The growth of red sequence galaxies in a cosmological hydrodynamic simulation

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ABSTRACT
We examine the cosmic growth of the red sequence in a cosmological hydrodynamic simulation that includes a heuristic prescription for quenching star formation that yields a realistic passive galaxy population today. In this prescription, haloes dominated by hot gas are continually heated to prevent their coronae from fuelling new star formation. Hot coronae primarily form in haloes above $\sim 10^{12}$ M$_\odot$, so that galaxies with stellar masses $\sim 10^{10.5}$ M$_\odot$ are the first to be quenched and move on to the red sequence at $z > 2$. The red sequence is concurrently populated at low masses by satellite galaxies in large haloes that are starved of new fuel, resulting in a dip in passive galaxy number densities around $\sim 10^{10}$ M$_\odot$. Stellar mass growth continues for galaxies even after joining the red sequence, primarily through minor mergers with a typical mass ratio $\sim 1:5$. For the most massive systems, the size growth implied by the distribution of merger mass ratios is typically approximately two times the corresponding mass growth, consistent with observations. This model reproduces mass–density and colour–density trends in the local Universe, with essentially no evolution to $z = 1$, with the hint that such relations may be washed out by $z \sim 2$. Simulated galaxies are increasingly likely to be red at high masses or high local overdensities. In our model, the presence of surrounding hot gas drives the trends with both mass and environment.

Key words: galaxies: evolution – galaxies: formation.

1 INTRODUCTION
A substantial fraction of galaxies today inhabit a tight locus in colour–magnitude space known as the red sequence. Such galaxies typically have elliptical morphologies, little or no star formation, little cold gas, and live in dense environments. They host the majority of stellar mass in the local universe (Hogg et al. 2002), and therefore are a critical population for understanding the global evolution of galaxies across cosmic time.

Despite a growing wealth of data, the origin of red sequence galaxies is still not fully understood. In the currently favoured cold dark matter (CDM) paradigm, massive galaxies should be surrounded by haloes of hot gas that can potentially cool and fuel new star formation (White & Frenk 1991). Yet, these galaxies show little cold gas or ongoing star formation. Debate continues as to what physical mechanisms can halt star formation and keep it halted for much of cosmic time, with recent work favouring feedback from active galactic nuclei (AGN) as the primary energy source (e.g. Croton et al. 2006; Hopkins et al. 2008).

Deep surveys have begun to place constraints on bright passive galaxies over cosmic time-scales, out to $z > 2$ (e.g. Bell et al. 2004; Brown et al. 2007; Faber et al. 2007; Cool et al. 2008; Kriek et al. 2008; Stutz, Papovich & Eisenstein 2008; Brammer et al. 2009; Taylor et al. 2009; Marchesini et al. 2010; Whitaker et al. 2010), and recent surveys should probe down to stellar masses $\sim 10^9$ M$_\odot$ at such redshifts [e.g. Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS); Grogin et al. 2011; Koekemoer et al. 2011]. Current data indicate that the red sequence has grown by two times from $z \sim 1$ to 0, but the most massive galaxies were already in place 7+ Gyr ago. Furthermore, high-resolution imaging has revealed that passive galaxies are typically much smaller at $z > 1$, by factors of $\sim 5$ compared to their present-day descendents (Daddi et al. 2005; van Dokkum et al. 2008, 2010). These data provide strong constraints on passive galaxy formation models, and only recently have such constraints been explored in the context of hierarchical models (Khochfar & Silk 2006; Fan et al. 2008; Nipoti et al. 2009, 2012; Naab, Johansson & Ostriker 2009; Oser et al. 2010, 2012; Shankar et al. 2010; Cimatti, Nipoti & Cassata 2012).

Numerous physical processes are thought to contribute to the formation and evolution of passive galaxies, and many potential effects have proven difficult to rule out. Gas-rich galaxy mergers that induce a starburst and rapid black hole growth may drive the initial quenching of massive red galaxies (Springel, Di Matteo & Hernquist 2005; Hopkins et al. 2006, 2008). Alternatively, hot gaseous coronae...
that form in haloes above $\sim 10^{12} M_\odot$, supplemented by additional heating from an AGN or another energy source, may starve galaxies of fuel for star formation (Birnboim & Dekel 2003; Kereš et al. 2005; Croton et al. 2006; Cattaneo et al. 2006; Dekel & Birnboim 2006). Among satellite galaxies additional processes may drive quenching: starvation and/or ram-pressure stripping by the hot intergalactic medium, or glancing interactions between galaxies (Gunn & Gott 1972; Richstone 1976; Larson, Tinsley & Caldwell 1980; Moore, Lake & Katz 1998; Abadi, Moore & Bower 1999; Quilis, Moore & Bower 2000; Bekki, Couch & Shioya 2002). All these processes may act in combination to form passive galaxies as observed.

Once ‘red and dead’, the evolution of these galaxies may be deceptively complex. Although there is little or no new star formation, the stellar population sheds $\sim 1/2$ of its mass via stellar winds (Jungwiert, Combes & Palouš 2001; Bruzual & Charlot 2003, hereafter BC03). Mergers can alter galaxy structure (e.g. Barnes 1990), change the characteristic size of the galaxy (Cox et al. 2006), strip stars into the intracluster medium (ICM) (Gallagher & Ostrik 1972; Murante et al. 2004) and possibly add cold gas. Such processes may all contribute to the observed evolution of the red sequence.

In this work, we study passive galaxy growth from high redshift until today using cosmological hydrodynamic simulations. These simulations incorporate physically motivated but heuristic quenching mechanisms (described in Gabor et al. 2011) that yield a $z = 0$ population of passive galaxies whose colour and luminosity distributions match observations. In particular, we include a prescription where we ensure that haloes dominated by hot gas are continuously heated to keep circum-galactic gas hot. This simple and extreme prescription, approximating the effects of a heat source such as an AGN radio jet, successfully cuts off the fuel supply for star formation in massive haloes which eventually yields passive galaxies. Although significant challenges remain for our favoured model, it provides a general qualitative guide for models where hot massive haloes are the main drivers of passive galaxy formation. While Gabor et al. (2011) focused on the $z = 0$ red galaxy population and compared various quenching mechanisms, here we focus on our most successful quenching mechanism and its implications for passive galaxy evolution from high redshift until today. Our model should not be considered physically correct in detail, but rather as broadly illustrative of the impact of some (unspecified) quenching mechanism that keeps hot halo gas hot on passive galaxy evolution over the past 10 billion years.

We begin by presenting an overview of our simulations in Section 2. Then we present our results, beginning in Section 3 where we examine number density and colour evolution, Section 4 where we look at how passive galaxies grow in mass and size via mergers, and Section 5 where we study mass and colour evolution versus environment. Finally, we summarize and discuss our conclusions in Section 6.

## 2 SIMULATIONS

### 2.1 Simulation methodology

We analyse the same cosmological hydrodynamic simulations described in Gabor et al. (2011). For completeness, we summarize the simulations here. They were run with an extended version of the N-body + smoothed particle hydrodynamics code GADGET-2 (Springel 2005). In addition to the basic N-body and hydrodynamical calculations, our version of the code includes sub-resolution modelling of gas cooling, star formation, a model for chemical enrichment via asymptotic giant branch (AGB) stars and both Type Ia and core-collapse supernovae, galactic winds associated with star formation, and simple prescriptions for quenching star formation.

We include both primordial and metal-line cooling assuming collisional ionization equilibrium (Sutherland & Dopita 1993), with the metallicities self-consistently tracked within simulations (see Oppenheimer & Davé 2006, 2008 for details). We include heating from a metagalactic photo-ionizing background (Haardt & Madau 2001), assuming all particles are optically thin.

For star formation, we employ the two-phase model of Springel & Hernquist (2003) based on the analytic description of McKee & Ostriker (1977). Gas particles above a density threshold of $0.13 \text{ cm}^{-3}$ are treated as cold, star-forming clouds embedded within a hot diffuse medium, and they form stars on a time-scale consistent with the observed relation to surface gas density (Kennicutt 1998). Star-forming gas particles are converted into collisionless star particles stochastically, with a probability derived from the star formation rate.

As a gas particle is undergoing star formation, it self-enriches with metals from core-collapse supernovae. Furthermore, star particles share energy, mass and metals with neighbouring gas particles as a result of stellar mass loss from AGB stars and Type Ia supernovae. Stellar mass loss is calculated by assuming a Chabrier (2003) initial mass function, applying the stellar population models of BC03, which account for the mass lost by a stellar population at discrete times after the initial star formation event. We use Type Ia supernova rates from Scannapieco et al. (2006), and each such supernova results in the production of metals (mainly iron) that are shared with neighbouring gas particles.

Our code further includes feedback in the form of galactic winds driven by star formation (Oppenheimer & Davé 2006, 2008). Just as a star-forming gas particle has some probability of being converted to a star particle, it has a probability of being kicked in a wind, which is given by $\eta$ (the mass loading factor) times the star formation probability. A wind particle is expelled from its host galaxy at a velocity $v_w$, typically a few hundred km s$^{-1}$. The velocities are chosen to match observations of local galaxy winds (Martin 2005; Rupke, Veilleux &Sanders 2005) and those seen at higher redshifts (e.g. Steidel et al. 2010). In particular, $v_w \propto$ the galaxy velocity dispersion, and $\eta \propto$ the galaxy circular velocity as calculated from an on-the-fly galaxy finder (Oppenheimer & Davé 2008); these scalings are predicted for momentum-driven winds (Murray, Quataert & Thompson 2005). A galaxy in a $10^{12} M_\odot$ halo at $z = 1$ typically expels a wind with $v_w \approx 500 \text{ km s}^{-1}$ and $\eta \approx 1.7$ (Oppenheimer et al. 2010). Once launched, winds are decoupled from the hydrodynamic calculation until they reach a density 10 per cent of the critical density for star formation, up to a maximum duration of 20 kpc $v_w^{-1}$. With this prescription, our simulations match a broad array of observational constraints on star-forming galaxies and the intergalactic medium (Davé, Finlator & Oppenheimer 2006, 2007; Oppenheimer & Davé 2006, 2008; Finlator, Davé & Oppenheimer 2007; Finlator & Davé 2008; Oppenheimer et al. 2010).

Despite their broad success, winds driven by star formation generally do not result in the formation of red and dead galaxies. We incorporate an additional heuristic quenching model specifically to solve this problem (Gabor et al. 2011). For this model, we run a spherical overdensity algorithm on-the-fly to identify galaxy haloes and distinguish gas above and below 250,000 K in each galaxy’s halo. In haloes with $> 60$ per cent of all gas above this temperature cut-off, we apply constant heating (at every time-step) to all circum-galactic halo gas to force it to remain at the halo virial temperature. We exclude star-forming gas particles from this heating.
Such heating could plausibly result from an AGN radio jet, but our model in fact uses more energy than thought to be available from observed AGN sources (Gabor et al. 2011). Other possible heat sources include cosmic rays (e.g. Mathews 2009) or gravitational heating by infalling gas clumps (Dekel & Birnboim 2008; Khochar & Ostriker 2008; Birnboim & Dekel 2011). We remain agnostic about the exact mechanism, and instead examine whether an effective heating source can lead to a realistic population of quenched galaxies. We emphasize that our simulations do not track the growth of supermassive black holes.

The heating we apply to circum-galactic gas is sufficient to prevent it from condensing on to the galaxy, thus starving the galaxy of new fuel for star formation. Over 1–2 Gyr, star formation will exhaust any remaining cold gas, and star formation will cease. This model results in a bimodal colour distribution of galaxies, and red galaxy luminosity functions that match observations of the local Universe. Although the model has some difficulties (like the required energy mentioned above), it should be a good representation of models where galaxies are quenched due to starvation enabled by their surrounding hot coronae.

2.2 Runs and galaxy identification

For this paper, we use a simulation of a 48 $h^{-1}$ comoving Mpc random cosmological cube with 256$^3$ dark and 256$^3$ gas particles that incorporates all the above physics. We use a Wilkinson Microwave Anisotropy Probe concordance cosmology (Komatsu et al. 2009) with $H_0 = 100 h = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, matter density $\Omega_m = 0.28$, baryon density $\Omega_b = 0.046$, a cosmological constant $\Omega_{\Lambda} = 0.72$, root mean square mass fluctuation at separations of 8 Mpc $\sigma_8 = 0.82$, and a spectral index of $n = 0.96$. Our simulation uses a gravitational softening length of 3.75 $h^{-1}$ kpc. The initial gas particle mass is $1.2 \times 10^3 M_{\odot}$, the typical star particle mass is half that, and our simulation results in $\sim$3000 resolved galaxies at $z = 0$. We have also used a simulation with $2 \times 384^3$ particles and the same volume to explicitly check that our main results are resolution-converged, as expected from previous work (Finlator et al. 2006; Davé, Oppenheimer & Finlator 2011). We note that high-resolution zoom simulations of individual galaxies can produce quenched galaxies without explicit feedback, but they have too much stellar mass (Naab et al. 2007).

We save snapshots of the simulation at 108 redshifts, starting at $z = 30$ and ending at $z = 0$. The time between snapshots ranges from a few tens of Myr at high redshift to $\sim$300 Myr at low redshift. The snapshots contain information for simulation particles, such as position, velocity, mass, metallicity, gas density, gas temperature and star formation rate. From these particle data, we determine galaxy properties to compare with observables.

We use SKID to identify galaxies (cf. Gelb & Bertschinger 1994; Kereš et al. 2005). SKID provides a list of member particles (star and star-forming gas) for each simulated galaxy. The sum of member star particle masses is then the galaxy stellar mass, and the instantaneous star formation rates of the gas particles are summed to give the star formation rate of the galaxy.

We then calculate galaxy spectra using the models of BC03, as in Finlator et al. (2006). We treat each star particle as a single stellar population with an age and metallicity determined directly in the simulation. By adding up the spectra of all star particles within a galaxy, we obtain the spectrum of that galaxy, from which we measure galaxy colours and magnitudes in various bands. Since we focus on the passive galaxy population that is thought to be mostly dust-free (Lauer et al. 2005), we ignore dust reddening and extinction.

2.3 Building merger trees

Beyond knowing galaxy properties at a given redshift, we wish to study the histories of individual galaxies as they evolve. For this we must connect each galaxy at $z = 0$ to its progenitor galaxies at earlier redshifts, i.e. build a merger tree. We do so by determining, for every star particle in a given galaxy, which galaxy from an earlier snapshot that star particle lived in. If the star formed recently it would not have lived in any previous galaxy. By tracing star particles in this way, we determine the immediately preceding progenitors of each galaxy. Galaxies with multiple progenitors must have undergone a merger (or at least some galaxy interaction, such as stellar stripping).

Creation of a merger tree from a cosmological simulation involves handling a number of pathological circumstances owing to the stochastic nature of the gas and star particles. A common annoyance is that if two galaxies fly by each other in a close encounter, SKID (and most other galaxy finders) will often identify them as a single galaxy during one or a few time-steps, but then again as separate galaxies at later times. Sometimes star particles are not assigned to any group. While these issues do not affect the majority of galaxies and hence do not strongly impact the overall results, they must nevertheless be handled in an appropriate manner.

To surmount these difficulties, we follow strategies described in Maller et al. (2006), who dealt with the same issues. If a star particle is not assigned to any SKID groups at a given time-step, we trace its history through earlier time-steps to find the last galaxy it was in, and assign it to the descendant of that galaxy. When two SKID groups at one time-step have a single common progenitor at an earlier time-step, we assume that the two groups are a merging pair and assign them to the same galaxy.

The above prescription assumes that once galaxies are joined by SKID, they will eventually merge. But some fly-by interactions will not lead to mergers. To account for this, we identify galaxies at $z = 0$ that are composed of multiple SKID groups and separate those groups into distinct galaxies. We find the earliest time-step when both groups’ stars are assigned to the same galaxy, and from then on assign a new galaxy ID to those stars in the smaller of the two groups. Once every star particle is assigned to a galaxy at every time-step, we have the full merger history.

2.4 Environment measures

In order to study where red galaxies emerge in our simulation, we measure the local galaxy density around SKID galaxies. We use two density measures. An intuitive and simple approach is to count the number of simulated galaxies within $1 h^{-1}$ Mpc of the galaxy of interest (Blanton 2006). For some purposes this measure is too noisy, as it places galaxies into discrete bins of density, and some galaxies have few neighbours within $1 h^{-1}$ Mpc. Thus, as an alternative we use SMOOTH, which calculates the mean density at each galaxy’s location after smoothing over the nearest 16 galaxies with a spline kernel (similar to an SPH density calculation). This allows us to quantify low densities less stochastically than by simply counting galaxies within some fixed distance. In some cases, we

1 http://www-hpcc.astro.washington.edu/tools/skid.html

2 http://www-hpcc.astro.washington.edu/tools/smooth.html

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use a galaxy’s local overdensity measured relative to the mean resolved galaxy density in our simulation volume. Based on numerous tests, our density estimator based on SMOOTH is comparable to and correlated with common observable density estimators such as a fifth-nearest neighbour density (e.g. Kovač et al. 2010).

3 EVOLUTION IN COLOUR AND NUMBER DENSITY

3.1 Colour–mass diagrams and stellar mass functions

In this section we examine how colours and number densities (parametrized via the galaxy stellar mass function) evolve with redshift in our simulations. We note that our simulations do not perfectly match present-day observations of passive galaxies, as detailed in Gabor et al. (2011). For instance, the colours are slightly too blue and the red sequence does not have the correct slope, owing to an underproduction of massive galaxies’ metallicities by ~50 per cent (see Gabor et al. 2010, 2011, for a full discussion). Nonetheless, our simulations clearly identify two general trends in passive galaxy evolution. First, passive galaxies emerging at $z > 2$ are at the massive end of the galaxy stellar mass function, followed shortly by small satellites, then finally the intermediate region of $10^{10} M_{⊙}$ galaxies. Secondly, the most massive red galaxies in our model grow substantially at late times.

Fig. 1 shows colour–mass diagrams and galaxy stellar mass functions for simulated galaxies at redshifts 0, 0.3, 1 and 2. The $g - r$ colours are rest-frame Sloan Digital Sky Survey (SDSS) filter bands (Fukugita et al. 1996; York et al. 2000), and do not include any correction for obscuration due to dust – these are intrinsic colours. Dust reddening can induce large changes in galaxy colours (see Gabor et al. 2010), but for a given simulated galaxy the dust reddening is highly uncertain. We thus focus on the more robust intrinsic properties of simulated galaxies.

Our quenching model leads to an obvious bimodality in (intrinsic) galaxy colours, which corresponds to a bimodality between star-forming and quiescent galaxies. We divide the galaxy population into blue and red using a straight line in $g - r$ colour versus $r$ magnitude space in the same way as in Gabor et al. (2011). We evolve the normalization (but not the slope) of our colour separation in a simple linear way that approximately accounts for passive evolution: $y_{\text{sep}}(z) = y_{\text{sep}}(z=0) - 0.1z$. Here $y_{\text{sep}}$ is the $y$-intercept (i.e. colour) of the line of separation, and $z$ is the redshift. The hatched region on the left of the figure denotes the mass range of galaxies that may be inadequately resolved. The colour–mass diagrams show strong growth in the passive galaxy population from $z = 2 \rightarrow 0$. Both the blue and red galaxy populations become redder with time, at roughly the same rate.

The lower set of panels of Fig. 1 shows galaxy stellar mass functions separated into blue (dashed line) and red (solid line) populations. We plot mass function observations taken from Drory et al. (2009) and Brammer et al. (2011), who likewise split galaxies into star-forming and quiescent populations (blue versus red points). Since dust reddening adds difficulty and complexity to the separation of star-forming and quiescent galaxies (and since we use different separation criteria), we emphasize that comparisons with observations are only qualitative. We note that Brammer et al. (2011) paid particular attention to separating truly passive from dusty star-forming galaxies.

The simulated blue galaxy stellar mass function evolves only weakly with redshift, but the red galaxy mass function undergoes drastic growth from $z > 2$ to 0. The buildup of passive galaxies reflects the quenching of star-forming galaxies due to starvation in our model (see Gabor et al. 2011). The red sequence grows from mostly non-existent at $z \sim 5$ to dominating the galaxy population at $z \sim 0$. The mass functions clearly show that the most massive galaxies are the first to become red, followed by low-mass galaxies that turn out to be satellites to the massive ones. This directly results from the fact that the most massive galaxies in our simulations are the first to form a corona of hot gas. Massive galaxies have massive dark matter haloes, and only massive dark matter haloes form stable hot gas coronae (Birnboim & Dekel 2003).

Figure 1. Redshift evolution of colour–mass diagrams (top row) and galaxy stellar mass functions (bottom row). Redshift increases from left to right, as labelled. Red and blue galaxies are separated using a redshift-dependent cut, as illustrated by the red and blue colour-coding in the CMD. In the mass function panels, solid lines denote the simulated red sequence, dashed lines the simulated blue cloud, and observed data points are taken from the literature. The hatched region indicates poorly resolved galaxies. Massive red galaxies are present at $z = 2$, but not in sufficient numbers compared to observations. There is a dearth of intermediate-mass galaxies ($\sim 10^{10} M_{⊙}$) that is more pronounced at higher redshifts.

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3.2 A dearth of passive galaxies at $M_* \sim 10^{10} \, M_\odot$

Examination of Fig. 1 reveals a characteristic ‘dip’ in the simulated red galaxy mass function at $M_* \approx 10^{10} \, M_\odot$, which persists at all redshifts but is more prominent at high redshifts. The red mass function peaks at high masses $M_* \approx 10^{10.6} \, M_\odot$, declines to intermediate masses $M_* \approx 10^{10.0} \, M_\odot$, and then rises again to low masses $M_* \lesssim 10^{9.8} \, M_\odot$.

The first passive galaxies form at the massive end by $z \approx 3$ (which is an underestimate since our limited simulation volume does not probe the most massive structures at $z > 3$). Soon thereafter, small satellites of the first quenched galaxies become red as well, owing to starvation of gas in growing hot haloes (Simha et al. 2009). Intermediate-mass galaxies with $M_{\text{stellar}} \approx 10^{10} \, M_\odot$ are the last to quench, filling in the gap between the centrals and satellites such that by $z \approx 0$ this bimodality within the red sequence is not so evident. Therefore, a strong prediction of this quenching mechanism is that there is a distinct gap between the massive and low-mass ends of the red sequence that becomes more pronounced with redshift.

A variety of observational studies already suggest that there are fewer red galaxies at intermediate mass than at the high-mass peak, especially at high redshift, as our simulated mass functions imply (Stutz, Papovich & Eisenstein 2008; Drory et al. 2009; Rudnick et al. 2009, 2012; Yang, Mo & van den Bosch 2009; Mortlock et al. 2011; Tal et al. 2012). At $z \approx 0$, recent studies show a slight decline in the red galaxy mass function from high to intermediate masses, requiring a characteristic double-Schecter function to get a good fit (Baldry et al. 2008; Yang et al. 2009; Peng et al. 2010; Baldry et al. 2012). Unlike our simulation, however, observations do not typically show an upturn towards lower masses (but see Drory et al. 2009; Yang et al. 2009). Some semi-analytic models show an analogous mass bimodality for elliptical galaxies (De Lucia, Fontanot & Wilman 2012a), although the driving processes are likely different.

Although further observations will be required to confirm that there are more high-mass than intermediate-mass quenched galaxies (especially at higher redshift), this trend naturally emerges from our quenching model. Our simple model, where hot gas dictates the formation of the red sequence, provides a compelling physical picture, which we describe next.

3.3 Central and satellite evolution along the red sequence

The separation in mass range between central and satellite galaxies along the red sequence is more pronounced at earlier epochs, leading to a sort of bimodality along the red sequence itself. This is naturally understood within a hierarchical structure formation model, as we outline here.

In our model, the initial emergence of the massive red sequence is directly tied to the requirement that a galaxy’s halo be dominated by hot gas for quenching to begin. Galaxy evolution models have long predicted that gas in the haloes of galaxies should be virialized and thus hot (Rees & Ostriker 1977; Silk 1977; White & Rees 1978). Gas in haloes with masses below a few $10^{11} \, M_\odot$, however, will have short cooling times, so that it never reaches the virial temperature of the halo (Binney 1977; White & Frenk 1991; Birnboim & Dekel 2003; Kereš et al. 2005). In our simulations with metal-line cooling the threshold for a hot gas-dominated halo is $\sim 10^{12} \, M_\odot$ (Gabor et al. 2010), with little or no redshift evolution.

The key assumption in our model is that in such hot-gas dominated haloes, gas is very inefficiently deposited on to the galaxy, likely owing to the contribution of some preventative feedback process(es) like AGN heating (e.g. Bower et al. 2006; Cattaneo et al. 2006; Croton et al. 2006; Dekel & Birnboim 2006; Birnboim, Dekel & Neistein 2007). Since galaxy stellar masses are well-correlated with halo masses below the cut-off for quenching, only central galaxies with the highest stellar masses will live in hot haloes at early times.

As the universe evolves and individual haloes grow, more galaxy haloes become massive enough to support hot coronae. Massive central galaxies thus continue to move on to the red sequence. Our hot gas fraction cut-off of 60 per cent roughly corresponds to a stellar mass of about $10^{10.5} \, M_\odot$, though there is significant scatter. Once galaxies exceed this stellar mass, they will tend to migrate towards the red sequence over the span of 1–2 Gyr. We note that this mass cut-off is unlikely to be universal at $z > 2$, since there are seen to be a number of star-forming galaxies with stellar masses approaching and even exceeding $10^{11} \, M_\odot$ (e.g. Daddi et al. 2007). These galaxies may be fed by cold streams that are dense enough to penetrate the hot halo (Dekel, Sari & Ceverino 2009).

What happens with satellite galaxies? When a central galaxy becomes quenched by its own hot corona, its satellites are likely to be embedded within that hot corona as well. Based on our criteria for quenching, these satellites will be quenched as well. In Lambda cold dark matter (LCDM), the most massive subhalo is typically less than 10 per cent of the mass of its parent halo (Gao et al. 2004) – when a central galaxy of mass $10^{10.5} \, M_\odot$ is quenched, its satellites will usually be $< 10^{9.5} \, M_\odot$. This creates a ‘gap’ where there are no red galaxies around $10^{10} \, M_\odot$.

As time progresses, massive quenched haloes merge with nearby haloes owing to hierarchical growth. For example, a star-forming galaxy with a mass of $M_\odot = 10^{10} \, M_\odot$ may fall into a more massive, group-sized halo. As the smaller halo falls into the region dominated by hot gas, its central galaxy becomes a satellite and is quenched by the hot ICM on a 1–2 Gyr time-scale (Simha et al. 2009; Skibba 2009; Wetzel et al. 2012). These infalling (former) central galaxies begin to populate the intermediate-mass portion of the red sequence. Therefore, hierarchical growth combined with starvation by the hot corona results in a gradual ‘filling in’ of the intermediate-mass red sequence. These trends will be explored in more detail, particularly in relation to environment, in Section 5.

In summary, our model predicts that galaxies with $M_{\text{stellar}} \sim 5 \times 10^{10} \, M_\odot$ are the first to become passive. Galaxies in the ‘gap’ at $M_{\text{stellar}} \sim 10^{10} \, M_\odot$ catch up with time. The key feature driving these trends is that our quenching mechanism, tied to the hot gas corona that form in haloes $\sim 10^{12} \, M_\odot$, selects a characteristic mass for passive galaxies. That is, once a star-forming galaxy achieves a mass $\gtrsim 10^{10.5} \, M_\odot$, it will become quenched and move to the red sequence. Less massive galaxies are only quenched as satellites (or nearby haloes) of more massive haloes. More massive red galaxies can only be obtained via merging. While quantitative details may vary with parameter choices, these are generic outcomes for hierarchical quenching models keyd to a critical halo mass.

3.4 Paths to the red sequence

Here we focus on the path of individual galaxies in colour–mass space: given a red galaxy at $z > 0$, what path did it take to get there? It turns out that massive galaxies in our models follow paths much like those in the schematic diagram of Faber et al. (2007): they move on to the red sequence at masses near the turnover in the mass function, then grow further through mergers and accretion of satellite galaxies.
Figure 2. Example evolutionary paths in the colour–mass diagram. We show the paths of three galaxies (coloured lines) as they evolve through the colour–mass diagram, as represented by \( z = 0 \) galaxies (small points) in the background. This is analogous to the schematic diagram of Faber et al. (2007). Dots indicate redshifts along the evolutionary paths, as labelled for the most massive galaxy. Galaxies grow in stellar mass along the blue sequence, then move vertically to the red after quenching. Once on the red sequence, galaxies grow only via mergers and accretion of satellites. Such growth can be substantial, as for the path of the most massive galaxy shown.

In Fig. 2 we show the paths of three typical galaxies (coloured lines) in the colour–mass diagram. We plot a background of simulated galaxies at \( z = 0 \) (points), and we correct for passive evolution of colours for the galaxy paths in the same way that we evolved our line separating blue and red galaxies (Section 3.1). We do not include dust reddening.

All three of these galaxies build stellar mass via star formation for several Gyr before moving on to the red sequence. Once quenched, they stop building stellar mass and cross vertically and rapidly over the green valley to the red sequence in \( \lesssim 2 \) Gyr (see the star formation histories in Gabor et al. 2011). The least massive galaxy makes this transition at late times (\( z \sim 0.1 \)), and does not change in mass or colour after reaching the red sequence because it does not have time to undergo mergers. The most massive galaxy, in contrast, reaches the red sequence at \( z \sim 0.5 \) when its mass is several \( 10^{10} M_\odot \), and then continues to grow in mass along the red sequence via mergers, eventually obtaining a mass of \( \sim 10^{11} M_\odot \).

More broadly, these paths are fairly representative for galaxies in their respective mass ranges. Low-mass galaxies tend to move on to the red sequence at late times, and grow little after doing so, while massive galaxies become passive at earlier epochs and grow in mass by merging with smaller galaxies.

3.5 Specific star formation rates

A key observational constraint on the transition of galaxies on to the red sequence is provided by the distribution of specific star formation rates (sSFR) versus stellar mass. This contains similar information to the colour–mass plots above, but here we additionally compare our current quenching simulations with previous similar runs without quenching from Davé et al. (2011). We particularly examine the stellar mass range over which the transition to passive occurs, since the observed lack of a sharp delineation in stellar mass between passive and star-forming galaxies has been used as an argument against a quenching prescription based on halo mass (as ours is, approximately).

Fig. 3 shows sSFR as a function of stellar mass for a simulation without any quenching (green points) and the halo quenching run presented in this paper (red). Blue lines show a running median for each. Galaxies with \( sSFR \leq 10^{-3} \) Gyr\(^{-1} \) are shown along bottom of the plot. The no-quenching run employs the same cosmology, volume, input physics (besides quenching) and outflow model, but it has somewhat better resolution (\( \times 3 \)).

The form and evolution of the sSFR for the non-quenched case is discussed extensively in Davé et al. (2011). Key points are that the relation is flat at high \( z \) moving towards a mildly negative slope by \( z \sim 0 \), sSFR increases with redshift at a given stellar mass steadily out to \( z = 2 \), and the scatter is typically \( \sim 0.2 \) dex or less. The relation fundamentally arises from gravitationally driven smooth
cold accretion that dominates galaxy fuelling, and diminishes with time as the Universe expands (e.g. Davé 2008; Cen 2011).

The impact of halo quenching is clearly seen at masses $\gtrsim 3 \times 10^{10} M_\odot$, the same mass where many galaxy properties are observed to undergo a strong transition (Kauffmann et al. 2004). Below this transition mass, there is a minimal difference ($<0.2$ dex) in the quenched and non-quenched relations. Above this transition mass, the sSFR drops quickly towards small values, which is qualitatively similar to observations (e.g. Salim et al. 2007). The transition mass evolves very little with redshift, being only marginally higher at $z \sim 2$. The highest mass galaxies are still forming a ‘frosting’ of stars at a much reduced yet non-trivial rate (Trager et al. 1998; Trager, Faber & Dressler 2008), reflecting the infall of satellites that are not fully quenched. In our model there are very few galaxies above the transition mass on the main star-forming sequence, in conflict with observations. This conflict is also found in semi-analytic models (SAMs) with similar quenching mechanisms (Somerville et al. 2008).

Particularly noteworthy are the intermediate-mass galaxies that we argued earlier are ‘filling in’ the gap of the red sequence at stellar masses of $\sim 10^{10} M_\odot$. As these galaxies become more numerous towards lower redshifts, the transition between quenched and unquenched is significantly blurred, such that many quenched galaxies are present at masses below the nominal transition mass. Hence the argument that the observed gradual transition from unquenched to quenched galaxies rules out a model based on halo mass quenching (which our model approximates) may not be justified. While our simulations qualitatively resemble observations, it is worth noting that such environmental quenching processes are not as robustly modelled as we would like in our simulations, and hence a more quantitative comparison will have to await improved modelling of the interactions of galaxies moving through hot halo gas.

4 GROWTH ALONG THE RED SEQUENCE

4.1 Mergers since quenching

We have seen that a galaxy does not stop growing and evolving once it reaches the red sequence (see Fig. 2). Its existing stellar population ages, that population sheds mass via stellar winds and it obtains new stars (and gas) via mergers. Here we show that the most massive galaxies, which are quenched at early times ($z > 1$), often grow by factors of a few between quenching and the present day. In contrast, low-mass red galaxies (mostly satellites) tend to lose mass through stellar evolution and stripping without undergoing significant mass growth via mergers.

The top-left panel of Fig. 4 shows the distribution of the redshift at which galaxies are quenched, $z_{\text{quench}}$, as a function of the final stellar mass at $z = 0$. We plot the 50th (solid), 10th and 90th percentiles (dashed) of the distribution in each bin. The quenching redshift is defined as the redshift when a galaxy first appears red in the colour–magnitude diagram (CMD), with an evolving dividing line between red and blue galaxies as described in Section 3.1. Low-mass galaxies on the $z = 0$ red sequence, which are predominantly satellites, are quenched at fairly late times (generally $z < 1$). Massive galaxies $\gtrsim 10^{11} M_\odot$ are quenched earlier, typically at $z > 1$ and beyond.

The bottom-left panel of Fig. 4 shows, as a function of the $z = 0$ stellar mass, the fractional mass growth of red sequence galaxies between the redshift of quenching and the present day, $y \equiv M_{\text{stellar}}(z = 0)/M_{\text{stellar}}(z = z_{\text{quench}})$. Since many galaxies are quenched at late times, and such galaxies have not had time to undergo mergers, we only plot the mass growth for galaxies with $z_{\text{quench}} > 0.5$. This gives a long enough time baseline ($\sim 5$ Gyr; much longer than the halo dynamical times) to assess red galaxy growth via mergers. Galaxy points are colour-coded by $z_{\text{quench}}$, as indicated on the right-hand side of the panel.

Departures from the $y = 1$ line (i.e. no change in stellar mass, dotted line) increase with quenching redshift: the blue points that are the most recently quenched galaxies typically lie near $y = 1$, and in fact are slightly below owing to stellar mass loss. At higher quenching redshifts, galaxies span a wider range in $y$. In some rare cases, galaxies lose mass catastrophically by tidal interactions with other galaxies, and end up near $y = 0$. A significant proportion of galaxies quenched at earlier times with $M > 10^{11.5} M_\odot$, however, have grown substantially, by factors up to $>3$. Since these massive galaxies live in high-density environments, and they have been quenched for longer, they have had more opportunities to acquire mass via mergers than their lower-mass counterparts. Hence $y$ reflects the amount of mass growth by mergers in massive galaxies since the time of quenching, and in fact underestimated the growth since stellar mass loss also occurs. We note that a small number of galaxies become quenched at $z < 0.7$ yet undergo mass growth by $>2$ times via several major mergers. Some low-mass galaxies with $y > 2$ are only marginally resolved in our simulation.

The top-right panel of Fig. 4 shows the fraction of $z = 0$ red sequence galaxies that have undergone at least one major merger ($1:3$ mass ratio or larger) since being quenched. Post-quenching major mergers are generally rare, happening in typically only $\sim 10$ per cent of galaxies, and up to $\sim 20$ per cent of galaxies with $M_\star \sim 10^{11} M_\odot$. Galaxies quenched at the earliest times have major merger fractions as high as $\sim 30$ per cent. Semi-analytic models indicate major merger fractions reaching $>50$ per cent for massive galaxies (De Lucia et al. 2006; Wang & Kauffmann 2008). These studies, unlike ours, have considered the integrated merger history of the model galaxies. Since mergers are more common at higher redshifts (e.g. Hopkins et al. 2010b), restricting ourselves to mergers since the time of quenching naturally leads to a lower fraction of galaxies with at least one merger. In our model, major mergers play a sub-dominant role in the overall growth of massive red galaxies.

With little or no in situ star formation, the growth of red galaxies must therefore owe predominantly to minor mergers. The bottom-right panel of Fig. 4 shows the mean merger mass ratio as a function of $z = 0$ stellar mass. By weighting each merger by its mass, we can assess the contribution that mergers of a given mass ratio make to the overall growth of passive galaxies. The typical merger mass ratio for red sequence galaxies in our simulations is $\sim 0.2$ or 1:5, below the commonly used 1:3 cut-off for major mergers (thin dotted line). This typical value agrees with that obtained in higher-resolution individual galaxy re-simulations by Oser et al. (2012). At all stellar masses, red galaxy mass growth is dominated by minor mergers.

In summary, massive red sequence galaxies in our simulation grow by factors of up to several in mass between the time they are quenched (typically $z > 1$) and redshift 0. Lower-mass passive galaxies (both satellites and centrals) tend to be quenched at later epochs, and grow less, typically even diminishing in mass owing to stellar evolution. Mass growth at all masses is dominated by minor mergers with a characteristic ratio of 1:5, with at most a 30 per cent contribution from major mergers.

4.2 Size evolution

Observations indicate that massive passive galaxies are more compact at high redshifts than at $z \sim 0$ by factors of at least 2 and
Growth of red galaxies

Figure 4. Growth of galaxies along the red sequence. In our model, the most massive galaxies typically grew by factors of a few since being quenched at $z \sim 1$, and that mass growth is dominated by minor mergers. Top left: median (solid line), 10th and 90th percentiles (dashed) of the redshift at which red sequence galaxies were quenched ($z_{\text{quench}}$) in different mass bins. Bottom left: fractional mass growth of red sequence galaxies since $z_{\text{quench}}$, as a function of stellar mass at $z=0$, among galaxies quenched before $z=0.5$. Galaxy points are colour-coded by $z_{\text{quench}}$, and galaxies with higher $z_{\text{quench}}$ have larger symbol sizes. Top right: the fraction of galaxies per bin that have undergone at least one major merger since being quenched, among galaxies with $z_{\text{quench}}>0.5$. The fraction for galaxies with $0.5<z_{\text{quench}}<1.0$ (dotted) is typically lower than that for galaxies quenched earlier, $z_{\text{quench}}>1.5$ (dashed). Bottom right: the mass-weighted average merger mass ratio, among galaxies with $z_{\text{quench}}>0.5$. The mean merger is always a minor merger ($<1/3$, thin dotted line). Galaxies quenched at high redshifts (dashed line) all have a merger mass ratio of $\approx 0.2$, while those quenched at somewhat lower redshifts (dotted) show stronger variation with mass.

possibly up to 6 (Toft et al. 2007; Trujillo et al. 2007; van der Wel et al. 2008; van Dokkum et al. 2008; Trujillo, Ferreras & de La Rosa 2011). While observational biases presented an initial concern, recent work suggests that much of the evolution must be physical, and probably arises from a combination of several physical processes. These processes include adiabatic expansion associated with stellar mass loss, major mergers, minor mergers and evolution in mass-to-light ratios (e.g. Boylan-Kolchin, Ma & Quataert 2006; Naab et al. 2009; Bezanson et al. 2009; Hopkins et al. 2010a).

Our simulations make specific predictions about the distribution of merger mass ratios that contribute to red galaxy growth. Therefore, even though the spatial resolution of our simulations is not well-suited to study the internal structure of individual galaxies, we can use simple analytic merger-based estimates to approximate the size growth that our simulated galaxies might undergo.

We construct a simple model for the effects of mergers following the formalism presented in Naab et al. (2009), which arises directly from the virial theorem plus energy conservation. The model is appropriate for a purely collisionless system, so we implicitly ignore any effects of dissipation – since this model concerns quenched galaxies this is a reasonable simplification, but it may lead to an overestimate of the size growth due to mergers. Given a stellar accretion event (i.e. a merger) of mass $M_a$ on to a galaxy of mass $M_g$, the ratio of final to initial size of the galaxy is given by

$$r_f = r_i (1 + \eta)^2 / (1 + \eta \epsilon).$$

Here, $\eta = M_a/M_g$ is the fractional mass increase, and $\epsilon = \langle v_r^2 \rangle / \langle v_z^2 \rangle$ is the ratio of the two galaxies' stellar populations' mean square velocity dispersions. Using high-resolution simulations, Naab et al. (2009) have shown that this formula accurately describes the size evolution of early-type galaxies undergoing hierarchical mergers.

To estimate size growth, we must therefore estimate the mass ratio and the velocity dispersion ratio between the satellite (i.e. less massive) and central (more massive) galaxies. We know the ratio of stellar masses directly from our merger tree. For the velocity dispersion, since we do not accurately resolve it in our simulations (Oppenheimer & Davé 2008), we instead employ an observational result relating it to stellar mass from Gallazzi et al. (2006): $\log \sigma = -0.895 + 0.286 \log M_{\text{stellar}}$. With this relation, we obtain $\epsilon = \langle \sigma_r^2 \rangle / \langle \sigma_z^2 \rangle = (M_a/M_g)^{0.57}$, which gives comparable results to the theoretical relation with an exponent of 2/3 at any redshift (Mo,
Figure 5. The ratio of size growth to mass growth for red sequence galaxies, since $z = 1$, as a function of their stellar mass at $z = 0$. A solid line indicates the median. More massive galaxies show more size growth than lower-mass ones. In some rare cases the galaxy size may evolve several times (approximately three) more than the mass. This is roughly in line with observations, where the ratio is typically $\sim 2$ for evolution since $z \sim 2$.

Based on this simple modelling, minor mergers appear to be numerous enough to drive factors of several in size growth of passive galaxies over time. Galaxies with stellar masses $> 10^{11} M_{\odot}$ show typical size growth a factor of 2 greater than their mass growth, indicating that a series of minor mergers tend to puff up these galaxies, as argued by Naab et al. (2009). Lower-mass galaxies have not grown as much since moving on to the red sequence, since as we showed in Fig. 4 they undergo less merging. These results, using a simple analytic model, are broadly consistent with the idea that minor mergers drive the rapid size growth seen in massive red galaxies since high redshift.

In summary, a simple model of red galaxy size growth driven by mergers shows that massive galaxies with $\gtrsim 10^{11} M_{\odot}$ in our simulation typically have grown in size by a factor of 2 relative to their mass growth since $z = 1$. The degree of size growth increases with stellar mass. These results are broadly consistent with observations as well as previous simulation results.

5 ENVIRONMENTAL FACTORS

5.1 Bivariate dependence of environment on colour and $M_{\text{stellar}}$

We have shown that the massive and low-mass ends of the red sequence grow first in our model – not until $z \lesssim 0.3$ do intermediate galaxies around $10^{10} M_{\odot}$ appear in comparable numbers along the red sequence. In this section, we examine how environmental factors drive this behaviour.

We illustrate these environmental effects in Fig. 6. On the left we show a colour–mass diagram where the galaxies are colour-coded by their local galaxy density. The resulting trend is clear: the very highest and low-mass red galaxies live in the densest regions, while intermediate-mass passive galaxies ($M_{\ast} \sim 10^{10}–10^{11} M_{\odot}$) live in lower-density regions. This trend matches that seen in SDSS.
observations, at least qualitatively (Hogg et al. 2003; Kauffmann et al. 2004; Blanton et al. 2005). Physically, this trend emerges because massive galaxies with $M_* \gtrsim 10^{10.5} \, M_\odot$ once massive enough, can get to the red sequence ‘on their own’ by forming their own hot haloes even in (relatively) low-density environments. Massive galaxies that are quenched at early epochs live in the highest overdensities, and thus grow to be the most massive galaxies at $z = 0$ by accreting other galaxies (see Section 4). Low-mass ($\lesssim 10^{10} \, M_\odot$) galaxies can typically only be quenched by living in the hot environment of more massive neighbours.

In the right-hand panel of Fig. 6 we show only central galaxies colour-coded by the normalized distance to the nearest halo with a mass $> 10^{13} \, M_\odot$. This is roughly the halo mass where hot haloes will form independently in our simulations. Grey crosses are for galaxies at the centres of massive haloes, and coloured points are for central galaxies in lower-mass haloes.

The first clear difference when looking only at centrals is that there is a deficit of $M_* \sim 10^{10} \, M_\odot$ red central galaxies, which as we argued in Section 3.3 arises because red galaxies at that mass are predominantly satellites quenched at late times.

However, there are still some central galaxies that are along the red sequence at intermediate to low masses. Such galaxies at low mass tend to be fairly close to a quenched halo (i.e. the points are blue). This suggests a larger environmental effect – these galaxies are part of super-group structures whose hot gas can be felt beyond the virial radius of the group halo. Thus environmental factors beyond the halo mass may play some role in quenching of star formation. Observations have suggested a role for environment (beyond halo mass) in some galaxy properties (Cooper et al. 2008a,b, 2010), though it is typically secondary to galaxy mass.

Fig. 7 shows another representation of the relationship between red fraction and environment. Here we plot contours of red fraction (in colours from blue to red) in the plane of stellar mass versus local galaxy overdensity (determined using SMOOTH). This figure can be compared to fig. 6 of Peng et al. (2010), who argued for two different quenching mechanisms, namely ‘environment quenching’ of all galaxies above a given overdensity, and ‘mass quenching’ above a given stellar mass.

Our simulation with quenching (left-hand panel) quantitatively reproduces the observed trends almost exactly, although it has far fewer galaxies than in the SDSS data of Peng et al. (2010), and hence the trends are less smooth and there are regions in this space where this simulation yields no galaxies (black). Broadly, our models reproduce the strong increase in red fraction to both high mass and high overdensity, and the ‘boxy’ contour shape noted by Peng et al. (2010). In our simulations, environment quenching is predominantly associated with satellites at lower masses living in hot haloes, although as discussed above there are a fair number of small centrals living in dense environments that are also quenched. Meanwhile, mass quenching is well reproduced by our hot gas threshold for quenching, which translates roughly into a halo mass threshold. To a large extent ‘mass’ and ‘environment’ quenching can alternatively be separated into central and satellite quenching (De Lucia et al. 2012b; Peng et al. 2011).

In the right-hand panel of Fig. 7 we illustrate ‘environment quenching’ in our simulation without explicit quenching feedback. This simulation produces fewer red galaxies (Gabor et al. 2011), and the figure shows that red galaxies form only at high overdensities. The red galaxies in this case are almost all satellite galaxies. ‘Mass quenching’, indicated by vertical contours in the left-hand panel, is a direct result of adding heat to hot haloes in our quenching simulation – it is absent from the right-hand panel. Our explicit quenching mechanism also boosts the red fraction among satellites in dense regions.

In summary, our simulations are consistent with the interpretation by Peng et al. (2010) that there are two quenching mechanisms that deliver galaxies to the red sequence, associated with environment and mass, though they can be described more physically as central and satellite quenching. But our simulations further suggest that both mechanisms are ultimately the result of red galaxies living in regions dominated by hot gas, which occurs at both high overdensities and high masses.

Figure 7. Left: smoothed distribution of red fraction (colours) in stellar mass versus overdensity space in our quenching simulation. Galaxies are increasingly red at both higher masses and overdensities. Small galaxies at high overdensity are red because they live within or close to larger haloes dominated by hot gas, while larger galaxies are red because they are typically centrals living within hot haloes maintained hot via our quenching feedback mechanism. Dashed lines show the best-fitting parametrization of red fraction of SDSS data from Peng et al. (2010). Right: same as left panel, but for a simulation without explicit quenching, and with a different colour-scale. Even without adding heat ‘by hand’ in hot haloes, some satellite galaxies in high-density regions are quenched.
5.2 Evolution of the mass–density and colour–density relations

We show the evolution of the stellar mass–density relation and the colour–density relation in Fig. 8. Here the local galaxy density is found using SMOOTH.

The mass–density relation (top row of Fig. 8) for all galaxies shows a very shallow rise in density with mass for stellar masses below $10^{10.5} \, M_\odot$. Above this mass, density rises steeply. This behaviour agrees qualitatively with observations at $z = 0$ (Hogg et al. 2003; Blanton et al. 2005). The red galaxy sample departs from the average trend because low-mass red galaxies live in dense regions. For these trends, evolution is negligible out to $z = 1$ (top middle panel), but notable at the massive end to $z = 2$. This high-$z$ evolution is sensitive to the small numbers of massive galaxies at this redshift, and to the separation between blue and red galaxies, so we do not view it as a strong prediction at this time.

In the colour–density relation (bottom row of Fig. 8), density is uniformly low for blue galaxies (low values of $g - r$), and then rises steeply for red galaxies (higher values of $g - r$). Massive galaxies ($M > 10^{10.5} \, M_\odot$, dashed line) live at higher densities with a weaker colour–density trend. Low-mass galaxies, in contrast, must live in dense environments in order to become red. Evolution in the colour–density relation is minor to $z = 1$, in accordance with recent observations (although there is some debate; Cooper et al. 2006, 2007, 2010; Elbaz et al. 2007; Scodeggio et al. 2009).

In summary, although our quenching model is most directly tied to hot gas fraction and thus halo mass, environment plays a correlated role in quenching galaxies in our simulations. Halo mass is correlated with environment in a CDM universe, so we get the usual mass–density relation. Since our quenching is directly linked to the proportion of hot gas in a halo and thus halo mass (Birnboim & Dekel 2003; Kereš et al. 2005; Gabor et al. 2011), we also naturally get a pronounced colour–density relation. Evolution in the mass–density and colour–density relations is weak in this model and qualitatively consistent with data, perhaps showing an inversion in the colour–density relation only at the highest redshifts considered here.

6 SUMMARY AND CONCLUSION

We have analysed a cosmological hydrodynamic simulation to explore the evolution of the red sequence. A key feature of our simulation is a simple quenching prescription tied to the dominance of hot gas within the virial radius of a halo. In our quenching prescription, galaxies whose haloes have $> 60$ per cent of their baryons in hot gas are starved of star-forming fuel by continual heating of the halo gas. In a previous paper we showed that this simple model yields a distinct red sequence of galaxies whose number densities generally agree with observations (Gabor et al. 2011). This model thus provides a tool for studying the emergence and growth of the red sequence over cosmic time. While some details of our model are overly simplistic and in some cases are in conflict with observations, it serves as representative of a general class of quenching models where cessation of star formation is driven by the presence of hot coronae or is tied to halo mass.

In our simulations, the first galaxies to turn red at $z \gtrsim 2$ are among the most massive in the universe at that epoch, with $M_{\text{stellar}} \sim 10^{10.5} - 11 \, M_\odot$. Satellite galaxies at low masses are concurrently...
starved of fuel by the same hot halo that triggers our quenching mechanism, and therefore low-mass galaxies also appear on the red sequence at early times. Meanwhile, intermediate-mass galaxies at $\sim 10^{10} - 10^{10.5} \, M_{\odot}$ remain predominantly blue until late epochs, producing a pronounced dip in the red galaxy mass function at high redshifts. This dearth of intermediate-mass red galaxies is qualitatively consistent with observations, but our model may have too many red galaxies with lower masses. At late times, the number of intermediate-mass red galaxies catches up to the number of more massive ones, so that the dip in the red galaxy mass function is less pronounced by $z = 0$.

Essentially all simulated passive galaxies with stellar mass $> 10^{11} \, M_{\odot}$ form from smaller passive galaxies that grow mass via mergers once on the red sequence. Most of the mass growth of individual passive galaxies is due to minor mergers, with major mergers being rare and a sub-dominant component of mass growth. Based on a simple analytic model, these numerous minor mergers can lead to size growth that is a factor of 2 or more times that of a galaxy’s corresponding mass growth. This suggests that minor mergers dominate the dramatic size evolution of massive galaxies, in accordance with earlier work (Naab et al. 2009; Hopkins et al. 2010a).

The simple quenching model explored here qualitatively reproduces observed trends among colour, stellar mass and environment at $z = 0$. In detail, it also reproduces the observed mass–density trend for the red sequence: low-mass and high-mass passive galaxies live in the densest regions, whereas galaxies in-between (around $M*$) live in less dense regions. The mass–density and colour–density trends persist to at least $z = 1$. Quenching occurs at both high density, roughly independent of stellar mass, and high stellar mass, roughly independent of density. As argued from corresponding observations by Peng et al. (2010), this indicates two quenching processes associated with environment and mass, which in our model both arise due to starvation when the local environment is dominated by hot gas.

Our analysis explicitly avoids any considerations of galaxy morphologies. A key question that we therefore do not address is that why are most red and dead galaxies elliptical? While some authors argue that it owes to major mergers that can transform star-forming spirals into elliptical galaxies (Milhos & Hernquist 1996), the simple cessation of star formation at sufficiently early epochs typically results in substantial later growth via dry (i.e. purely or almost purely stellar) mergers. In this scenario, galaxies would quench first when entering a hot halo (or its immediate environment), become red spirals (Skibba et al. 2009; van der Wel et al. 2009, 2011; Bundy et al. 2010; Masters et al. 2010), and then undergo subsequent dry mergers that alter its morphology (e.g. De Lucia & Blaizot 2007; Guo & Oh 2008; Feldmann et al. 2010; Oser et al. 2010, 2012; De Lucia et al. 2011). Our models indicate that larger galaxies living in denser environs undergo more such growth, and so would be expected to have dynamical signatures indicating more dry merging such as boxier isophotes (Naab, Khochfar & Burkert 2006; Bournaud, Jog & Combes 2007); these trends are qualitatively consistent with observations. Whether the quantitative predictions of this model are in accordance with detailed observations remains to be seen.

More broadly, it appears that a quenching mechanism based on a simple hot gas fraction threshold (which is well correlated with a halo mass threshold) is capable of reproducing a variety of observations not only at the present epoch but also out to $z \sim 1$ and beyond. However, there are significant failures, such as a dearth of the most massive galaxies, and a too-sharp cut-off in the blue galaxy mass function suggesting that both today and at high redshifts in the real Universe, some galaxies are able to be star forming despite living in hot gas-dominated haloes. Hence this model represents only a step towards understanding the physical processes driving red galaxy evolution. Comparisons to observations particularly probing the intermediate-mass regime out to high redshifts can place strong constraints on models such as these, and highlight additional physical processes that may need to be considered.

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