists over the entire mass range probed without any break or feature at any mass scale. From a spectral analysis of galaxies at z = 0.4–0.8 based on the ESO Distant Cluster Survey, Poggianti et al. (2009) find that the incidence of K+A galaxies increases strongly with increasing velocity dispersion of the environment from groups to clusters. McGee et al. (2011), examining the SF
properties of group and field galaxies from SDSS at \( z \sim 0.08 \) and from ultraviolet imaging with Galaxy Evolution Explorer (GALEX) at \( z \sim 0.4 \), find that the fraction of passive galaxies is higher in groups than the field at both redshifts, with the difference between the group and field growing with time and being larger at low masses. With the NOAO Extremely Wide-Field Infrared Imager (NEWFIRM) Survey of the All-wavelength Extended Groth Strip International Survey (AEGIS) and Cosmic Evolution Survey (COSMOS) fields, Whitaker et al. (2011) show evidence for a bimodal color distribution between quiescent and star-forming galaxies that persists to \( z \sim 3 \). Presotto et al. (2012) study the evolution of galaxies located within groups by using the group catalog obtained from zCOSMOS spectroscopic data and the complementary photometric data from the COSMOS survey at \( z = 0.2–0.8 \) and find the rate of SF quenching to be faster in groups than in the field. Muzzin et al. (2012) analyze galaxy properties at \( z = 0.85–1.20 \) by using a spectroscopic sample of 779 cluster and field galaxies drawn from the Gemini Cluster Astrophysics Spectroscopic Survey, finding that post starburst galaxies with \( M^* = 10^{10.3} - 10^{10.7} \, M_\odot \) are three times more common in high-density regions compared with low-density regions. On the basis of the data from the zCOSMOS survey, Tanaka et al. (2012) perform an environmental study and find that quiescent galaxies prefer more massive systems at \( z = 0.5–1 \). Rasmussen et al. (2012), analyzing GALEX imaging of a statistically representative sample of 23 galaxy groups at \( z \sim 0.06 \), suggest an average quenching timescale of \( \gtrsim 2 \, \text{Gyr} \). Mok et al. (2013), with deep GMOS-S spectroscopy for 11 galaxy groups at \( z = 0.8–1 \), show that the strongest environmental dependence is observed in the fraction of passive galaxies, which make up only \( \sim 20\% \) of the field in the mass range of \( M_{\text{star}} = 10^{10.3} - 10^{11.3} \, M_\odot \) but are the dominant component of groups. Using SDSS (\( z \sim 0.1 \)) and AEGIS (\( z \sim 1 \)) data, Woo et al. (2013) find a strong environmental dependence of quenching in terms of halo mass and distance to the centrals at both redshifts.

The widespread observational evidence of environment quenching is unsurprising theoretically. In regions of overdensity, whether around a large collapsed halo or an unvirialized structure (e.g., a Zel'dovich pancake or a filament), gas is gravitationally shocked heated when converging flows meet. In regions filled with hot shock-heated gas, multiple gasdynamical processes would occur. One of the most important gasdynamical processes is ram pressure stripping of gas when a galaxy moves through the ambient hot gas at a significant speed, which includes but is not limited to the infall velocity of a satellite galaxy. The theoretical basis for the ram pressure stripping process is laid down in the seminal work of Gunn & Gott (1972). Recent works with detailed simulations of this effect on galaxies (in noncosmological settings) include those of Mori & Burkert (2000), Quilis et al. (2000), Kronberger et al. (2008), Bekki (2009), and Tonnesen & Bryan (2009).

Even in the absence of ram pressure stripping, ubiquitous supersonic and transonic motions of galaxies of complex acceleration patterns through the ambient medium (intergalactic or circumgalactic medium) subject them to the Raleigh–Taylor and Richtmyer–Meshkov instabilities. Large shear velocities at the interfaces between galaxies and the ambient medium allow the Kelvin–Helmholtz (KH) instability to play an important role. When these processes work in tandem with ram pressure displacements, the disruptive effects are amplified. For example, the KH instability timescale is substantially shorter for a non-self-gravitating gas cloud (e.g., Murray et al. 1993) than for one sitting inside a virialized dark matter halo (e.g., Cen & Riquelme 2008).

Another important process in hot environments is starvation of cold gas that is fuel for SF (e.g., Larson et al. 1980; Balogh et al. 2000; Dekel & Birnboim 2006). In high-temperature and high-entropy regions, cooling of hot gas is an inefficient process for fueling SF, which is an important point noted long ago to account for the basic properties (mass, size) of galaxies (e.g., Binney 1977; Rees & Ostriker 1977; Silk 1977). This phenomenon may be understood by considering the dependence of cooling time on the entropy of the gas: the gas cooling time can be written as \( t_{\text{cool}}(T, S) = \frac{S^{3/2}}{2.0 \times 10^{15} \, \text{T}^{1/2} \, \text{A(T)}} \) (Scannapieco & Oh 2004). It follows that the minimum cooling time of a gas parcel just scales with \( S^{3/2} \). As a numerical example, for a gas parcel of entropy \( S = 10^9 \, \text{K cm}^2 \) (say, for temperature \( 10^7 \, \text{K} \) and density \( 10^{-3} \, \text{cm}^{-3} \)) and metallicity \( 0.1 \, Z_\odot \), its cooling time is no shorter than the Hubble time at \( z = 1 \), hence the gas can no longer cool efficiently to fuel SF.

It may be the combination of cold gas removal and dispersal by ram pressure stripping, hydrodynamical instabilities, and cold gas starvation, all of which are expected to become increasingly important in more massive environments, plays a primary role in driving the color migration from the blue cloud to the red sequence. In dense environments, gravitational tidal (stripping and shock) effects and relatively close fly-bys between galaxies (e.g., Moore et al. 1996) also become important. To understand the overall effect on SF quenching by these external processes in the context of the standard cold dark matter model, a realistic cosmological setting is imperative in order to capture complex external processes that are likely intertwined with large variations of the internal properties of galaxies. In this paper we perform ab initio Large-scale Adaptive-mesh-refinement Omniciscient Zoom-In cosmological hydrodynamic simulations, called LAOZI simulations, to obtain a large sample of galaxies to, for the first time, perform a chronological and statistical investigation on a very large scale. The large simulated galaxy sample size and very high resolution of LAOZI simulations provide an unprecedented opportunity to undertake the study presented. Our study shares similar perspectives with the work by Feldmann et al. (2011), who examine the evolution of a dozen galaxies falling onto a forming group of galaxies, with a substantial improvement in the simulation treatment, the simulation resolution, the range of the environment probed, and the analysis scope. Feedback from AGNs is not included in this simulation, partly because of its large uncertainties and present lack of definitive driving sources but primarily because of our intention to focus on external effects. Internal feedback due to SF are automatically included, and in our study we find no evidence that SF or merger triggered SF plays a primary role in quenching. The outline of this paper is as follows. In Section 2, we detail our simulations (Section 2.1), our method of making galaxy catalogs (Section 2.2), our construction of histories of galaxies (Section 2.3), our tests and validation of simulations (Section 2.4) and the produced bimodal distribution of galaxies colors (Section 2.5). Results are presented in Section 3 and organized in an approximately

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1 In this expression, \( k_B \) is Boltzmann’s constant, \( T \) is temperature, \( \Lambda \) is the cooling function, \( \mu = 0.62 \) and \( \mu_e = 1.18 \) are for ionized gas that we are concerned with, and \( S \) is the gas entropy defined as \( S = (T/n)^{3/2} \) in units of \( \text{K cm}^2 \) (\( n \) is the gas number density). If one conservatively adopts the lowest value of the term inside the bracket at the cooling peak at temperature \( T_{\text{min}} \sim 10^{-7} \, \text{K} \), it follows that the minimum cooling time of a gas parcel just scales with \( S^{3/2} \).
chronological order, starting with the ram pressure stripping effects in Section 3.1, followed by the ensuing period of gas starvation in the hot environment in Section 3.2. In Section 3.3 we discuss stellar mass growth and the evolution of the stellar mass function of red galaxies, and we present galaxy color migration tracks. Section 3.4 gives an example of a consequence of the found color migration picture—the galaxy age–mass relation. We present the observable environmental dependence of the galaxy makeup at $z = 0.62$ in Section 3.5. Conclusions are given in Section 4.

2. SIMULATIONS

2.1. Hydrocode and Simulation Parameters

We perform cosmological simulations with the AMR Eulerian hydro code, Enzo (Bryan & Norman 2000; Joung et al. 2009). First, we run a low resolution simulation with a periodic box of $120 \, h^{-1} \, \text{Mpc}$ (comoving) on a side. We identify a region centered on a cluster of mass of $\sim 3 \times 10^{14} \, M_\odot$ at $z = 0$. We then resimulate the chosen region with high resolution, embedded in the outer $120 \, h^{-1} \, \text{Mpc}$ box to properly take into account the large-scale tidal field and appropriate boundary conditions at the surface of a refined region. The refined region has a comoving size of $21 \times 24 \times 20 \, h^{-3} \, \text{Mpc}$ and represents a $+1.8 \sigma$ matter density fluctuation at that volume. The dark matter particle mass in the refined region is $1.3 \times 10^7 \, h^{-1} \, M_\odot$. The refined region is surrounded by three layers (each of $\sim 1 \, h^{-1} \, \text{Mpc}$) of buffer zones with particle masses successively larger by a factor of 8 for each layer, which then connects with the outer root grid that has a dark matter particle mass $8^4$ times that in the refined region. We choose the mesh refinement criterion such that the resolution is always smaller than $114 \, h^{-1} \, \text{pc}$ (physical), corresponding to a maximum mesh refinement level of 13 at $z = 0$. An identical comparison run that has a four times better resolution of $29 \, h^{-1} \, \text{pc}$ was also run down to $z = 3$, and some relevant comparisons between the two simulations are made to understand effects of limited resolution on our results. The simulations include a metagalactic UV background (Haardt & Madau 1996), a model for the self-shielding of UV radiation (Cen et al. 2005), and metallicity-dependent radiative cooling (Cen et al. 1995). Our simulations also solve relevant gas chemistry chains for molecular hydrogen formation (Abel et al. 1997), molecular formation on dust grains (Joung et al. 2009), and metal cooling extended down to 10 K (Dalgarno & McCray 1972). Star particles are created in cells that satisfy a set of criteria for SF proposed by Cen & Ostriker (1992). Each star particle is tagged with its initial mass, creation time, and metallicity; star particles typically have masses of $\sim 10^5 \, M_\odot$.

Supernova feedback from SF is modeled following Cen et al. (2005). Feedback energy and ejected metal-enriched mass are distributed into 27 local gas cells centered at the star particle in question and weighted by the specific volume of each cell, which is to mimic the physical process of supernova blastwave propagation that tends to channel energy, momentum, and mass into the least dense regions (with the least resistance and cooling). The primary advantages of this supernova energy-based feedback mechanism are three-fold. First, nature does drive winds in the least dense regions (with the least resistance and cooling). The primary advantages of this supernova energy-based feedback mechanism are three-fold. First, nature does drive winds in the least dense regions (with the least resistance and cooling).

Supernova feedback is important primarily for regulating SF and for transporting energy and metals into the intergalactic medium. The extremely inhomogeneous metal enrichment process demands that both metals and energy (and momentum) are correctly modeled so that they are transported in a physically sound (albeit still approximate at the current resolution) way.

We use the following cosmological parameters that are consistent with the WMAP7-normalized (Komatsu et al. 2011) ΛCDM model: $\Omega_M = 0.28$, $\Omega_b = 0.046$, $\Omega_{\Lambda} = 0.72$, $\sigma_8 = 0.82$, $H_0 = 100 \, h \, \text{km} \, s^{-1} \, \text{Mpc}^{-1} = 70 \, \text{km} \, s^{-1} \, \text{Mpc}^{-1}$, and $n = 0.96$. These parameters are consistent with those from Planck’s first-year data (Planck Collaboration et al. 2013) if we average Planck-derived $H_0$ with SN Ia and Hubble-Space-Telescope-based $H_0$.

We note that the size of the refined region, $21 \times 24 \times 20 \, h^{-3} \, \text{Mpc}$, is still relatively small and the region is biased, which is of course designed that way on purpose. Because of that, however, we are not able to cover all possible environments, such as the center of a void, and we have avoided addressing any measures that require a precise characterization of the abundance of any large galaxy systems, such as the mass function or luminosity function of massive galaxies or groups. Despite that, measures that are characterized as a function of the environment/system masses should still be valid. Our environmental coverage is substantially larger than that probed in, for example, Feldmann et al. (2011). In Tonnesen & Cen (2012), we show that the present simulation box (C box; run to $z = 0$ with a lower resolution previously) spans a wide range in the environment from rich clusters to the field, and there is a substantial overlap in the field environment with another simulation centered on a void (V box). It is the density peaks higher than we model here (i.e., more massive clusters of galaxies) that we fail to probe. As it should be clear later, this shortcoming should not affect any of our conclusions, which may be appropriately extrapolated.

2.2. Simulated Galaxy Catalogs

We identify galaxies in our high resolution simulations by using the HOP algorithm (Eisenstein & Hu 1999) operating on the stellar particles, which is tested to be robust and insensitive to specific choices of concerned parameters within reasonable ranges. Satellites within a galaxy down to a mass of $\sim 10^9 \, M_\odot$ are clearly identified separately in most cases. The luminosity of each stellar particle in each of the SDSS five bands is computed using the GISEL stellar synthesis code (Bruzual & Charlot 2003) by supplying the formation time, metallicity, and stellar mass. Collecting luminosity and other quantities of member stellar particles, gas cells, and dark matter particles yields the following physical parameters for each galaxy: position, velocity, total mass, stellar mass, gas mass, mean formation time, mean stellar metallicity, mean gas metallicity, SFR, luminosities
in five SDSS bands (and various colors), and others. At a spatial resolution of 159 pc (physical) with thousands of well-resolved galaxies at $z \sim 0.6-6$, the simulated galaxy catalogs present an excellent (by far, the best available) tool to study galaxy formation and evolution.

2.3. Construction of Histories of Simulated Galaxies

When we start the analysis for this paper, the simulation has reached $z = 0.62$. For each galaxy at $z = 0.62$ a genealogical line is constructed from $z = 0.62$ to $z = 6$ by connecting galaxy catalogs at a series of redshifts. Galaxy catalogs are constructed from $z = 0.62$ to $z = 1.40$ at a redshift increment of $\Delta z = 0.02$ and from $z = 1.40$ to $z = 6$ at a redshift increment of $\Delta z = 0.05$. The parent of each galaxy is identified with the one at the next higher redshift catalog that has the most overlap in stellar mass.

We call galaxies with $g - r < 0.55$ “blue,” those with $g - r = 0.55-0.65$ “green,” and those with $g - r > 0.65$ “red,” in accordance with the bimodal color distribution that we will show below and with that of observed galaxies (e.g., Blanton et al. 2003b), where $g$ and $r$ are magnitudes of SDSS $g$ and $r$ bands.

In subsequent analysis, we will examine gasdynamic processes, e.g., cold gas loss or lack of cold gas accretion, under the working hypothesis that ram pressure stripping and gas starvation are the primary detrimental processes for star formation. We should assume that other processes, such as hydrodynamical instabilities (e.g., RT, KH, tidal shocks, etc.), may either be “lumped together” with ram pressure stripping or play some role to enhance cold gas destruction that is initiated by ram pressure stripping. It may be instructive to note that while tidal stripping would affect both stars and gas, ram pressure operates only on the latter. As one will see later, in some cases the stellar masses of galaxies decrease with time, which is likely due to tidal effects.

A simple argument suggests that ram pressure effects are likely to be more far-reaching spatially and are more consistent with the environmental effects becoming effective at $2-3$ virial radii than tidal stripping that we will show later. Let us use a specific example to illustrate this.

Assume that the primary and infalling galaxies have a velocity dispersion of $\sigma_1$ and $\sigma_2$, respectively, and that they both have isothermal sphere density profiles for both dark matter and baryons. The virial radius is proportional to its velocity dispersion in each case. Under such a configuration, we find that the tidal radius for the satellite galaxy at its virial radius is equal to the virial radius of the primary galaxy. On the other hand, the ram pressure force on the gas in the satellite at its virial radius is already equal to the gravitational restoring by the satellite, when the satellite is ($\sigma_1/\sigma_2$) virial radii away from the primary galaxy. In reality, of course, the density profiles for dark matter and baryons are different, and neither is isothermal; the gas may display a varying degree of nonsphericity. However, the relative importance of ram pressure and tidal stripping is likely to remain the same for relatively diffuse gas. The relative situation is unchanged if one allows the gas to cool and condense. As an example, if the gas within the virial radius of the satellite and the primary galaxies in the above example is allowed to shrink spherically by a factor of 10 in radius (we will continue to assume that the velocity dispersion or rotation velocity remains flat and at the same amplitude), we find that the tidal stripping radius is now a factor of 10 smaller than before (equal to 0.1 times the virial radius of the primary galaxy), while the new ram pressure stripping radius is $\sigma_1/\sigma_2$ times the new tidal stripping radius. As a third example, if the gas within the virial radius of the satellite galaxy in the above example is allowed to shrink spherically by a factor of 10 in radius but the gas in the primary galaxy does not shrink in size, it can be shown that in this case the tidal stripping radius is equal to 0.1 times the virial radius of the primary galaxy, while the new ram pressure stripping radius is now 0.1 times ($\sigma_1/\sigma_2$) times the virial radius of the primary galaxy. As the last example, if the gas within the virial radius of the satellite galaxy in the above example is allowed to shrink by a factor of 10 in radius to become a disk but the gas in the primary galaxy does not shrink in size, it can be shown that in this case the tidal stripping radius is equal to 0.1 times the virial radius of the primary galaxy. The new ram pressure stripping radius depends on the orientation of the motion vector and the normal of the disk: if the motion vector is normal to the disk, the tidal stripping radius is 0.1 times $\sigma_1/\sigma_2$ times the virial radius of the primary galaxy; if motion vector is in the plane to the disk, the tidal stripping radius is zero.

We denote a point in time when the galaxy turns from blue to green as $t_q$ and a point in time when the galaxy turns from green to red as $t_r$. The convention for time is that the Big Bang occurs at $t = 0$. We identify a point in time, searched over the range $t_q = 2$ Gyr to $t_r + 1$ Gyr, when the derivative of the SFR with respect to time, $dSFR/dt$, is most negative as $t_q$ (q stands for quenching). In practice, to reduce uncertainties due to temporal fluctuations in the SFR, $t_q$ is set as equal to $t(n + 1)$ when the sliding-window difference ($SFR(n + 3) - SFR(n)/(t(n + 3) - t(n))$ is most negative, where $t(1), t(2), ..., t(n), ...$ are the times of our data outputs as noted earlier. Galaxies at $t_q$ are collectively called star formation quenching galaxies. To demonstrate the reliability and accuracy of identification of $t_q$, we show in Figure 1 the histories of a set of four randomly selected red galaxies at $z = 0.62$ of stellar mass $\sim 10^{11} M_\odot$. The vertical dashed line in each panel shows $t_q$, which is the location of steepest drop of the SFR (solid dots). In all four cases, our method identifies the location accurately. Figure 2 is similar to Figure 1 but for galaxies of stellar mass $\sim 10^{10} M_\odot$, where we see our method identifies $t_q$ with a similar accuracy.

Similarly, we identify a point in time, in the range of $t_q = 2$ Gyr to $t_r + 1$ Gyr, when the derivative of the amount of cold gas, $(M_{10}, M_{30}, M_{100})$ within radial ranges of $(0-10, 0-30, 0-100) \text{kpc}$, with respect to time is most negative as $(t_{q10}, t_{q30}, t_{q100})$, respectively. We define cold gas as gas with a temperature of less than $10^3$ K. The exponential decay timescale of the SFR at $t_q$ is defined by $t_q \equiv (d \ln SFR/dt)^{-1}$. The exponential decay timescales of $(M_{10}, M_{30}, M_{100})$ at $(t_{q10}, t_{q30}, t_{q100})$ are defined by $[t_{q10} \equiv (d \ln M_{10}/dt)^{-1}, t_{q30} \equiv (d \ln M_{30}/dt)^{-1}, t_{q100} \equiv (d \ln M_{100}/dt)^{-1}]$. The time interval between $t_q$ and $t_r$ is denoted as $t_{q-r}$. The time duration that the galaxy spends in the green valley before turning red is called $t_{green}$. The time duration that the that galaxy has spent in the red sequence by $z = 0.62$ is denoted as $t_{red}$.

We make a necessary simplification by approximating the ram pressure, denoted as $p_{200}$, by $p_{300} \equiv \rho_{200}(300)$, where $\rho_{200}(300)$ and $T(300)$, respectively, are the mean density of gas with a temperature of $\geq 10^5$ K and the mean mass-weighted gas temperature within a proper radius of 300 kpc centered on the galaxy in question. This tradeoff is chiefly made because of the difficulty of precisely defining the motion of a galaxy relative to its ambient gas environment, where the latter often has complex density and velocity structures, and the former has a complex, generally nonspherical gas distribution geometry. In a gravitationally shock-heated medium, this approximation should be
reasonably good, because the ram pressure is approximately equal to thermal pressure in post-shock regions. We define a point in time searched over the time interval between $t_q - 2\ \text{Gyr}$ and $t_q + 1\ \text{Gyr}$, when the derivative of $p_{300}$ with respect to time is at its maximum, as $t_{\text{ram}}$, which is intended to serve as the point in time when ram pressure has the steepest rise.

As stated in the Introduction, it is convenient to express a gas cooling time that is proportional to gas entropy to the power $3/2$,
the value of the environmental entropy $S_{300}$, defined to be the average gas entropy within a top-hat sphere of the proper radius 300 kpc.

For convenience, frequently used symbols and their definitions are given in Table 1.

### 2.4. Tests and Validation of Simulation

The galaxy formation simulation in a cosmological setting used here includes sophisticated physical treatment, ultra-high resolution, and a very large galaxy sample to statistically address cosmological and astrophysical questions. While this simulation represents the current state-of-the-art in these respects, feedback from SF is still far from being treated from first principles. Thus, it is necessary that we validate the feedback prescription empirically.

In Cen (2012b), we presented an examination of the damped Lyman alpha systems (DLAs) and found that the simulations, for the first time, are able to match all observed properties of DLAs, including abundance, size, metallicity, and kinematics. In particular, the metal distribution in and around galaxies over a wide range of redshift ($z = 0$–5) is shown to be in excellent agreement with observations (Rafelski et al. 2012). The scales probed by DLAs range from stellar disks at low redshift to about one-half of the virial radius at high redshift. In Cen (2012a), we further show that the properties of O VI absorption lines at low redshift, including their abundance, Doppler-column density distribution, temperature range, metallicity, and coincidence between O VII and O VI lines, are all in good agreement with observations (Danforth & Shull 2008; Tripp et al. 2008; Yao et al. 2009).

The agreement between simulations and observations with respect to O VI lines is recently shown to extend to the correlation between galaxies and O VI lines, the relative incidence ratio of O VI around red to blue galaxies, the amount of oxygen mass around red and blue galaxies, and cold gas around red galaxies (Cen 2013).

In addition to agreements with observations with respect to the circumgalactic and intergalactic medium, we find that our simulations are able to match the global SFR history (the Madau plot) and galaxy evolution (Cen 2011a), the luminosity function of galaxies at high (Cen 2011b) and low redshift (Cen 2011a), and the galaxy color distribution (Cen 2011a; Tonnesen & Cen 2012), within observational uncertainties. In Cen (2011a), we show that our simulations reproduce many trends in the global evolution of galaxies and various manifestations of the cosmic downsizing phenomenon. Specifically, our simulations show that at any redshift, the specific star formation rate of galaxies, on average, correlates negatively with galaxy stellar mass, which is opposite to what we find (e.g., Weinmann et al. 2012). Smoothed particle hydrodynamic simulations and semianalytic methods, in comparison, appear to produce a positive correlation between the specific star formation rate of galaxies and galaxy stellar mass, which is opposite to what we find (e.g., Weinmann et al. 2012). These broad agreements between our simulations and observations indicate that, among others, our treatment of feedback processes from SF, i.e., the transport of metals and energy from galaxies, and from SF sites to the megaparsec scale (i.e., from interstellar to intergalactic medium) are realistically modeled as a function of distance and environment, at least in a statistical sense, and it is meaningful to employ our simulated galaxies and circumgalactic and intergalactic mediums for understanding physical processes and for confrontations with other independent observations.

### Table 1

| Symbol/Name | Definition/Meaning |
|-------------|--------------------|
| $t_g$       | A point in time when galaxy has $g - r = 0.55$ |
| $t_r$       | A point in time when galaxy has $g - r = 0.65$ |
| $M_{10}$    | Amount of cold gas within a radius of 10 kpc |
| $M_{30}$    | Amount of cold gas within a radius of 30 kpc |
| $M_{100}$   | Amount of cold gas within a radius of 100 kpc |
| $t_q$       | A point in time of quenching for SFR |
| $t_{10}$    | A point in time of quenching for $M_{10}$ |
| $t_{30}$    | A point in time of quenching for $M_{30}$ |
| $t_{100}$   | A point in time of quenching for $M_{100}$ |
| $t_{	ext{ran}}$ | A point in time of largest first derivative of ram pressure w.r.t. time |
| $t_{ext}$   | Exponential decay time of SFR at $t_q$ |
| $t_{10}$    | Exponential decay time of $M_{10}$ at $t_{10}$ |
| $t_{30}$    | Exponential decay time of $M_{30}$ at $t_{30}$ |
| $t_{100}$   | Exponential decay time of $M_{100}$ at $t_{100}$ |
| $M_{10}$    | $M_{10}$ mass change between $t_q$ and $t_10$ |
| $M_{30}$    | $M_{30}$ mass change between $t_q$ and $t_30$ |
| $M_{100}$   | $M_{100}$ mass change between $t_q$ and $t_100$ |
| $r_{100}^{\text{SFR}}$ | Effective radius of young stars formed within the past 100 Myr |
| $T_{100}$   | Environmental temperature within physical radius of 300 kpc |
| $S_{100}$   | Environmental entropy within physical radius of 300 kpc |
| $p_{100}$   | Environmental pressure within physical radius of 300 kpc |
| $\delta_{100}$ | Environmental overdensity within comoving radius of $2 \, h^{-1} \, \text{Mpc}$ |
| $d/r_{10}^*$ | Distance to primary galaxy in units of virial radius of primary galaxy |
| $t_q$       | Time duration from $t_q$ to $t_1$ |
| $t_{green}$ | Time spent in green valley |
| $t_{red}$   | Time spent in red sequence |
| $M_{bh}$    | Halo mass of primary galaxy |
| $M_{bh}/M_*$ | Stellar mass ratio of satellite to primary galaxy |
In order to determine which galaxies in our simulations to use in our subsequent analysis, we create an empirical numerical convergence test. The top right panel in Figure 3 shows comparisons between galaxies of two simulations at \( z = 3 \) with different resolutions for the luminosity functions in the rest-frame \( g \) and \( r \) bands. The fiducial simulation has a resolution of 114 h\(^{-1}\) pc, and an identical comparison run has a four times better resolution of 29 h\(^{-1}\) pc. We are not able to make comparisons at redshift substantially lower than \( z = 3 \) at this time. In any case, we expect that the comparison at \( z = 3 \) is a more stringent test, because the resolution effect is likely more severe at higher redshift than at lower redshift in a hierarchical growth model where galaxies become increasingly larger with time. The comparisons are best done statistically, because not all individual galaxies can be identified on a one-to-one basis because resolution-dependent star formation and merging histories. Comparisons with respect to other measures, such as stellar mass function, SFR, etc., give comparable convergence. On the basis of the results shown, we decide to place a lower stellar mass limit of 10\(^5\) \( M_\odot \) which is more than 75\% complete for almost all relevant quantities, to the extent that we are able to make statistical comparisons between these two runs with respect to the global properties of galaxies (stellar mass, luminosity, SFR, sSFR, etc.).

In terms of checking the validity and applicability of the simulations, we also make comparisons for the galaxy cumulative mass function at \( z = 1 \) with observations in the top left panel of Figure 3. We see that the simulated galaxies have a higher abundance than observed by a factor of 4–5 in the low mass end, and the difference increases toward higher mass end. This difference is expected because the simulation volume is an overdense region that has a higher galaxy density overall and progressively higher densities for more rare, higher mass galaxies. This difference is also borne out by the comparisons between the simulated and observed rest-frame \( g \) band galaxy luminosity function at \( z = 0.62 \) and the \( B \) band luminosity function at \( z = 1 \) (bottom left panel of Figure 3). The difference between simulation and observations is also seen to increase with decreasing redshift, as expected. We note that at the high luminosity end dust effects may become very important, causing the apparent discrepancies between simulations and observations larger than they actually are. Overall, our simulation serves our purposes well for two reasons. First, it contains massive group/cluster systems as well as field regions that allow us to probe environmental effects with enough leverage/range. Second, the faint end slope of the galaxy population matches observations well, albeit with a larger overall amplitude; as a result, relative and comparative statements that we will make across the stellar mass range of 10\(^5\) to 10\(^11\) \( M_\odot \) are approximately valid even though the absolute number of galaxies may be off.

As it will become clear later, during quenching by ram pressure stripping and gas starvation, star formation often continues in the central 10 kpc regions of galaxies. Therefore, it is useful to have an estimate of the effective resolutions of simulations empirically as follows. Let us denote the actual resolution, given the maximum refinement resolution of \( \Delta x \), as \( \Delta x = C \Delta l \), where \( C \) is a constant that is expected to be larger than, but of order unity for, a mesh code. We then assume that the computed effective stellar radius (enclosing 50\% of stellar mass) of any galaxy is

\[
 r_c^2 = r_i^2 + (\Delta x)^2 = r_i^2 + (C \Delta l)^2, \tag{1}
\]

where \( r_c \) is the actual effective radius from simulation, and \( r_i \) is the true effective radius if one had infinite resolution.
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We have two equations of Equation (1) for the two simulations with different resolutions ($\Delta t = 114$ h$^{-1}$ pc and $\Delta l = 29$ h$^{-1}$ pc) and two unknowns (constant $C$ and vector $r_l$). We solve for $C$ by requiring the distributions of $r_l$ derived from the two simulations that have the closest agreement; $C = 1.84$ is found. The bottom right panel of Figure 3 shows the distributions of derived $r_l$ for all galaxies with stellar mass $\geq 10^{9.5}$ $M_\odot$ from the two simulations with $C = 1.84$. The effective resolutions ($C\Delta l$) for the two runs, 312 pc and 78 pc, are indicated by the vertical dashed lines corresponding to the histograms with the same colors. As we will show later, the central gas within 10 kpc is largely retained by the galaxy that is being subjected to ram pressure stripping. Clearly, our resolution is adequate to resolve gas distribution where it is needed to address ram pressure stripping physics. On the other hand, consistent with other panels of Figure 3, we see that at the stellar mass cut of $10^{9.5}$ $M_\odot$, while the majority of galaxies are effectively resolved with respect to their stellar distribution, a significant fraction of galaxies in our selected sample with stellar mass close to $10^{9.5}$ $M_\odot$ is under-resolved in the central regions. We expect that although our simulation may overestimate the ram pressure stripping effects for the most inner regions for some of the smaller galaxies, the numerical effect on overall ram pressure stripping process due to this limitation is likely to be small. This is because the amount of gas within our resolution limit (313 pc) is small compared with the total mass of gas within, say, 10 kpc, in which we will show later, gas is little affected by ram pressure stripping. In other words, an under-resolution should not materially impact the overall amount of ram pressure stripped gas, since the gas in the central region that is much larger than our resolution is not stripped anyway.

2.5. Bimodal Distribution of Galaxy Colors at $z = 0.62$

The main goal of this paper is to identify and understand the physical processes that produce the observed galaxy color bimodality. We first examine if our simulations actually reproduce the observed color bimodality. Figure 4 shows $g-r$ color distributions of simulated galaxies in three stellar mass ranges, $3 \times 10^5 - 1 \times 10^7$ $M_\odot$ (black), $1 \times 10^{10} - 3 \times 10^{10}$ $M_\odot$ (cyan), and $>3 \times 10^{10}$ $M_\odot$ (magenta), at $z = 0.62$. The $g-r$ color distributions show clear bimodalities for all three subsets of galaxies, with the red peak becoming more prominent for less luminous galaxies at $z = 0.62$, consistent with recent observations (e.g., Bell et al. 2004; Willmer et al. 2006; Bundy et al. 2006; Faber et al. 2007). We also caution that one should not overstate the success in this regard for two reasons. First, on the simulation side, since our simulation volume does not necessarily represent an “average” volume of the universe, a direct comparison to observations would be difficult. Second, observations at high redshift (i.e., $z \sim 0.62$) are perhaps less complete than at low redshift, and identification of low mass (and especially low surface brightness) galaxies, in particular those that are satellite galaxies and red, may be challenged at present (e.g., Knobel et al. 2013). Our main purpose is to make a comparative study of galaxies of different types in the simulation and to understand how blue galaxies turn red.

It is intriguing to note that there is no lack of red dwarf galaxies. While a direct comparison to observations with respect to abundant red dwarf galaxies cannot be made at $z = 0.62$, future observations may be able to do this. Since our simulation does not include AGN mechanical feedback, this suggests that the bimodal nature of galaxy colors does not necessarily require AGN feedback for galaxies in the mass ranges examined. This finding is in agreement with Feldmann et al. (2011), who find that AGN feedback is not an essential ingredient for producing quiescent, red elliptical galaxies in galaxy groups. While SF feedback is included in our simulation, our subsequent analysis shows that environmental effects play the dominant role in driving galaxy color evolution and consequently color bimodality. Our results do not, however, exclude the possibility that AGN feedback may play an important role in regulating larger, central galaxies, such as cD galaxies at the centers of rich clusters of galaxies, for which we do not have a sufficient sample to make a statistical statement. Our earlier comparison between simulated luminosity functions of galaxies at $z = 0$ and SDSS observations indicates that some additional feedback, likely in the way of AGNs, may be required to suppress star formation in the most massive galaxies (Cen 2011a).

3. RESULTS

Most of our results shown are presented through a variety of comparisons of the dependencies of galaxies of different types on a set of environmental variables, in order to learn how galaxies change color. We organize our analysis in an approximately chronological order. In Section 3.1 we focus on processes around the “quenching” time, $t_q$, followed by the ensuing period of gas starvation in the hot environment in Section 3.2. In Section 3.3 we discuss stellar mass growth and the evolution of stellar mass function of red galaxies, and we present galaxy color migration tracks. Section 3.4 gives an example of a consequence of the color migration picture—the galaxy age–mass relation. We present the observable environmental dependence of the galaxy makeup at $z = 0.62$ in Section 3.5.

3.1. Ram Pressure Stripping: Onset of Star Formation Quenching

Figure 5 shows the quenching timescale $t_q$ (star formation rate exponential decay time) against four environmental variables at the quenching time $t_q$: ram pressure $P_{300}$, environmental entropy $S_{300}$, distance to the primary galaxy $d/r_p$, and environmental overdensity $\delta_2$. Here we define some of the nomenclature used in our study. We have used the distance to the primary galaxy, $d/r_p$, as an environmental variable, which runs from zero to
values significant above unity. This is merely saying that any galaxy (except the most massive galaxy in the simulation) can find a larger galaxy at some distance and not necessarily at \( d/r_c \leq 1 \). The definition of “satellite galaxies” is reserved only for those galaxies with \( d/r_c \leq 1 \), shown clearly as red circles in the bottom left panel of Figure 5. The black circles, labeled as “centrals” are galaxies with \( d/r_c > 1 \), i.e., those that are not “satellite galaxies.”

The observation that galaxies are being quenched at all radii—\( d/r_c > 1 \) as well as \( d/r_c < 1 \)—indicates that the most likely physical mechanism for the onset of quenching is ram pressure. Tidal stripping is not expected to be effective at removing gas (or stars) at \( d/r_c > 1 \) (see Section 2.3 for a discussion). The fact that \( \tau_q \) decreases with increasing \( p_{300} \) is self-consistent with ram pressure being responsible for the onset of quenching. The outcome that \( \tau_q \) only very weakly anticorrelates with \( p_{300} \) indicates that the onset of quenching is some “threshold” event, which presumably occurs when the ram pressure exceeds the gravitational restoring force (i.e., the threshold), thus strongly reinforcing the observation that ram pressure is largely responsible for the onset of quenching. A “threshold” type mechanism fits nicely with the fact that the dispersion of \( \tau_q \) at a given \( p_{300} \) is substantially larger than the correlation trend, because galaxies that cross the “threshold” are expected to depend on very inhomogeneous internal properties among galaxies (see Figure 6 below). The weak anticorrelation between \( \tau_q \) and \( \delta_2 \) stems from a broad positive correlation between \( p_{300} \) and \( \delta_2 \). The fact that there is no discernible correlation between \( \tau_q \) and \( S_{300} \) indicates that the onset of quenching is not initiated by gas starvation.

The most noticeable contrast to the weak trends noted above is the difference between satellite galaxies (at \( d/r_c < 1 \)) and central galaxies (at \( d/r_c > 1 \)), in that \( \tau_q \) of the former is lower than that of the latter by a factor of \( \sim 2 \), which is explained as follows. First, at \( d/r_c < 1 \), ram pressure stripping and tidal stripping operate in tandem to accelerate the gas removal process, whereas at \( d/r_c > 1 \) ram pressure stripping operates “alone” to remove gas on somewhat longer timescales. Second, at \( d/r_c > 1 \), ram pressure stripping is, on average, less strong than at \( d/r_c < 1 \).

Possible internal variables that affect the effectiveness of ram pressure stripping include the relative orientation of the normal of the gas disk and the motion vector, the rotation velocity of the gas disk, whether gas disk spiral arms are trailing or not at the time of ram pressure stripping, the gas surface density amplitude and profile, and the dark matter halo density profile. As an obvious example, galaxies that have their motion vector and disk normal aligned are likely to have maximum ram pressure stripping effects, with everything else being equal. In the other extreme when the two vectors are perpendicular to each other, the ram pressure stripping effect may be minimized. Needless to say, given many factors involved, the onset of ram pressure stripping effect will be multivariant. We elaborate on the multivariant nature of ram pressure stripping with one example. The top panel of Figure 6 shows \( \tau_q \) as a function of the stellar surface density \( \Sigma_* \) within the effective stellar radius \( r_e \). We see a weak but positive correlation between \( \tau_q \) and \( \Sigma_* \) in the sense that it takes longer for ram pressure stripping to remove cold gas with higher central surface density (hence higher gravitational restoring force) galaxies. While this positive

**Figure 5.** \( \tau_q \), the exponential decay time of SFR, against four environmental variables at \( t_q \): ram pressure \( p_{300} \) on a 300 kpc proper scale, environmental entropy \( S_{300} \) on a 300 kpc proper scale, distance to the primary galaxy \( d/r_c \) in units of the primary galaxy’s virial radius, and environmental overdensity \( \delta_2 \) on a 2 \( h^{-1} \) Mpc comoving scale. The magenta solid dots with dispersions are the means.

(A color version of this figure is available in the online journal.)
We have made the case above that ram pressure stripping is primarily responsible for the onset of quenching process on the basis of evidence of the dependence of the exponential decay time of SFR at the onset of quenching process on environmental variables. We now make a direct comparison between \( t_q \) and \( t_{ram} \). Figure 7 shows the histograms of \( t_q - t_{ram} \). We see that the time difference between the two is centered around zero, indicating a causal connection between the onset of SFR quenching and the rapid rise of ram pressure. The width of the distribution of a few hundred Myrs reflects the fact that the exact strength of ram pressure stripping required to dislodge the gas varies greatly, depending on many variables as discussed above. This is as yet the strongest supporting evidence for ram pressure stripping being responsible for the onset of quenching, especially considering the conjunctional evidence that the onset of quenching could occur outside the virial radius of a larger neighboring galaxy where tidal stripping is expected to be less effective and yet ram pressure is expected to become important.

Evidence so far supports the notion that ram pressure stripping is the initial driver for the decline of SFR in galaxies that are en route to the red sequence. The immediate question is then: What region in galaxies does ram pressure stripping affect? To answer this question, we need to compare the amount of cold gas available at \( t_q \) with the amount of star formation that occurs subsequently. We compute the following ratios: the ratios of the amount of stars formed during the time interval from \( t_q \) to the time the galaxy turns red \( (t_f) \) to the difference between the amount of cold \((T<10^3 \, \text{K})\) gas at \( t_q \) and \( t_f \), denoted as \((-\Delta M_*/\Delta M_{10}, -\Delta M_*/\Delta M_{30}, -\Delta M_*/\Delta M_{100})\) within three radii \((10, 30, 100) \, \text{kpc}\). The minus signs are intended to make the ratios positive, since stellar mass typically increase with time, whereas the cold gas mass for galaxies being quenched decreases. Note that \( \Delta M_* \) could be negative. We set a floor value to the above ratios at \( 10^{-9} \). Figure 8 shows the distributions of \(-\Delta M_*/\Delta M_X\), where \( X = (10, 30, 100) \). We see that for \( r \leq 10 \, \text{kpc} \) the peak of the distribution (red histograms) for all stellar masses is at \(-\Delta M_*/\Delta M_{10} > 1\), typically in the range of \(2-10\), with the vast majority of cases at \( > 1\). For a larger radius, \( r \leq 30 \, \text{kpc} \), the distribution (green histograms) for all stellar masses is now peaked at \(-\Delta M_*/\Delta M_{30} < 1\), typically in the range of \(0.5 \, \text{at} \, r = 30 \, \text{kpc}\), which has a longer dynamic time and hence a shorter \( t_q \). This is in fact an incorrect interpretation. Rather, the gas in the central regions where \( \Sigma_e \) is measured is immune to ram pressure stripping in the vast majority of cases (see Figure 8 below). Instead, a higher \( \Sigma_e \) translates, on average, to a larger scale where gas is removed, which has a longer dynamic time and hence a longer \( t_q \).

Taken together, we conclude that while a high ram pressure provides the conditions for ram pressure stripping to take effect, the effectiveness or timescale for gas removal by ram pressure stripping also depends on the internal structure of the galaxies. It is very interesting to note that unlike between \( t_q \) and \( \tau \), \( \tau_{eq} \) (the time interval between the onset of quenching \( t_q \) and the time when the galaxy turns red) and \( \Sigma_e \) shown in the bottom panel of Figure 6, if anything, are weakly anticorrelated. We attribute this outcome to the phenomenon that galaxies with a higher central surface density have a shorter timescale for consuming the existing cold gas once the overall cold gas reservoir is removed. This explanation will be elaborated more later.

![Figure 6.](image-url)

**Figure 6.** Top panel: the exponential decay timescale of SFR, \( t_q \), as a function of the stellar surface density \( \Sigma_* \) within the stellar effective radius \( r_e \). Bottom panel: the time interval between onset of quenching and the time the galaxy turns red, \( t_{eq} \), as a function of \( \Sigma_e \). The magenta dots are the averages at a given \( x \)-axis value.

(A color version of this figure is available in the online journal.)

correlation between \( t_q \) and \( \Sigma_e \) is consistent with observational indications (e.g., Cheung et al. 2012), the underlying physical origin is in a sense subtle. Since ram pressure stripping is a “threshold” event, as noted earlier, when ram pressure force just exceeds the internal gravitational restoring force, one would have expected that a high surface density would yield a shorter dynamic time and hence a shorter \( t_q \). This is in fact an incorrect interpretation. Rather, the gas in the central regions where \( \Sigma_e \) is measured is immune to ram pressure stripping in the vast majority of cases (see Figure 8 below). Instead, a higher \( \Sigma_e \) translates, on average, to a larger scale where gas is removed, which has a longer dynamic time and hence a longer \( t_q \).
Figure 7. Histograms of $t_q - t_{\text{ram}}$ for red galaxies at $z = 0.62$, where $t_{\text{ram}}$ is the point in time when the derivative of $p_{300}$ with respect to time is at its maximum, and $t_q$ is the onset of quenching time for SFR. The vertical thick lines show the medians of the corresponding histograms of the same colors, and the vertical thin lines for each color are for 25% and 75% percentiles.

(A color version of this figure is available in the online journal.)

Figure 8. Distribution of $-\Delta M_*/\Delta M_X$ at three radial ranges, $X = (10, 30, 100)$. $\Delta M_*$ is the amount of stars formed during the time interval from the onset of quenching $t_q$ to the time the galaxy turns red $t_r$, and $\Delta M_X$ is the difference of the amount of cold ($T < 10^5$ K) gas within a radius $X$ kpc between $t_r$ and $t_q$. The vertical dashed lines show the medians of the corresponding histograms of the same colors.

(A color version of this figure is available in the online journal.)

observable consequences, consistent with the latest observations (e.g., Gavazzi et al. 2013).

We quantify how centrally concentrated the star formation is at the outset of SF quenching in Figure 9, in part to assess our ability to resolve SF during the quenching phase. The left panel shows the distribution of the effective radius of stars formed in the last 100 Myr prior to $t_q$, denoted as $r_{\text{SFR}}^{e}$, for galaxies in two stellar mass ranges. The right panel shows the distribution of the ratio of the decline of $r_{\text{SFR}}^{e}$ with respect to the decline of SFR, $dr_{\text{SFR}}^{e}/d\ln\text{SFR}$ at $t_q$. It is evident from Figure 9 that more massive galaxies tend to have larger $r_{\text{SFR}}^{e}$, as expected. It is also evident that the recent formation for the vast majority of galaxies occurs within a radius of a few kiloparsecs. It is noted that ongoing SF in a significant fraction of galaxies with stellar masses $\lesssim 3 \times 10^9 M_\odot$ is under-resolved, as indicated by the vertical dot-dashed line in the left panel. However, none of our subsequent conclusions would be much altered by this numerical effect, because (1) all of our conclusions appear to be
Our attention is stripping (in conjunction with other hydrodynamical processes), galaxies being quenched because of gas removal by ram pressure disconnecting galaxies from their cold reservoir on scales that \( \geq 30 \) kpc. The main role of ram pressure stripping appears to be "push" of galaxies into the red sequence is not as spectacular an event as the initial onset of quenching that is triggered by a cutoff of large-scale gas supply due to ram pressure stripping, and it is essentially the process of gas starvation in which the galaxy has entered a low cold gas density and/or high-temperature and/or high-velocity dispersion environment.

We present distributions of \( t_{qr} \) in Figure 11. The top left panel shows the distribution of \( t_{qr} \) for satellite galaxies (those with \( d/r_e^C \leq 1 \)), grouped into three primary halo mass ranges: \( M_h^C = 10^{11} - 10^{12} M_\odot \) (black), \( M_h^C = 10^{12} - 10^{13} M_\odot \) (green), and \( M_h^C > 10^{13} M_\odot \) (red); the medians of the distributions are \((1.2,1.3,1.2)\) Gyr, respectively. The top right panel shows the distribution of \( t_{qr} \) for satellite galaxies grouped into three ranges of the ratio of satellite to central stellar mass: \( M^s_h/M^c_h = 0.1-1 \) (black), \( M^s_h/M^c_h = 0.01-0.1 \) (green), and

\[
\text{PDF} = \frac{1}{\sqrt{2\pi} \sigma} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)
\]

\[
\text{log } SFR \quad (kpc)
\]

\[
\text{dr(SFR)/dlnSFR} \quad (kpc)
\]
$M_\ast^s/M_\ast^c = 0.001–0.01$ (red); the medians of the distributions of the three groups are nearly identical at $\sim 1.3$ Gyr. The bottom left panel shows the distribution of $t_{qr}$ for primary galaxies (those with $d/r_{vc} > 1$), grouped into two halo mass ranges: $M_\ast^s = 10^{10}–10^{11} \, M_\odot$ (black) and $M_\ast^s = 10^{11}–10^{12} \, M_\odot$ (green). We see that the medians of the distributions are 1.2 Gyr for both mass ranges. The bottom right panel plots the distribution of all satellite galaxies and all central galaxies, along with a simple Gaussian fit to the combined set. The bottom right panel of Figure 11 suggests that there is practically no difference between the two distributions. At first sight, this may seem in comprehensible. A closer examination reveals the underlying physics.

Figure 12 shows the distributions of $d/r_{vc}$ at $t_{qr}$ for satellite (red) and central (black) red galaxies at $z = 0.62$. While it is not a surprise that the vast majority of the satellite galaxies at $z = 0.62$ have their onset of quenching taking place at $d/r_{vc} \lesssim 3$ at $t_{qr}$, it is evident that the same appears to be true for the central galaxies at $z = 0.62$. This observation supports the picture that both satellite and central red galaxies at $z = 0.62$ have been subjected to similar environment effects that turn them red. It is noted again that this statement that red central galaxies have been subjected to similar processes as the red satellite galaxies has been quantitatively confirmed in Figure 11. The suggestion by Wetzel et al. (2013b) that some central galaxies are ejected satellite galaxies is consistent with our findings here. Our study thus clearly indicates that one should not confuse red central galaxies with those being quenched by processes other than the environment. In fact, all available evidence suggests that it is environment quenching that plays the dominant role for the vast majority of galaxies that turn red, whether or not they become satellite galaxies at $z = 0.62$. Feldmann et al. (2011), using a much smaller sample of simulated galaxies that form a group of galaxies, find that quenching of gas accretion starts at a few virial radii from the group center, in good agreement with our results. It is seen in Figure 12 that only about 20% of the onset of galaxy quenching occurs as satellites, i.e., within the virial radius of a larger galaxy, consistent with conclusion derived by others (e.g., van den Bosch et al. 2008).

In the bottom right panel of Figure 11, we provide an approximate fit to the distribution of $t_{qr}$ for all quenched galaxies normalized to galaxies at $z = 0.62$ as

$$f(\log t_{qr}) = \frac{1}{2\log t_{med}\sqrt{2\pi}} \exp\left[-(\log t_{qr}/\log t_{med} - 1)^2/8\right]. \quad (2)$$

where $t_{qr}$ and $t_{med}$ are in Gyr and $\log t_{med} = 0.08–1.5 \times \log((1 + z)/1.62)$. The adopted log $t_{med}$ is $0.08–1.5 \times \log((1 + z)/1.62)$ dependence on $z$ is merely an estimate of the timescale had it scaled with redshift proportional to the dynamical time of the universe. One is cautioned not to apply this literally. Nevertheless, it is likely that the median quenching time at lower redshift is longer than $\sim 1.2$ Gyr at $z = 0.62$, perhaps in the range of 2–3 Gyr. Incidentally, this estimated quenching time, if extrapolated to $z = 0$, is consistent with the theoretical interpretation of observational data in semianalytic modeling or $N$-body simulations (e.g., Taranu et al. 2012; Wetzel et al. 2013a).
Figure 11. Top left panel: the distribution of $t_{qr}$ for satellite galaxies at $z = 0.62$, separated into three primary halo mass ranges: $M_h^* = 10^{11}$–$10^{12}$ $M_\odot$ (black), $M_h^* = 10^{12}$–$10^{13}$ $M_\odot$ (green), and $M_h^* > 10^{13}$ $M_\odot$ (red). Top right panel: the distribution of $t_{qr}$ for satellite galaxies at $z = 0.62$, separated into three ranges of satellite stellar mass to primary stellar mass ratio: $M_s^*/M_h^* = 0.1$–$1$ (black), $M_s^*/M_h^* = 0.01$–$0.1$ (green), and $M_s^*/M_h^* = 0.001$–$0.01$ (red). Bottom left panel: the distribution of $t_{qr}$ for primary galaxies at $z = 0.62$, separated into three primary halo mass ranges: $M_h^* = 10^{10}$–$10^{11}$ $M_\odot$ (black), $M_h^* = 10^{11}$–$10^{12}$ $M_\odot$ (green), and $M_h^* > 10^{12}$ $M_\odot$ (red). The three vertical dashed lines of the order (thin, thick, thin) are the (25%, 50%, 75%) percentiles for the histograms of the same color. Bottom right panel: the distribution of $t_{qr}$ for all satellite galaxies (blue), all primary galaxies (red), and all galaxies (black) at $z = 0.62$. An eyeballed lognormal fit is shown as the magenta line (see Equation (2)).

(A color version of this figure is available in the online journal.)

Figure 12. Distribution of the relative distance $d/r_\star$ of progenitors at $t_{qr}$ of red galaxies at $z = 0.62$ for two subsets of galaxies: the red histogram for those that are within the virial radius of a larger galaxy (i.e., satellite galaxies at $z = 0.62$) and the black histogram for those that are not within the virial radius of a larger galaxy at $z = 0.62$. The thick blue vertical dashed lines are 50% percentiles for all galaxies being quenched, and the thin blue vertical dashed lines are 25% and 75% percentiles.

(A color version of this figure is available in the online journal.)

In semianalytic modeling (e.g., Kimm et al. 2009), the quenching time is often taken to be a delta function. In other words, the satellite quenching process is assumed to be uniform and independent of the internal and external properties of the satellites. Our simulation results (see Equation (2)) indicate that such a simplistic approach is not well motivated physically. We suggest that if a spread in quenching time is introduced in the semianalytic modeling, it may result in an improvement on the agreement between predictions based on semianalytic modeling and observations.

In summary, we find that within the environmental sphere of influence, galaxies are disconnected with their large-scale cold gas supply by ram pressure stripping, and a subsequent lack of gas cooling and/or accretion in a high-velocity environment ensures a prolonged period of gas starvation that ultimately turns galaxies red. This applies to satellite galaxies as well as the vast majority of “apparent” central red galaxies. The dominance of environment quenching that is found in ab initio cosmological simulations here is in accordance with observations (e.g., van den Bosch et al. 2008; Peng et al. 2012; Kovac et al. 2013).

3.3. Color Migration Tracks

On its way to the red sequence, a galaxy has to pass through the green valley. Do all galaxies in the green valley migrate to the red sequence? We examine the entire population of green galaxies in the redshift range of $z = 1$–$1.5$. Tracing these green galaxies to $z = 0.62$, we find that for galaxies with stellar masses greater than $(10^{9.5}, 10^{10}, 10^{10.5}) M_\odot$, respectively, (40%, 40%, 48%) of galaxies in the green valley at $z = 1$–$1.5$ do not become red galaxies by $z = 0.62$. While this is an important prediction of our simulations, we do not provide more information on how one might distinguish these two different populations of galaxies in the green valley, except to point out that attempts to identify galaxies in the green valley as progenitors of red galaxies may...
generate some confusion. We examine the distributions (not shown) of the time that red galaxies spent in the green valley, \( t_{\text{green}} \), en route to the red sequence. The trends that are seen with respect to \( M_h \) and \( M_*^\text{green} / M_*^\text{red} \) are similar to those seen in Figure 11. No significant differentiation among halo masses of central galaxies is visible, once again supportive of environment quenching. Overall, one may summarize the results in three points. First, \( t_{\text{green}} \) is almost universal and is independent of being satellites or not, the mass, or the ratio of masses. Second, the range \( t_{\text{green}} = 0.30 \pm 0.15 \) Gyr appears to enclose most of the galaxies, although there is a significant tail toward the high end for satellites in low mass central halos. Third, comparing \( t_{\text{green}} \sim 0.3 \) Gyr with the interval from the onset of quenching to the time of the galaxy turning red of \( t_q = 1.2–1.3 \) Gyr indicates that from the onset of quenching to turning red, typical galaxies spend about 25% of the time in the green valley.

Let us now examine the migration tracks of galaxies that eventually enter the red sequence. Figure 13 shows the color–stellar mass diagram for 30 semi-randomly selected red galaxies. It is striking that the color evolution in the green valley and red sequence is mostly vertical, i.e., not accompanied by a significant change in stellar mass. This means that the stellar mass growth of most galaxies must occur in the blue cloud. One can see easily that the blue tracks are mostly moving from the bottom left to the top right with the time for \( g-r \leq 0.3 \), indicating that galaxies grow when in the blue cloud. In the blue cloud, it is seen that there are occasional horizontal tracks, representing mergers that maintain overall color. These are mergers that do not result in red galaxies. The examples of these include the two most massive galaxies in the plot with final stellar masses of \( \sim 10^{11.6} M_\odot \), where there is a major binary merger of \( (10^{11.25} + 10^{11.25}) M_\odot \) at \( g-r = 0.26 \). There are also cases where the tracks temporarily go from northwest to southeast, indicating significant/major mergers triggering starbursts that render the remnant galaxies bluer. This anecdotal evidence that galaxies do not significantly grow mass in the red sequence will be confirmed below quantitatively. Feldmann et al. (2011), using a small sample of simulated galaxies that form a group of galaxies, find that mergers and significant mass growth in galaxies occur, prior to their entering a grouped environment, which is consistent with the findings here. Thus, this “skyrockets” diagram of color–stellar mass evolution in Figure 13 turns out to be a fair representation of typical tracks of galaxies that become red galaxies.

We address the stellar mass growth of red galaxies quantitatively in two different ways. The left panel of Figure 14 shows the histogram of the ratio of stellar mass of red galaxies at \( z = 0.62 \) to their progenitor’s stellar mass at the onset of quenching \( t_q \). We see that the overall stellar mass growth of red galaxies since the onset of quenching is relatively moderate, with the vast majority of galaxies gaining less than 30% of their stellar mass during this period, consistent with observations (e.g., Peng et al. 2010, 2012). There is a non-negligible fraction of galaxies that experience a decline of stellar mass due to tidal interactions and collisions, and 5%–10% of red galaxies gain more than \( \geq 40\% \) of their stellar mass during this period, possibly because of mergers and accretion of satellite galaxies. We do not address red galaxies more massive than \( 10^{12} M_\odot \) because of the lack of a statistically significant red sample. Since these larger galaxies tend to reside at the centers of groups and clusters, there is a larger probability that AGN feedback may play a significant role in them. Empirical evidence suggests that radio jets get extinguished in the near vicinity of the central galaxies in groups/clusters (e.g., McNamara & Nulsen 2007), in sharp contrast to AGNs in isolated galaxies where jets, seen as large radio lobes, appear to deposit most of their energy on scales much larger than the star formation regions. Thus, AGN feedback in the central massive galaxies in clusters/groups may be energetically important to have a major effect on gas cooling and star formation in them (e.g., Omma & Binney 2004). Thus, our neglect of AGN feedback in the simulation cautions us not
to draw any definitive conclusion with respect to this special class of galaxies at this time. The stellar mass growth of individual red galaxies shown in the left panel of Figure 14 contains very useful information. However, it does not address a related but separate question: How does the stellar mass function of red galaxies evolve with redshift? We address this question here. We compute the cumulative stellar mass function of red galaxies at \( z = 0.62 \) and \( z = 0.86 \) separately and show them in the right panel of Figure 14. We see that for red galaxies with stellar masses greater than \( \sim 3 \times 10^{10} M_{\odot} \), when matched in abundance, the stellar masses grow a factor of \( \sim 1.6 \) from \( z = 0.86 \) to \( z = 0.62 \), much larger than 10% (for about 75% of galaxies) as seen in the left panel of Figure 14. We refrain from making a direct comparison to observations in this case, because our limited simulation volume is highly biased with respect to the massive end of the mass function.

We restrict ourselves to a comparative analysis of galaxies in our simulation volume and ask the question of how red galaxies in our simulation volume grow with time. The most important point to note is that this apparent growth of the stellar mass of red galaxies based on abundance matching could not be due to the growth of individual red galaxies in the red sequence, since the actual stellar mass increase since the onset of quenching is moderate, \( \lesssim 10\% \) typically, as seen in the left panel of Figure 14. Physically, this suggests that dry mergers do not play a major role in the “apparent” stellar mass growth of red galaxies, consistent with observations (e.g., Pozzetti et al. 2007). Rather, galaxies grow their stellar mass when they are still in the blue cloud, as illustrated in Figure 13.

A physical picture of galaxy color migration emerges based on our results. The migration from the blue cloud to the red sequence proceeds in a staggered fashion: stellar masses of individual galaxies continuously grow, predominantly in the blue cloud, and blue galaxies over the entire mass range continuously migrate into the red sequence over time. Galaxies migrate from the blue cloud to the red sequence almost vertically in the usual color–magnitude diagram (see Figure 13). For simplicity we will call this type of color migration “vertical tracks,” which correspond most closely to “B tracks” proposed by Faber et al. (2007), with the growth since the onset of quenching being moderate (\( \lesssim 30\% \)).

3.4. Galaxy Age–Mass and Age–Environment Relations

The vertical tracks found have many implications on observables. The first question one asks is this: If galaxies follow the vertical tracks, is the galaxy age–mass relation consistent with observations? We address this question in this subsection. Figure 15 shows a scatter plot of red galaxies in the stellar mass \( M_* \)-mean galaxy formation time \( t_f \) plane at \( z = 0.62 \) (top) and \( z = 1 \) (bottom), where \( t_f \) is the stellar formation time—not the lookback time. The red galaxies are subdivided into two groups: centrals (black circles) and satellites (red circles). For the purpose of comparison to observations, we only show galaxies with a high surface brightness of \( \mu_B < 23 \) mag arcsec\(^{-2} \) (e.g., Impey & Bothun 1997). Several interesting results can be learned.

First, no systematic difference between satellite and central galaxies is visible, supporting earlier findings that there are no appreciable differences between satellites and centrals with respect to the duration from quenching to turning red \( t_q \) (Figure 11). Second, at any given redshift, the brightest red galaxies are relatively “old” (but not necessarily the oldest), with ages of several billion years (age \( t_H = t_q \) and \( t_H = (7.85, 5.94) \) Gyr for \( z = (0.62, 1) \), consistent with observations. Third, at stellar masses greater than \( 10^{10.2} - 10^{10.7} M_{\odot} \), red galaxies have a nearly uniform mean age; the age spread at a given stellar mass of \( \sim 1 \) Gyr is consistent with observations (e.g., Demarco et al. 2010). Fourth, fainter red galaxies are younger than brighter red galaxies in the mass range of \( 10^{10.5} - 10^{10.8} M_{\odot} \); we see that the age difference between the two ends of the mass range is \( \sim 2.5 \) Gyr and \( 1.3 \) Gyr, respectively, at \( z = 0.62 \) and \( z = 1 \), suggesting a steepening with decreasing redshift of the age difference between galaxies of different masses in the red sequence. Demarco et al. (2010) find an age difference between the faint and bright ends of red sequence galaxies of \( \sim 2 \) Gyr at \( z = 0.84 \), in excellent agreement with our results. The physical origin for the steepening with decreasing redshift of the age difference between galaxies of different masses in the red sequence is traceable to the steepening of a specific SFR with stellar mass with decreasing redshift that is,
in a fundamental way, related to the cosmic downsizing phenomenon (Cen 2011a).

It is interesting to note that in Figure 15, scatters notwithstanding, there appears to be a critical stellar mass of $\sim 10^{10.2} - 10^{10.7} M_\odot$, above which the age (or formation time) of red galaxies flattens out to a constant value. At least for the redshift range that we have examined, $z = 0.62 - 1$, this critical stellar mass appears to be redshift-independent. At still higher redshift, we do not have enough statistics to see if this critical mass remains the same. This critical mass is tantalizingly close to the division mass of $\sim 10^{10.5} M_\odot$ discovered by Kauffmann et al. (2003) at low redshift, which appears to demarcate a number of interesting trends in galaxy properties. This physical origin of this mass is unclear and deferred to a future study.

Given the “vertical tracks,” i.e., lack of significant stellar mass growth subsequently to quenching, one may ask this: Is the age–mass relation of red galaxies inherited from their blue progenitors? We will now address this question. To select progenitors of red galaxies at $z = 0.62$, we note that the majority of galaxies that turn red by $z = 0.62$ have $t_{qr} = 1 - 1.7$ Gyr. Thus, we choose galaxies in the redshift range of $z = 0.80 - 0.94$ (8 snapshots with $z = (0.80, 0.82, 0.84, 0.86, 0.88, 0.90, 0.92, 0.94)$), where the Hubble time differences between $z = 0.62$ and $z = 0.80$ and $z = 0.94$ are $(1.0, 1.7)$ Gyr, respectively, enclosing the vast majority of blue progenitors of red galaxies at $z = 0.62$ near the onset of quenching. We separate the blue galaxies into two groups: one group contains the blue progenitors of $z = 0.62$ red galaxies, and the other group other blue galaxies that have not turned into red galaxies by $z = 0.62$. Figure 16 shows the stellar mass $M_*$-mean galaxy formation time $t_f$ scatter plot for blue galaxies at $z = 0.80 - 0.94$ that are progenitors of red galaxies at $z = 0.62$ (top left) and those that do not become red galaxies (top right). Each small group of mostly linearly aligned circles is one galaxy that appears multiple times (maximum is eight). Within the scatters we see that the green dashed line, borrowed from Figure 15, provides a good match to the near constant age at the high mass end for the progenitors of red galaxies. The magenta dots, borrowed from Figure 15, match well the trend for the blue dots in the mass range of $10^{9.5} - 10^{10.5} M_\odot$. These results are fully consistent with our initial expectation based on the observation (of our simulation) of two physical processes: (1) that stellar mass growth is moderate during $t_{qr}$, hence evolution during $t_{qr}$ does not significantly alter the mean star formation time of each galaxy, and (2) less massive forming galaxies have a higher sSFR than massive galaxies, causing a steepening of the age–mass relation at the low mass end. This explains the physical origin of the age–mass relation seen in Figure 15. It is prudent to make sure that these important general trends seen in the simulation are robust. In the bottom two panels of Figure 16, we make a comparison between blue galaxies of two simulations with different resolutions, at $z = 3$. The bottom left panel is from the fiducial simulation with a resolution of $114 h^{-1}$ pc, and the bottom right panel is from an identical simulation with four times better resolution of $29 h^{-1}$ pc. We see that both the age–mass trend at the low mass end and the near constancy of stellar age at the high mass end are shared by the two simulations, suggesting that results from our fiducial simulation are sufficiently converged for the general trends presented at the level of concerned accuracies.

A comparison between the top left and top right panels in Figure 16 makes it clear that the age–mass relation of the blue progenitors of red galaxies at quenching is, to a large
degree, shared by blue galaxies that do not become red galaxies by $z = 0.62$. One subtle difference is that the most massive nonprogenitor blue galaxies are slightly younger than the most massive progenitors of red galaxies, suggesting that the blue progenitors of red galaxies, on “their way” to becoming red galaxies, have started to “foreshadow” quenching effects mildly.

### 3.5. Environmental Dependencies of Various Galaxy Populations

At a given redshift, the cumulative environmental effects are imprinted on the relative distribution of galaxies of different color types and possibly on the properties of galaxies within each type. We now present predictions of our simulations with respect to these aspects. Figure 17 shows distributions of three types of galaxies as a function of distance to the primary galaxy in units of the virial radius of the primary galaxy at $z = 0.62$. All galaxies with a distance larger than 4 virial radii of the primary galaxy are added to the bin with $d/r_c^* = 4–5$. We use the total galaxy population above the respective stellar mass threshold as a reference sample, and distributions in the top (blue galaxies), middle (green galaxies) and bottom (red galaxies) panels are normalized relative to reference sample. Comparing the top (blue galaxies), middle (green galaxies), and bottom (red galaxies) panels, we see clear differences of environmental dependencies of the three types of galaxies. For blue galaxies, there is a deficit at $d/r_c^* \lesssim 2$, which is compensated by a comparable excess at $d/r_c^* \gtrsim 3$. The range of $d/r_c^* = 2–3$ seems to mark the region where there is an excess of green galaxies, about one half of which will become red galaxies during the next 1–1.7 Gyr. It is useful to recall that not all galaxies in the green valley will turn into red galaxies, which perhaps has contributed in part to some of the “irregularities” of the distribution of the green galaxies (middle panel). For red galaxies, we see a mirror image of blue galaxies: there is an excess at $d/r_c^* \lesssim 2$ and a deficit $d/r_c^* \gtrsim 3$. This trend is in agreement with observational indications (e.g., Woo et al. 2013). The emerging picture found here that environment quenching plays a dominant role in quenching galaxies is in accordance with observations (e.g., van den Bosch et al. 2008; Peng et al. 2010, 2012).

Figure 18 shows distributions of three types of galaxies as a function of environmental entropy $S_{300}$. We see that the excess of red galaxies starts at $S_{300} = 100$ keVcm$^2$ and rises toward higher entropy regions for red galaxies. The trend for blue galaxies is almost an inverted version of that for red galaxies. The trend for green galaxies lie in between those for blue and red galaxies, as expected. In Cen (2011a), we put forth the notion that a critical entropy, $S_c = 100$ keVcm$^2$ (at $z = 0.62$ and weakly dependent on redshift), marks a transition to a regime of inefficient gas cooling and hence cold gas starvation, because above this entropy the gas cooling time exceeds the Hubble time. This is borne out by our more detailed analysis here. We also plot (not shown here) distributions of three types of galaxies as a function of the environmental pressure $p_{300}$ and environmental overdensity $\delta_2$, respectively, and find that the trend is broadly similar to that see in Figure 18. Overall, our results are in accordance with the observed density–morphology relation (e.g., Oemler 1974; Dressler 1980; Postman & Geller 1984; Cooper et al. 2006; Tanaka et al. 2007; Bundy et al. 2006; Quadri et al. 2012; Muzzin et al. 2012) and with the general observed trend of the galaxy population becoming bluer or the mean/median specific star formation rate becoming higher toward underdense regions in the local universe (e.g., Lewis et al. 2002; Goto et al. 2003; Gómez et al. 2003; Tanaka et al. 2004; Rojas et al. 2004).

![Figure 16](https://example.com/figure16.jpg)

**Figure 16.** Stellar mass $M_*$-mean galaxy formation time $t_f$ scatter plot for blue galaxies at $z = 0.80–0.94$ that become red galaxies (top left) and those that do not become red galaxies (top right). Each small group of mostly linearly aligned circles is one galaxy that appears multiple times (maximum is 8). The blue dots indicate average values. The green horizontal dashed lines and the magenta dots are the same in the top panel of Figure 15, indicating the mean formation time of the most luminous red galaxies and the average formation time of red galaxies at $z = 0.62$. Bottom left panel: the stellar mass $M_*$-mean galaxy formation time $t_f$ scatter plot for blue galaxies at $z = 3$ with the fiducial resolution 114 h$^{-1}$ pc. Bottom right panel: the stellar mass $M_*$-mean galaxy formation time $t_f$ scatter plot for blue galaxies at $z = 3$ with the four times better resolution of 29 h$^{-1}$ pc. The blue dots indicate average values. (A color version of this figure is available in the online journal.)
Having examined the dependencies of three types of galaxies on environmental variables, we now explore the dependencies on two additional variables: the mass of the halo of the primary galaxy and the secondary to primary galaxy stellar mass ratio. Figure 19 shows fractions of three populations of galaxies in terms of color (red, green, blue) as a function of the secondary to primary galaxy stellar mass ratio. The (left, middle, right) columns are for primary galaxies of halo masses in three ranges ($10^{11}$–$10^{12}$ $M_\odot$, $10^{12}$–$10^{13}$ $M_\odot$, $10^{13}$–$10^{14}$ $M_\odot$), respectively. The four rows from top to bottom are for secondary galaxies within four different radial shells centered on the primary galaxy ($r_c$, [1–2]$r_c$, [2–3]$r_c$, [3–4]$r_c$). We adopt the following language to make comparative statements: the environment quenching is important if the fraction of blue galaxies is less than the fraction of red galaxies and vice versa. We see two separate trends in Figure 19. First, more massive environments are more able to quench star formation; for primary galaxies with halo masses in the range of $10^{13}$–$10^{14}$ $M_\odot$, the quenching appears to extend at least to [2–3]$r_c$, whereas for primary galaxies with lower halo masses, the quenching effect is no longer significant at [2–3]$r_c$. Second, for any given primary galaxy halo mass, the quenching is more effective when the ratio of secondary to primary stellar mass is smaller. That the impact of environmental effects increases with decreasing secondary to primary galaxy stellar mass ratio is perhaps not surprising and is consistent with observations (e.g., Poggianti et al. 2009; Thomas et al. 2010; Wetzel et al. 2012), but it is at odds with the assumption of mass-independent environment quenching in empirical modeling (e.g., Peng et al. 2010). Our finding that quenching is still effective down to at least a halo mass range of $10^{11}$–$10^{12}$ $M_\odot$ for the primary is in agreement with observations (e.g., Wetzel et al. 2012).

Mok et al. (2013), using deep GMOS-S spectroscopy for 11 galaxy groups at $z = 0.8$–1, show that the strongest environmental dependence is observed in the fraction of passive galaxies, which make up only $\sim$20% of the field in the mass range $M_{\text{star}} = 10^{10.3}$–$10^{11.0} M_\odot$ but are the dominant component of groups. If we take the radial range [3–4]$r_c$ as the “field,” we see that the fraction of red galaxies is in the range of 20%–30% (Figure 19), reaching 65%–90% within 2$r_c$, in agreement with Mok et al. (2013). In a large galaxy sample study of a $z = 0.83$ cluster, Patel et al. (2009) find that the red galaxy fraction is 93$\pm$3% in the central region of the cluster and declines to a level of 64% $\pm$ 3% at a projected cluster-centric radius of $\sim$3Mpc. In the right column of Figure 19, for halos in the mass range of $10^{13}$–$10^{14}$ $M_\odot$, we see that within the virial radius the red fractions are in the range of 60%–90%, depending on the satellite to primary galaxy mass ratio, with the overall mean of the red fraction within the virial radius in the range of
Figure 19. Fractions of three populations of galaxies in terms of color (red, green, blue) as a function of the satellite to primary galaxy stellar mass ratio. The (left, middle, right) columns are for primary halo mass of \(10^{11} - 10^{12} \), \(10^{12} - 10^{13} \), \(10^{13} - 10^{14} \). The four rows from top to bottom are for satellites within four different radial shells centered on the primary galaxy (\(r_{sv} \), \(1-2 r_{sv} \), \(2-3 r_{sv} \), \(3-4 r_{sv} \)).

(A color version of this figure is available in the online journal.)

Figure 20. Specific SFR of blue galaxies at \(z = 0.62 \) as a function of each of the four environmental variables. Black circles are for central galaxies and red for satellites. The size of each circle indicates the stellar mass of a galaxy, as shown in the legend. The blue dots indicate median values.

(A color version of this figure is available in the online journal.)

80%-90%. The more central region has a red fraction higher than 80%-90%, consistent with their observation. Patel et al. (2009) also find that the environmental effect extends even beyond 3Mpc, which is about 3 virial radii for their cluster. From the right column in Figure 19, we see that red galaxies dominate up to 3 virial radii, in reasonable accordance with observations.

Some of our results are not necessarily straightforward enough to enable one to see the big picture in the absence of simulations and detailed analyses. For example, the interpretation
by Presotto et al. (2012) that the rate of SF quenching is faster in groups than in the field may be interpreted differently from the context of our results. The excess of quenched galaxies in group environments is larger than in less dense environments as seen in Figures 17 and 18, which is consistent with observations (Presotto et al. 2012). However, we show that the quenching time depends weakly on environment as shown in Figure 11.

In other words, our simulations suggest the following picture: environment quenching of star formation in galaxies is more efficient in more hostile environments (closer to a larger galaxy, higher density, high pressure, high entropy, etc.), but it is not faster, for the most part. This point has been noted based on observational data (e.g., Andreon 1996; Newman et al. 2013).

Given the unambiguous environmental effects on the relative distributions of galaxy colors, we ask the following reverse question: Can we decipher environmental effects on a set of blue galaxies alone across different environments at any given epoch? Figure 20 shows the specific SFR (sSFR) distributions of blue galaxies as a function of the four environmental variables at $z = 0.62$. While one sees trends of the overall number of galaxies with respect to each of the environmental variables, as already shown in Figures 17 and 18, there is no strong visible trend of the mean value of sSFR with respect to environment for blue galaxies. To put it a little differently, the variations of the sSFR among blue galaxies at any given mass are sufficiently large, and the quenching effects on galaxies at a given sSFR and stellar mass are sufficiently varied so that at any environment the scatter in sSFR at a given stellar mass is larger than the difference in averaged sSFR across different environments. We attribute this result physically to the combined effects of the substantial nonuniformity of the properties of blue galaxies prior to entering the environmental “spheres” of influence and substantial nonuniformity of the environment on galaxies illustrated in Figures 5 and 6. This result—that the intrinsic properties of star-forming galaxies appear to be independent of environment—is, however, in accordance with observations (e.g., Ideue et al. 2012; Wijesinghe et al. 2012; Brodwin et al. 2013).

4. CONCLUSIONS

Utilizing ab initio LAOZI simulations of the standard cold dark matter model, we perform a chronological and statistical study of the formation and evolution of (1664, 367, 1296) (blue, green, red) galaxies of stellar mass $10^{9.5}-10^{12.5} M_\odot$ at $z = 0.62$. The simulations have an ultra-high resolution of $\lesssim 114$ h$^{-1}$ pc with an additional calibration run of resolution 29 h$^{-1}$ pc. The soundness of the treatment of relevant physical processes, especially the uncertain feedback processes from star formation, is verified and confidence is built by comparisons with a large set of independent observations over a range of scales and redshift. Here we examine some global trends of the formation and evolution of galaxies, focusing on galaxy star formation quenching and color migration. We do not include AGN feedback, in part because of its large uncertainties but primarily because of our intention to focus on external effects. We summarize the main points of our findings below.

1. Environment quenching is shown to be responsible for making the vast majority, if not all, of red galaxies. Two environmental conditions appear to be necessary in the making of a typical red galaxy: ram pressure stripping and cold gas starvation. The ram pressure stripping disconnects a galaxy from its large-scale cold gas reservoir, while existing cold gas in the central ($\sim 10$ kpc) region is unaffected by ram pressure but is consumed by diminishing SF with an exponential time of several hundred Myr. Subsequently, gas starvation in the high-velocity environment guards against further significant SF, pushing it through the green valley to the red sequence. The total duration from the initial sharp drop of the SFR to the time of entry into the red sequence is $\sim 0.6-3$ Gyr (see Equation (2) for a fitting formula), with the median of 1.2 Gyr for red galaxies at $z = 0.62$. We suggest that adopting a spread in quenching time in the semi-analytic modeling may result in an improved treatment in that approach.

2. The radius of a galaxy’s quenching sphere depends on the properties of the infalling galaxy being quenched, causing large variations in the quenching timescales at a given radius and large variations in the quenching radius at a given mass of infalling galaxy. Nevertheless, the vast majority of red galaxies are found to be within three virial radii of a larger galaxy at the onset of quenching, when the specific star formation rate experiences the sharpest decline to fall below $(10^{-2}-10^{-1})$ Gyr$^{-1}$ (depending on the redshift when it occurs). The exponential decay time of the SFR at the onset of quenching is, on average, about a factor of two shorter for events occurring within the virial radius of the quenching galaxy than for those outside the virial radius of the quenching galaxy, which may be evidence of enhanced quenching with the additional aid of tidal stripping when the onset of quenching takes place within the virial radius. However, it is stressed that the overall duration from the onset of quenching to the time entering the sequence does not depend much on environment.

3. Not all galaxies in the green valley migrate to the red sequence; (40%, 40%, 48%) of green valley galaxies of stellar mass $\geq (3 \times 10^9, 10^{10}, 3 \times 10^{10}) M_\odot$ do not proceed to become red galaxies at $z = 0.62$ after having turned green for $\geq 2$ Gyr. For those galaxies that are en route to the red sequence, the time spent in the green valley is brief, typically 300 Myr.

4. Throughout the quenching period and the ensuing period in the red sequence, galaxies follow nearly vertical tracks in the color–stellar mass diagram, which correspond most closely to “B tracks” proposed by Faber et al. (2007). In contrast, individual galaxies of all masses grow most of their stellar masses in the blue cloud, prior to the onset of quenching, and progressively more massive blue galaxies with already relatively old mean stellar ages continue to enter the red sequence. Consequently, correlations among observables of red galaxies—such as the age–mass relation—are largely inherited from their blue progenitors. The age–mass relation of simulated red galaxies is found to be in good agreement with observations.

5. While environmental effects are responsible for producing the environmental dependence of the color makeup of the galaxy population, the average properties (e.g., SFR) of blue galaxies as a subpopulation display little dependence on the environment, which is in agreement with observations. Overall, the excess (deficit) of red (blue) galaxies occurs within about three virial radii, in good agreement with a wide range of observations. Our detailed examination suggests that the excess of quenched galaxies in a progressively denser environment (groups, clusters, etc.) is, for the most part, a result of quenching being more efficient.
but not faster, on average, in a denser environment. Physically, this comes about because most of the time it takes to drive a blue star-forming galaxy to the red sequence is spent during the starvation phase and not the initial gas removal phase by ram pressure stripping that displays a stronger dependence on environment.

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