The transformation and quenching of simulated gas-rich dwarf satellites within a group environment

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ABSTRACT

The underlying mechanisms driving the quenching of dwarf-mass satellite galaxies remain poorly constrained, but recent studies suggest they are particularly inefficient for those satellites with stellar mass \(10^9 \, M_\odot\). We investigate the characteristic evolution of these systems with chemodynamical simulations and idealised models of their tidal/hydrodynamic interactions within the \(10^{13} - 10^{13.5} \, M_\odot\) group-mass hosts in which they are preferentially quenched. Our fiducial simulations highlight the role played by secular star formation and stellar bars, and demonstrate a transition from a gas-rich to passive, H I-deficient state (i.e. \(\Delta \text{SFR} \leq -1\), \(\text{def}_{\text{HI}} \geq 0.5\)) within 6 Gyr of first infall. Furthermore, in the 8-10 Gyr in which these systems have typically been resident within group hosts, the bulge-to-total ratio of an initially bulgeless disc can increase to \(0.3 < B/T < 0.4\), its specific angular momentum \(\lambda_R\) reduce to \(< 0.5\), and strong bisymmetries formed. Ultimately, this scenario yields satellites resembling dwarf S0s, a result that holds for a variety of infall inclinations/harassments albeit with broad scatter. The key assumptions here lie in the rapid removal of the satellite’s gaseous halo upon virial infall, and the satellite’s local intra-group medium density being defined by the host’s spherically-averaged profile. We demonstrate how quenching can be greatly enhanced if the satellite lies in an overdensity, consistent with recent cosmological-scale simulations but contrasting with observationally-inferred quenching mechanisms/timescales; an appraisal of these results with respect to the apparent preferential formation of dS0s/S0s in groups is also given.

Key words: galaxies: interactions – galaxies: dwarf

1 INTRODUCTION

Besides their initial and often rapid formation, the evolution of most galaxies can be defined by a gradual suppression of star formation (quenching), usually coincident with a transformation from a disc to elliptical morphology, much of which is observed to occur within cosmologically overdense regions like groups and clusters (Butcher & Oemler 1984; Dressler et al. 1997; Lewis et al. 2002; Kauffmann et al. 2003a; Balogh et al. 2004; Weinmann et al. 2006).

In the context of the \(\Lambda\)CDM framework, these observations partially reflect the early hierarchical assembly of massive galaxies via merging and their quenching via radio-mode AGN feedback (Balogh et al. 2004; Bluck et al. 2014). This mass-quenching appears to dominate at high-z and for masses above a characteristic \(10^{10} \, M_\odot\) (Peng et al. 2012; Wetzel et al. 2013). The (dwarf) galaxies that lie below this threshold are rarely found quenched in the field (Geha et al. 2012), but tracing their recent quenching/transformation to specific mechanisms as satellites remains difficult.

The main mechanisms are speculated to include tidal shock/heating by a host potential well (Mayer et al. 2001; Kazantzidis et al. 2011), harassment by successive tidal encounters (Moore, Lake & Katz 1998; Wetzel & White 2010; Bekki & Couch 2011), and hydrodynamical interactions with the hot gas halo of a host (Intra-cluster medium; ICM). The latter, often invoked to explain a suppression of star formation (SF), include in particular the ram pressure stripping of a satellites’ cold gas disc (Gunn & Gott 1972; Koopmann & Kenney 2004; Chung et al. 2007) and the stripping of the satellites’ hot gaseous corona that would otherwise fuel star formation (strangulation; Larson, Tinsley & Caldwell 1980).

The efficiency of these processes within a given environ-
ment is expected to vary with properties of the constituent baryons (i.e. satellite velocity dispersion, ICM temperature) and host halo. In practice, a bimodal (red and blue) galaxy population is observed in most overdense regions (van den Bosch et al. 2008; Cibinel et al. 2013; Bluck et al. 2014) since $z = 0.2 - 0.5$ (McGee et al. 2011; Popesso et al. 2012). This bimodality extends down to the host mass scale of $10^{13} \ M_{\odot}$, in which the majority of all galaxies reside (Treu et al. 2000; Eke et al. 2004; Rasmussen et al. 2012).

Recently, statistical analyses of large cosmological simulations and surveys (e.g. SDSS) have been adopted to establish i) the timescale of satellite quenching/transformation, with respect to ii) the time since accretion to an overdense region (e.g. De Lucia et al. 2012). The finding that these timescales lie on the order of several Gyr is consistent with a slow quenching facilitated by strangulation (McCarthy et al. 2008; Weinmann et al. 2010), as contrasted with the relatively rapid action of ram pressure stripping, which in some models produces too many passive satellites (Wang et al. 2007).

Other studies have gone further to suggest that the quenching timescale is independent of host halo masses above $10^{12-13} \ M_{\odot}$ (e.g. Wetzel et al. 2013), where any apparent variability corresponds instead to the hierarchical growth of such environments. In the event of this pre-processing, previously quenched satellites may be accreted as part of their host to a more massive host (Zabludoff & Mulchaey 1998; McGee et al. 2009; Peng et al. 2012). This remains far from conclusive, however, with numerical studies differing in their prediction for the onset of these quenching mechanisms and their subsequent efficiency (Bekki 2009; McCarthy et al. 2008; Wetzel et al. 2013; Bekki 2014; Cen, Pop & Bahcall 2014; Bahe & McCarthy 2015).

The uncertainty concerning environmental processing motivates a study in which we simulate in detail the fundamental tidal and hydrodynamical mechanisms acting on a dwarf satellite. Specifically, we consider the apparent inefficiency with which $10^{7} \ M_{\odot}$ satellites are environmentally-quenched (Wheeler et al. 2014, and references therein). By comparing the observed quenched fraction of these systems (Geha et al. 2012) with their associated fraction residing as subhalos in a more massive host (as deduced with a mock catalog constructed from the Millenium II Simulation), Wheeler et al. find that up to only 30 percent are quenched by their environment (most commonly a $10^{13-13.5} \ M_{\odot}$ host). Using simple analytical models, they hypothesize that the corresponding quenching mechanism must act only on long timescales (e.g. $\geq 7.5$ Gyr).

This inefficiency contrasts with the distinct transition from blue irregulars to red early-types acknowledged amongst the smallest of the $10^{6-9} \ M_{\odot}$ dwarf galaxies when crossing the virial radius of the Local Group’s largest galaxies (McConnachie 2012). While ram pressure interactions with the Galactic hot halo and cosmic reionisation have been demonstrated to reproduce their current paucity of detectable gas (Mayer et al. 2001), the tidal stirring mechanism (the repeated tidal shock/heating of a satellites stellar disc) reveals the efficiency with which groups environments can transform very faint dwarf galaxies (Mayer et al. 2001; Kazantzidis et al. 2011) and even Galactic-mass systems (Bekki & Couch 2011; Villalobos et al. 2012). Group mechanisms also appear to be responsible for the dramatic number growth, since at least $z = 0.5$, of the quenched and early-type systems known as Lenticular (SO) galaxies (Dressler et al. 1997; Willman et al. 2009; Just et al. 2010).

In this analysis, we adopt methods demonstrated in our previous studies (Bekki & Couch 2011; Yozin & Bekki 2014; Bekki 2014) and the results of previous cosmological studies that predict the infall epochs and group orbits for this stellar mass regime (e.g. De Lucia et al. 2012; Villalobos et al. 2012), and devise an idealised model of this $10^{9} \ M_{\odot}$ satellite and a $10^{13} \ M_{\odot}$ host system to characterise its long-term evolution.

Other studies have considered the tidal transformation of dwarves within groups/clusters (Smith, Davies & Nelson 2010; Kazantzidis et al. 2011; Villalobos et al. 2012; Bialas et al. 2015), and the star formation histories of Galactic-mass satellites in groups (Feldmann, Carollo & Mayer 2011). Besides our novel choice of satellite and group masses, we distinguish this work with i) an estimation of the SF history and H I-deficiency using our chemodynamical model of the interstellar medium (ISM); ii) an interpretation of our results in terms of the stochasticity/evolutionary scatter introduced by infall inclinations/satellite interactions/group mass assembly, and iii) complementary simulations of hydrodynamical (ram pressure) interactions between the group medium and satellite.

Section 2 describes the group and satellite models, while in Section 3, we illustrate the results of a suite of the tidal/hydrodynamical simulations. A summary and interpretation of these results in the context of previous observational/numerical studies is given in Section 4.

2 METHOD

We model satellite galaxy infall into a $10^{13} \ M_{\odot}$ halo to assess the efficiency/mechanisms by which it is transformed and quenched. This involves placing an idealised dwarf galaxy (pristine bulgeless disc) at or beyond the virial radius ($r_{\text{vir}}$) of a static group potential, with a trajectory prescribed from previous studies on the most cosmologically-common infall orbit. This evolution is assessed from a lookback time of 8 to 10 Gyr, which represents the median epoch at which $10^{9} \ M_{\odot}$ satellites resident in group-mass hosts ($10^{13} \ M_{\odot}$) at $z = 0$ were first accreted from isolation (McGee et al. 2009; De Lucia et al. 2012). A schematic of this scenario is illustrated in Fig. 1.

This method permits us to disentangle the primary mechanisms presently believed to govern dwarf satellite evolution, namely group tides, harassment, ram pressure and secular evolution. Crucially, we utilise satellite models with a $10^{3-4}$-fold improvement on baryonic resolution with respect to the cosmological-scale simulations whose results motivated this study. However, our method has disadvantages insofar as the group model neither follows the mass growth (by factor 2) expected from hierarchical growth over this timescale (Fakhouri, Ma & Boylan-Kolchin 2010), nor allows for the potential merging and/or resonant stripping of jointly accreted satellites (Gnedin 2003; d’Onghia et al. 2009). We must further assume the instantaneous stripping of the satellites’ extended gas reservoir upon first crossing
Fig. 1. Schematic of group models at $z=1$ and $z=0$ (left and right panels respectively). Black lines represent the satellite orbit in each case, with black circles denoting initial locations; red circles represent the initial locations of other group satellites (size linearly correlated with satellite mass). In each case, the group halo density is conveyed in a logarithmic scale with the grey shaded region (darker = higher density).

Figure 1.

Table 1. Summary of group model and orbital parameters

| Parameter                     | Value at $z=1$ | Value at $z=0$ |
|-------------------------------|----------------|----------------|
| Virial mass ($M_{\odot}$)     | $10^{13}$      | $10^{13}$      |
| Virial radius (kpc)           | 329            | 556            |
| $c_{\text{NFW}}$              | 4.87           | 9.74           |
| Apocentre ($r_{\text{ap}}$)   | 1.2            | 1.0            |
| Pericentre ($r_{\text{peri}}$)| 0.24           | 0.2            |
| Pericentre Velocity (kms$^{-1}$)| 650-700       | 550-600        |

Table 1.

To overcome the idealistic nature of our static group model, we adopt two representations of a group at distinct epochs of $z=1$ and $z=0$, whose combined results encompass the characteristic evolution of a dwarf satellite accreted since $z=1$. We fix the group mass to $10^{13}$ $M_{\odot}$ at both epochs, and extract $c_{\text{NFW}}/r_{\text{vir}}$ from the similar models of Villalobos et al. (2012); the adopted properties are summarised in Table 1.

For the subset of simulations in which we explicitly add other group galaxies, we adopt the method introduced in Bekki & Couch (2011) in which they are modelled as collisionless point masses, orbiting freely within the group, with an interaction softening length fixed to half each satellites’ $r_{\text{vir}}$. The total mass of galaxies $M_{\text{gr}}$ is established according to the total luminosity $L_{\text{gr}}$, with the relation of Marinoni & Hudson (2002):

$$M_{\text{gr}}/L_{\text{gr}} = 350 \left( \frac{M_{\text{gr}}}{5 \times 10^{14} M_{\odot}} \right)^{0.335}.$$  \hspace{1cm} (2)

Monte-Carlo sampling is adopted to fit satellites, limited to a luminosity range 0.01 to 2.5$L_{\odot}$ and with an assumed mass-to-light ratio of 40, to the Schechter function with a faint-end slope -1.07 consistent with groups as established by Yang, Mo & van den Bosch (2008). Thus, our $10^{13}$ $M_{\odot}$ group hosts 52 satellites, with an initial spatial distribution prescribed with a NFW profile and a concentration of 3.0 to match the galaxy distributions revealed in K-band studies (Lin, Mohr & Stanford 2004). Fig. 2 demonstrates good agreement between the corresponding linear fit to our LF with that obtained for groups in the mass range 12.9<$\log_{10}[M_{\odot}]<$13.2 from the SDSS DR4 (Yang, Mo & van den Bosch 2008). The corresponding velocity dispersion of these satellites, a proxy for the influence yielded by satellite-satellite tidal encounters, is consistent with observations at between 125 and 150 kms$^{-1}$.

Figure 2. Luminosity function for group satellites in the Tidal/$z=1$ simulations, shown in terms of binned luminosity (grey bars) and line-of-best-fit (red dashed line), compared with the equivalent data from SDSS DR4 (Yang, Mo & van den Bosch 2008; Y08) for groups in the mass range 12.9<$\log_{10}[M_{\odot}]<$13.2, where open and closed circles denote satellite and central galaxies respectively.

2.1 Group Model

Our group model is built on the assumption of a virialized group environment in which most substructure is accreted into a spherically symmetric background halo. For simplicity, both the dark halo and IGM are modelled with a NFW density profile (Navarro, Frenk & White 1996), which statistical analyses of clusters suggest provides an acceptable mass distribution (van der Marel et al. 2000):

$$\rho(r) \propto \frac{1}{r/r_{\text{group}}(1 + r/r_{\text{group}})^2},$$  \hspace{1cm} (1)

where $r$ is the group-centric radius and $r_{\text{group}} = r_{\text{vir}}/c_{\text{NFW}}$ where $c_{\text{NFW}}$ is the concentration factor.

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is satisfactory live model of this halo requires significant resolution to avoid discreteness effects (a resource we choose instead to dedicate to the satellite model); given that analytical methods are not sufficiently accurate (Jiang et al. 2008) and that this drag is nominally weak for dwarf satellites (Smith, Davies & Nelson 2010), we exclude this friction in our model.

Fig. 3 conveys how we establish from Villalobos et al. an elliptical orbit at epochs $z = 1$ and $z = 0$ from the mean pericentres and apocentres across an 8-10 Gyr interval since first crossing the group $r_{\text{vir}}$. In each case, the apocentre-to-pericentre ratio is consistent with the median among large-scale simulations (i.e. 4-5 Ghigna et al. 1998). Qualitatively, it can be seen that each orbit differs significantly in its pericentre radii and orbital period; given that each is smaller in the $z = 1$ case, we expect its satellite evolution to be most dramatic. In each case, we deem the orbit sufficiently far from the group centre not to warrant the explicit modelling of a massive central galaxy often found lying at the X-ray temperature peak among groups (Zabludoff & Mulchaey 1998), and responsible for potentially efficient tidal shocks (Mayer et al. 2001).

2.3 Disc Model

Table 2 summarises the initial conditions of our satellite, a gas-rich bulgeless disc, which is comprised of a dark halo and stellar/gaseous disks. All galaxy models are comprised of $1.5 \times 10^6$ particles, divided between halo, stellar and gas components with $10^6$, $3 \times 10^5$ and $2 \times 10^5$ particles respectively.

For the stellar disc mass $M_{\text{d1}} = 10^9 \, M_\odot$, we find a halo mass $M_h \simeq 100 M_{\text{d1}}$ from observed intermediate-$z$ dwarf galaxies and abundance matching within large-scale simulations (Miller & Bregman 2013; Munshi et al. 2013; Behroozi, Wechsler & Conroy 2013), but note that the latter may produce too much substructure, in which case our $M_h$ may be a slight overestimate. We assume a top hat collapse model in which the mean halo density enclosed within $r_{\text{vir}}$ reflects the critical density at formation, and therefore use a scaling relation of the form $r_{\text{vir}} \propto M_h^{1/3}$ normalised by properties of the Galaxy (Klypin, Zhao & Somerville 2002), from which we establish a satellite $r_{\text{vir}}$ of 120 kpc. We utilise a NFW density profile for the halo; the single distinction between our satellite at $z = 1$ and $z = 0$ lies in its initial concentration $c_{\text{NFW}}$, which we constrain from mass-redshift-dependent relations of Munoz-Cuartas et al. (2011), and establish an evolution of $c_{\text{NFW}}$ since $z = 1$ from 7 to 12.

An exponential disc morphology is adopted for the satellite, truncated at $5 r_d$ with a density defined for a cylindrical radius $r$ and height $z$:

$$\rho(r, z) \propto \exp\left(-\frac{r}{r_d}\right) \exp\left(-\frac{z}{2 r_d}\right),$$

where $r_d$ is a stellar scalelength derived from size-mass scaling relations (Ichikawa, Kajisawa & Akhlaghi 2012) which exhibit a power law (index $\alpha = 0.5)$. This differs
from simple self-similar models of galaxy formation (e.g. Mo, Mao & White 1998) which do not account for mass-dependent processes such as outflow. Disc kinematics are constrained on the basis that the typical late-type disc with this $M_\odot$ will not host a secular bar instability (i.e. Melvin et al. 2014). Initial velocity dispersions, assigned according to epicyclic theory (with the vertical dispersion at a given radius is half that of the associated radial velocity dispersion), are thus chosen with a Toomre’s parameter of $Q = 2$ to inhibit expedient axisymmetric collapse (Combes & Sanders 1981).

We enforce a gas-to-stellar mass ratio of unity from semi-empirical scaling laws for the gas mass (as a function of $z$) based on indirect measures of H I and H$_2$ content (e.g. the SF rate), which compares well with the high observed gas fractions of dwarves (Popping, Behroozi & Pee 2014, and references therein). We assume this mass is also distributed with the aforementioned exponential profile, albeit with a gas scalelength $r_h = 2.6 r_d$ as established from the normalised galaxy sample of Kravtsov (2013), and an assumed scaleheight $z_h = 2s_d$.

Fig. 4 illustrates how the initial rotation curve of this model fits acceptably to that of the LMC (van der Marel & Kallivayalil 2013), an exemplary galaxy in this stellar mass regime.

### 2.4 Numerical modelling

We utilise an original parallelised chemodynamical code GRAPE-SPH (GRAvity PipE-Smoothed particle hydrodynamics; Bekki 2009). Gravitational dynamics are computed with a softening length for halo and stellar particles ($\eta_h = 2.1$ kpc and $\eta_s = 200$ pc respectively) which is set by the mean particle separation at the halo and stellar half-mass radii respectively. The ISM is modelled with smoothed particle hydrodynamics (SPH), with a minimum smoothing length of $\sim 30$ pc, and can cool radiatively (see Bekki 2014, for more details). This depends on an initial galaxy-wide mean metallicity of $[Fe/H] = -0.9$ prescribed from mass-metallicity relations (Kirby et al. 2013), and a fixed in-plane radial metallicity gradient of $0.04$ dex kpc$^{-1}$.

Star formation (SF) occurs via the conversion of gas particles to new stellar particles; this process is limited to collapsing Jeans-unstable regions with volumetric density exceeding a threshold $\rho_{th}$ and relies on a probability parameter, $P_{SF}$, introduced in Bekki (2013):

$$P_{SF} = 1 - \exp(-\Delta t \rho^2 \tau^{-1})$$

where $\Delta t$ is the timestep width for a given gas particle. If $P_{SF}$ exceeds a randomly generated number $R$ with $0 \leq R \leq 1$, the conversion proceeds, based on the assumption that the timescale for star formation is shorter for higher density gas particles. This condition softens the numerical limitation that the giant molecular clouds which host SF lie below the resolution of gas particles.

Stellar feedback is implemented with a sub-grid Supernova (SN) model (see Bekki 2014, for more details) in which each subgrid SN type II expels a canonical $10^{51}$ ergs, with 90 percent delegated to thermal UV emission which is conferred upon neighbouring gas particles over a prescribed adiabatic expansion timescale $\tau_{SN}$. The rate at which SNe occur is governed by an initial mass function (IMF), for which we adopt the standard Salpeter power law ($\alpha = -2.35$) normalised to within the range $0.1$ M$_{\odot}$ and $100$ M$_{\odot}$.

This ISM model is simple in terms of its IMF and the lack of an explicit modelling of H$_2$-formation/outflow. However, in Fig. 5 we illustrate how our choice of free parameters $\rho_{th}$ and $\tau_{SN}$ (1 cm$^{-3}$ and $10^6$ yr respectively) can sufficiently replicate the observed SF law of dwarf galaxies Bigiel et al. (2008), who adopt far UV and 24um emission to trace the inefficient (relative to the Kennicutt relation) SF in 7 nearby spirals. We also ameliorate the concern that weak feedback schemes permit the existence of unphysical dark matter cusps, with the finding of a flat density profile within 1-2 percent of the satellite $r_{1/2}$ (e.g. Brook et al. 2012).

For the subset of simulations in which we exclusively model the interactions between the satellite ISM and group IGM (i.e. no group potential), we adopt a method introduced in Bekki (2014) in which the self-gravitating galaxy model is placed within a cubic lattice of SPH particles (side length $25 r_d$) that represents the IGM local to the satellite. The galaxy model is fixed, such that variations in the relative velocity and density of its surrounding IGM are applied by modifying at each time step the properties of the IGM SPH particles, according to the satellite’s orbit. Therefore, each IGM particle is assigned a density of $f_{ICM}(r)$, which is the group-centric radius, $r$ is the same NFW profile adopted to describe the group halo potential, and $f_{ICM}$ is the mass quotient of the ICM with respect to the group halo. A fixed gas temperature of $T_{ICM} = 5.6 \times 10^6$ K is obtained for a $10^{13}$ M$_{\odot}$ group from Matsumoto & Tsuru (2000).

### 2.5 Simulations

This study analyses the results of 37 self-consistent simulations, whose details are summarised in Table 3. As a baseline case, we analyse the tidal influence of the group spherical potential at $z = 1$ and $z = 0$ (labelled ‘Tidal’), with respect to the pure secular evolution of an identical galaxy (Isolated).

Simulations labelled Ram refer to those in which a self-gravitating galaxy model interacts only hydrodynam-
Table 3. Summary of simulations

| Simulation | Description |
|------------|-------------|
| Isolated   | Isolated model (not orbiting within group potential) |
| Tidal/\(z = 1\) | Satellite under tidal influence from the group potential only; orbit and group properties at \(z = 1\) |
| Tidal/\(z = 0\) | As above, but with orbit and group properties at \(z = 0\) |
| Ram/\(z = 1\) | Satellite under Ram Pressure only; properties at \(z = 1\) |
| Ram/\(z = 1/\text{Overdense}\) | As above, but with IGM density increased by factor 10 |
| Tidal/\(z = 1/\text{Orientations}\) | Tidal/\(z = 1\), but with 16 variations on the initial orientation w.r.t orbital plane |
| Tidal/\(z = 1/\text{Harassment}\) | Tidal/\(z = 1\), but with other group satellites included, 16 variations on initial position |

2.6 Diagnostics

Simulation data is stored and reduced at 70 Myr increments. The following diagnostics are utilised to compare the evolution of each simulation in terms of transformation and quenching/gas deficiency.

2.6.1 Morphology

The stellar/DM/gas mass dynamically associated with the satellite is established with an iterative procedure, wherein gravitationally-bound material discerned in one step is used to build a more refined spherical mass distribution of the galaxy in the following step, until the centre of bound mass is converged upon.

Stellar magnitudes are approximated in this work with synthesis models for the evolution of stellar mass to light ratios (Bruzual & Charlot 2003; Portinari, Sommer-Larsen & Tantalo 2004). Assuming infall at a lookback time of 8-10 Gyr, an initial stellar age distribution is established from an estimated SF history up to \(z = 2.5\), calculated using extrapolated SFR-stellar relations from Whitaker et al. (2012). We approximate the H I-mass as a factor \(1.38^{-1}\) of each gas particle mass. The attenuation by dust is approximated with the gas column density and an assumed gas-to-dust-extinction ratio of \(5 \times 10^{21} \text{ cm}^{-2} \text{A}_V\), consistent with bright dwarf/LMC-type galaxies (Dobashi et al. 2008).

The surface brightness profile \(\mu(r)\) is composed from the corresponding attenuated luminosity, from which a bulge-to-disc mass ratio \((B/T)\) is estimated with the excess light lying within 2 effective radii with respect to a fitted exponential disc profile, and normalised with the integrated flux of the disc. The fitted disc profile is estimated with an algorithm that progressively smooths the radial light profile until the underlying disc (which we find to exist in all cases except where the disc is completely destroyed) can be distinguished from the bulge and/or (positive or negative) truncation components of \(\mu(r)\) by lying coincident with a global minimum of \(d\mu/d\sigma^2\).

A \(B/T\geq0.5\) is often associated with an early-type morphology (Kormendy & Kennicutt Jr. 2004; Willman et al. 2009), although recent studies have highlighted an inherent flaw in adopting simple fits to \(\mu(r)\) insofar as it incorporates features such as bars/ovals/lenses in the excess light. In the case of early-type systems such as dS0/S0s in which these features are hypothesized to be critical to their formation, this can lead to a significant overestimate of \(B/T\) (Laurikainen et al. 2009).

For this reason, we also compare our satellite’s stellar kinematics with those of observed E and/or S0s, using a specific angular momentum \(\lambda_R\) computed in the manner of Emsellem et al. (2007), who adopt \(\lambda_R\) to distinguish galaxies as fast/slow rotators:

\[
\lambda_R = \frac{\sum F_i R_i |V_i|}{\sum F_i R_i \sqrt{V_i^2 + \sigma_i^2}},
\]

where \(F_i\), \(R_i\), \(V_i\), and \(\sigma_i\) are the total flux, radius, mean stellar velocity and velocity dispersion respectively, at the \(i\)th radial bin up to the effective radius \(r_e\).

A quantitative demarcation between fast- and slow-rotators can be asserted by the relation \(\lambda = 0.31 \sqrt T\) found.
among 260 early-type galaxies in the ATLAS$^3$D project (Emsellem et al. 2011), where the apparent stellar ellipticity $\varepsilon = 1 - 0.5 c/a$, and the axial ratio $c/a$ is computed here from the eigendecomposition of the angular inertia tensor for all bound stars with $r < 2 r_\star$. Approximately, $\lambda_{\text{HI}} \leq 0.2$ corresponds to a bright early-type system (E), while S0s and fainter ellipticals can exhibit significant rotational support; this distinction can provide insight as to their formation, featuring less overlap between types than other metrics e.g. $V/\sigma$.

The formation/survival timescales of bisymmetric structures that are associated with transformation mechanisms are conveyed with two metrics. The bar radius, normalised by the stellar scalelength ($r_{\text{bar}}/r_\star$), is estimated via an empirical method (see Yozin & Bekki 2014, and references therein); briefly, we detect a bar if a succession of ellipses fit to isophotes of the deprojected, face-on surface brightness distribution (incrementally, from 21 to 28 mag arcsec$^{-2}$) deviate in phase by less than 10 degrees, where the outer most ellipse has an axis ratio no larger than 0.4.

The disc-wide presence of spiral/tidal arms is quantified with $A_{\text{HI}}$, the mean amplitude of the second Fourier mode in concentric shells spanning radii from the bar radius up to 2 effective radii; where spiral arms typically register in the range $0.15 < A_{\text{HI}} < 0.6$ (Rix & Zaritsky 1995).

2.6.2 Star formation

We express the logarithmic SF rate (SFR) in terms of an offset ($\Delta SFR$) from that expected for a galaxy of its instantaneous stellar mass, for which we adopt the linear relation devised from star-forming galaxies in the SDSS catalog by Kauffmann et al. (2003b). By considering the colour bimodality expressed by the general galaxy population, a passive classification for a galaxy can be determined if $\Delta SFR < -1$ (i.e. SFR reduced by a factor 10), with the red sequence lying at approximately -2 (see also Bluck et al. 2014). A similar result is obtained if we assume that a galaxy can be classified as quenched if its specific SFR ($sSFR$) $< 10^{-11}$ yr$^{-1}$, as implied from a bimodality in the sSFRs of central galaxies in the SDSS DR 7 (Wetzel et al. 2013).

Furthermore, the visual signature of SF can manifest in strong H$\alpha$ emission, a tracer of massive star formation which we can approximate with the relation (Kennicutt 1998):

$$L(H\alpha) = SFR(M_\odot \text{yr}^{-1}) \times 1.26 \times 10^{41} \text{ergs}^{-1}$$

where the SFR is estimated from new stellar particles with age less than $3 \times 10^7$ yr (the approximate age of an $\sim 8 M_\odot$ star).
Gas mass associated with the satellite

We quantify the simulated loss of gas with a def\(_{\text{HI}}\) parameter (Solanes, Giovanelli & Haynes 1996):

\[
\text{def}_{\text{HI}} = a + \log_{10}(hD_{\text{opt}}) - \log_{10}(M_{\text{HI}}),
\]

(7)

where \(h\) is the Hubble parameter (~0.7) and \(D_{\text{opt}}\) is the linear optical diameter, which we assume equivalent to the galacto-centric radii at which the deprojected azimuthally-averaged surface brightness falls under 25 mag arcsec\(^{-2}\). \(M_{\text{HI}}\) is the total mass of gravitationally bound gas in our simulated galaxy, and \(a\) and \(b\) are statistically-inferred coefficients which vary according to morphological type. At each time step of our simulations, we classify the type with \(B/T\) and linearly interpolate between the appropriate coefficients; this, combined with a \(D_{25}\) that evolves according to our adopted stellar synthesis models, yields a def\(_{\text{HI}}\) parameter comparable with observations.

3 RESULTS

3.1 Dependence of the satellite evolution on group tides since infall at \(z = 1\)

Fig. 6 shows the deprojected face/edge-on distribution of stars (in \(\mu_{\text{HI}}\)) and gas from our baseline Tidal and Isolated simulations, in a series of snapshots spanning 10 Gyr since their first crossing of the group virial radius. It illustrates how their first pericentre following infall excites the formation of tidal arms and a bar; the associated tidal heating thickens the disc (resulting in boxy isophotes), while the incorporation of an ISM, funnelled to the centre by the bar and tidal torquing, contributes to bulge growth and bar dissipation. Neither tidal stripping nor secular/induced SF can remove the satellites’ gas completely within this 10 Gyr timescale.

3.1.1 Star formation history

In the absence of gas accretion, the SF rate among our baseline simulations is shown in Fig. 7 to follow an exponential decline in SFR. This is interrupted only by tidally-triggered SF at each pericentre passage, with an enhancement factor of up to 5 consistent with previous numerical studies (Di Matteo et al. 2008), and attributed to gas infall from the HI-rich disc.

The SFR metric implies the mean timescale of 8 Gyr since the accretion of a luminous dwarf galaxy is sufficient for its classification as passive, with a stellar mass growth in the intervening time of only 20 percent. From SFR-mass relations (Whitaker et al. 2012), a characteristic SFR of order \(1\ M_{\odot}\) yr\(^{-1}\) between \(z = 0 - 1\) for a \(10^9\ M_{\odot}\) galaxy would indicate an analogous isolated galaxy could grow by a factor of 1-5, the majority of which fuelled by a cold gas accretion mode which dominates in this stellar mass regime for all \(z\) (Dekel et al. 2009). In conservative analytical models approximating the outflow strength and recycled fraction of gas, the SFR due to fresh accreted gas can be as much as 50 to 90 percent of the total SFR within a gas consumption timescale, for those galaxies hosted by low mass halos in which outflow is relatively efficient (Sanchez Almeida et al. 2015). The deficit between the initial SFR of our star forming simulations with respect to \(\Delta\text{SFR}=0\) can therefore be explained by the exclusion of accretion and a gaseous halo from our code, but the subsequent evolution will depend
sensitive on the timescale in which this accretion is shut off, which we here assume as instantaneous.

An observable implication of this unreplenished gas reserve, combined with the influence of group tides, is the outside-in truncation of SF (Fig. 8). Previously reproduced by Bekki & Couch (2011) in simulations of massive group spirals and attributed to the heating of the outer disc/gas infall, we extend this result here to dwarf satellites, and indeed find the radial extent of SF typically lies where the stellar/gas Q parameters ($= \sigma_\kappa/3.36G\Sigma$, where $\sigma$, $\kappa$, $G$ and $\Sigma$ are the radial velocity disperion, epicyclic frequency, gravitational constant and surface mass density respectively) exceed the canonical range of 1.5-2 required for axisymmetric stability. A similar phenomenon was obtained by Bekki, Couch & Shioya (2002), who also attributed the growth in Q and concurrent spiral arm fading with ceased halo gas accretion.

The ongoing presence of H$\alpha$ emission beyond 8 Gyr ago infall means these satellites (under exclusively tidal influence) would not meet the definition of a quenched system (e.g Geha et al. 2012) nor that of a classical S0; their bluecores are however comparable with a sample of dEs/dS0s observed in recently accreted subgroups of the Ursa Major cluster (Pak et al. 2014) for which no evidence of significant hydrodynamical influence is found.

3.1.2 Gas and halo loss

An initial $\Delta M_{\text{HI}}$ of zero is consistent with our satellite commencing with the mean structural properties/$\Sigma_{\text{gas}}$ of its mass/type, with a subsequent increase with time corresponding to tidal stripping, outflow and consumption of gas via SF. Uncertainties in $\Delta M_{\text{HI}}$ among observed galaxies can be large ($\sim0.25$ dex; Pappalardo et al. 2012), motivating Cortese, Catinella & ad S Heinis (2012) to adopt $\Delta M_{\text{HI}}>0.5$ to denote a deficient galaxy among their sample of 322 nearby galaxies. Adopting this threshold, we find a timescale of 8 Gyr within the group environment sufficient to render an originally gas-rich galaxy H-I-deficient, albeit not removed of gas entirely.

Fig. 9 shows how this reflects a loss of at least 30-60 percent of its original cold disc gas; by comparison, the dark matter halo is truncated such that only 5 percent of its original gas remains bound to the galaxy (Fig. 9); In practice, the dynamical mass evolution within the tidal radius of the satellite (which is dominated by baryons) only amounts to a largely monotonic reduction in time by 50 percent. This result contrasts sharply with those of Wetzel et al. (2013) proposed substantial stellar mass growth following group infall as part of a two-stage quenching process wherein the initial stripping of the satellite’s halo gas is inefficient.

The gas mass loss exhibited in Tidal simulations includes a secular component which we assume equal to that demonstrated by Isolated; this amounts therefore to about 20 percent loss over 10 Gyr, divided between consumption by SF and outflows. As a sanity check, the corresponding gas depletion timescale of Isolated ($\sim50$ Gyr) is compared with that expected for its stellar mass, where for the latter we assume a typical HI-to-stellar mass ratio for a $10^9 M_\odot$ galaxy of 1 to 5 (e.g Haynes et al. 2011) and a median SFR of 0.1 to 0.2 $M_\odot/yr$ (Kauffmann et al. 2003b). This yields an acceptable discrepancy by a factor 2-3, broadly attributed to our simple outflow model and the artificial closed-box nature of Isolated.

3.1.3 Transformation mechanisms and efficiency

Fig. 10 illustrates the light profile of Tidal/z = 1 & 8 Gyr after initial infall. In contrast with the single exponential profiles obtained in the collisionless but otherwise similar simula-
tions of Villalobos et al. (2012), our satellites' profiles comprise a bulge component strongly linked with tidally-induced SF (Christlein & Zabludoff 2004), and an anti-truncation (up-turn) in the outer disc whose origin is less clear. We find tentative evidence for the break strength $T$ (ratio of inner and outer disc scalelengths) to increase as a function of time resident in the group potential (inset panel). This contrasts with an analysis of the $V$-band $μ(r)$ profiles of 280 classical S0s by Maltby et al. (2015), a morphological type also preferentially formed in groups (Willman et al. 2009) but for which no environmental-dependence of $T$ is found. Instead, Maltby et al. compare their sample with equivalent spiral galaxies and propose this up-turn is a manifestation of extended bulge light that dominates a fading disc.

The quantitative growth of the central bulges of Tidal/z = 1/Tidal/z = 0 and Isolated is shown in Fig. 7. In the absence of merger activity, these are not classical bulges, as further indicated with line-of-sight velocities of the disc which reveal a cylindrical profile in the nucleus. The slow secular growth exhibited by isolated is consistent with the assertion by Kormendy & Kennicutt Jr. (2004) that pseudo-bulges can comprise up to 10 percent of the total disc mass. By contrast, the bulge growth of the Tidal simulations, whose $B/T$ is consistent with the corresponding range, for this stellar mass, of $0<B/T<0.4$ collated by Bluck et al. (2014), emerges principally as a series of large enhancements coincident with pericentre passages.

The underlying mechanism of this bulge growth is revealed by the formation of a stellar bar, as indicated by $r_{b}$ at 8 Gyr after infall. In both Tidal simulations, the first pericentre passage following infall is sufficient to tidally-trigger this structure to its largest observed radius. A subsequent enhancement in the SF rate and increase in $B/T$ is thus consistent with gas infall being facilitated by tidal torques/the stellar bar. However, this simple observable correlation between bar and bulge breaks down with time because the growth of the bulge increasingly dominates the shape of isophotes in the inner disc and thus weakens the visual signature of the bar, whilst the concentration of SF in the bulge means $B/T$ can also grow due to the relative fading of the bar and disc. A decline in $r_{b}$ is also to be expected after several pericentre passages due to the buckling of the bar by significant gas infall, similarly reported in simulations of Virgo clusters satellites by Mastropietro et al. (2005), and the progressive weakening of the bar through angular momentum exchange (Bournaud, Combes & Semelin 2005).

An important result however is that the simulated $B/T$ is at no point consistent with the range $0.5 < B/T <$ P04 associated with an early-type morphology (Kormendy & Kennicutt Jr. 2004; Willman et al. 2009). This limited morphological evolution, wherein late-type structure is fundamentally maintained, is also reflected in $λ_R$. In expanding upon Fig. 7, which highlights the sharp loss in angular momentum upon each pericentric passage of the Tidal simulations (with respect to the stability of Isolated), Fig. 11 illustrates the evolution of $λ_R$ as a function of the apparent stellar ellipticity $ε$. Their evolution towards lower $ε$ and $λ_R$ is consistent with the thickening/heating of the inner disc by tidal shocks upon pericentre passages and the triggered bar. The final kinematics thus ultimately resemble those observed for Sa and S0 morphological types, lying in agreement with our prior determination of its type with $B/T$. Gas accretion from filaments/other galaxies could in principle raise $λ_R$ if corotating with the stellar disc, although we have assumed no such process occurs within our group environment.

A key feature of these Tidal simulations that precludes their association with the transitory S0 classification is that disc spiral structure beyond the bar proves to be quite robust, being triggered by tides upon all four pericentre passages of the Tidal/z = 1 simulation. The peak amplitudes

\[ \frac{B}{T} \text{ at 8 Gyr} \]

\[ r_{b} \]

\[ ε \]

\[ λ_R \]
of these arms are short-lived (or order a Gyr) and weaker on successive orbits because i) the stellar disc is increasingly concentrated, and ii) SF that would otherwise be triggered in these outer disc regions is suppressed by the prior infall/stripping of gas and the absence of external gas accretion (e.g. Bekki, Couch & Shioya 2002). Nonetheless, there is only a ~Gyr window (in Tidal/z = 0) in which our Tidal satellites do not bear the signature of an arm (i.e. where A_\text{II} < 0.15), strongly suggesting they cannot in general exhibit the axisymmetries inherent to E/S0s.

3.2 Dependence of the satellite evolution on orbital inclination

Fig. 12 compares the baseline simulation Tidal/z = 1 with the combined results of Tidal/z = 1/Orientations, wherein we find the former corresponds closely to the mean evolution of the latter in the various metrics that describe the satellite evolution. Variations, in particular those of the triggered starbursts upon first infall, primary stem from how the efficiency with which tidal shocks can trigger bar instabilities/gas infall depend on the disc/orbital plane alignment. On long timescales, however, this dependence becomes ambiguous (e.g. due to stochastic events/resonances of the disc; Kazantzidis et al. 2011). Moreover, the stripping efficiency of the extended gas disc and DM halo (the latter being prescribed with no initial net angular momentum) are (to first order) invariant with respect to infall inclination.

The clear exception lies in the growth of B/T which, although in part a manifestation of tidal heating (due to tidal shocks which prove weakly dependent on inclination), reflects also a sensitivity to the efficiency of bulge growth by the starburst upon first infall (Christlein & Zabludoff 2004). Acting upon a near pristine stellar/gas disc, the first group tide interactions that can induce a strong bar/gas infall in a prograde edge-on/inclined scenario (adopted in Tidal/z = 1) are conversely inefficient in a pure face-on and/or retrograde scenario. However, a weak enhancement in B/T in these latter cases corresponds to an inefficient manner in which the associated mechanisms described in Section 3.1.3 can destroy/obscure the bar.

We therefore identify a complex relationship between infall inclination and structural properties of a star-forming group satellite, which manifests in a broad range of B/T (since a mean infall lookback time of 8 Gyr) consistent with observations for this mass range (Bluck et al. 2014). However, the transition to a quenched status over this timescale, reflected in ΔSFFR and \text{def}_\text{II}, remains well described by the reference Tidal models of Section 3.1.

3.3 Dependence of the satellite evolution on satellite-satellite interactions

Fig. 12 compares the baseline simulation Tidal/z = 1 with the combined results of Tidal/z = 1/Harassment. The principle remark from this comparison lies in the broad scatter revealed by the latter sample; the width of this scatter depends on the interaction softening length, although our adopted constraint is compatible with the typical minimum separation between encounters (~50 kpc) found by Villalobos, De Lucia & Murante (2014), who similarly establish that tidal disruption of a satellite on an infalling orbit is, to first order, governed by interactions with the group halo rather than harassment by other group members.

Satellite encounters at large orbital radii trigger an elevated SF rate upon first infall compared with Tidal/z = 1 (and an associated enhancement in \text{def}_\text{II} also contributed to by tidal stripping), although the SF history largely remains defined by the secular exhaustion of the original gas disc. As noted in Section 3.1.3, the earliest triggers of gas infall/starbursts largely define the bulge mass, as subsequent tidal interactions are unable to trigger as large/strong a bar. These interactions are not sufficient to disrupt the disc directly; instead, three-body interactions or those of unequal mass ratios can either send the dwarf satellite to a higher energy orbit (increased pericentre, period) where the tidal influence of the group halo is weaker, or towards a efficiently disruptive path to the group centre. Two such examples are illustrated in Fig. 12 with a highly divergent evolution in their respective B/T.

3.4 Dependence of the satellite evolution on interactions with the Intra-Group Medium

Fig. 13 compares the evolution in ΔSFFR and \text{f}_{\text{gas}} as exhibited by Isolated and Ram simulations. A key observation here lies in the enhancement in SF with respect to Isolated following first infall, a phenomenon similarly reported by Bekki (2014) who attributed this star burst to the compression of the satellites’ ISM at the ICM-ISM interface (see also Kronberger et al. 2008). In Ram/z = 1, this enhancement can be long-lived because the stripping of the satellites’ cold disc gas is inefficient in this scenario, with a final \text{f}_{\text{gas}} of 60 percent.

The evolution of simulation Ram/z = 1/Overdensity indicates that a localised pocket of overdense ICM is sufficient to remove ~50 percent of the satellite’s cold gas disc within only its first orbit of the group. If combined with the gas loss exhibited in Tidal/z = 1 (i.e. combining simultaneous tidal and ram pressure mechanisms acting on the satellite since first infall), this satellite can lose all its gas and therefore be effectively quenched within 4-5 Gyr of first passing ρV^2.

This result is consistent with an apparent peak in the frequency of satellites being quenched by ram pressure stripping at z = 1, where this frequency is not simply a monotonic function of time (Bahe & McCarthy 2015). However, our result is largely qualitative insofar as our idealisation of the ICM distribution of a typical group at z = 1 carries some uncertainties. The strong dependence of the quenching timescale on the local ICM density of the satellite is therefore the main result of this section.

In an attempt to verify the gas loss simulated numerically in Ram/z = 1, we draw upon the analytical formulation for the satellite stripping radius (r_{\text{str}}, at which ρV^2 exceeds the orthogonal restoring force of the galaxy disc) of Gunn & Gott (1972):

$$\rho V^2 > \Sigma(r) \frac{\delta \phi(r)}{\delta z},$$

where \Sigma(r) is the gas surface mass density at galacto-centric radius r, and \delta \phi/\delta z is the gradient of the potential field.
Figure 12. Diagnostic of ΔSFR, def_{HI}, and B/T (as in Fig. 7), shown for simulation Tidal/z = 1 (red solid line), and the mean/1σ variation (black dotted line/grey shaded region) in the respective evolution of two sets of simulations run in accord with Monte-Carlo sampling, where the top row shows the results for 16 variants of Tidal/z = 1 where the initial orientation of the satellite (with respect to its orbital plane) is assigned randomly (Orientations), and the bottom row shows the results for 16 variants of Tidal/z = 1 where other group galaxies are incorporated in the model as point masses and the primary satellite is assigned a random initial location on the locus defined by the group halo r_{sat} (Harassment). In the B/T panels, the evolution of selected individual simulations from each set are shown, including a satellite accreted face-on in inclination, and two simulations in which harassment strongly alters the primary satellite’s orbit and thus its transformation process (red dotted lines).

4 DISCUSSION AND CONCLUSION

In Section 2, we developed a representative model of a gas-rich late-type dwarf galaxy (stellar mass \( \sim 10^8 \, M_\odot \)), using scaling relations and the mean properties of isolated galaxies in this mass regime, to match their observed mass distributions and SFR as a function of gas surface density. In Section 3, we establish the typical chemodynamical evolution of this satellite following first infall to a \((10^{13} \, M_\odot)\) group environment in a suite of simulations. We address the idealistic nature of the group model (where significant mass assembly is not modelled) by characterising the satellites’ evolution as bounded by two group models/infall orbits at \( z = 1 \) and \( z = 0 \).

We first establish, in a pure tidal model of a group (Section 3.1), that the mean time in which a low-z satellite of this mass has been resident with a group (\( \sim 8 \) Gyr) is sufficient to suppress SF to a passive (and H I-poor) status, if assuming rapid/instantaneous removal of external gas sources (Fig. 6). This galaxy is not quenched, insofar as SF is ongoing (but centrally concentrated); tidal heating plays an active role although the morphological transition to an early type is not complete within a 8-10 Gyr timescale.

In sections 3.2-3, we take a Monte-Carlo approach to assert the sensitivity of this evolution to a variety of orbital inclinations and satellite harassment (Fig. 11), and confirm that the above result is indeed sufficiently characteristic of a satellites’ typical evolution. There exists however a broad scatter, in particular for those simulations in which other group members are included, with the implication that the characteristic quenching/transformation can be mitigated for a significant proportion of infalling satellites whose orbits acquire significant energy.

In section 3.4, we simulate numerically the hydrodynamical ISM-ICM interaction (ram pressure stripping) with results that are consistent with a classic analytical model.
Kazantzidis et al. 2011), if most such satellites maintain their
motion. Our study is novel with respect to the adopted satel-
tile/host masses, but is otherwise consistent with previ-
sous numerical studies that demonstrate how satellites on
earlier infall times for lower mass satellites (Fig. 13), albeit with deviations that can be explained in
terms of a correlation of satellite and local ICM velocities.
We find in general an enhanced starburst upon first infall,
followed by a suppression whose rate depends on the local
ICM density; if matching the density to that preferentially
found around quenched satellites of previous numerical stud-
ies, we find a significant gas loss imposed by ram pressure
stripping, with a corresponding quenching of SF within 4–5
Gyr of first infall at z = 1.

To conclude, our simulations are consistent with ob-
servational evidence for the inefficiency with which a 10^9
M_☉ satellite is quenched in a (10^{13} M_☉) group environment
(Wheeler et al. 2014), if most such satellites maintain their
relatively slow orbital decay following satellite harassment,
and are not resident within a significant local overdensity of
the intra-group medium. Our simulations are however ide-
alised, albeit of far higher resolution than previously doc-
umented cosmological-scale simulations whose datasets en-
compase this scenario, motivating the following discussion
with proposals for future refinements to our model.

4.1 A comparison of group tidal mechanisms with
previous studies
Our study is novel with respect to the adopted satel-
ite/host masses, but is otherwise consistent with previ-
sous numerical studies that demonstrate how satellites on
eccentric orbits of a massive neighbour with weak dy-
namical friction experience a succession of impulsive tidal
shocks (due to the group tides) which heat the stellar
disc (Gnedin, Hernquist & Ostriker 1999). This mech-
anism will depend on the orbital pericentre radius/period

(McCarthy et al. 2008; Villalobos et al. 2012), with those
satellites that generally avoid the densest (central) regions of
their respective environment, such as those modelled in
this study, losing their disc (and rotational-support) least
efficiently (Mastropietro et al. 2005).

An integral part of this tidal transformation is the
triggering of a bar instability (Kazantzidis et al. 2011).
This is quite resolution-dependent, in light of the stochas-
tic nature of intrinsic disc evolution in numerical models
(Sellwood & Debattista 2009), so the robustness of our Is-
olated simulations to this instability over 10 Gyr provides
some confidence in our modelling: We predict therefore the
tidal triggering of a bar in a 10^9 M_☉ satellite on its most
common infall trajectory (Villalobos et al. 2012). The ef-
iciency with which stellar bars are destroyed by the sub-
sequent growth of a central mass concentration/angular
momentum exchange from infalling gas is also resolution-
dependent, but our results (a bar lifetime of order 1–2 Gyr)
are consistent with higher-resolution studies which consider
this problem in detail (Bournaud, Combes & Semelin 2005).

Assuming therefore the slow strangulation of a 10^9
M_☉ group satellite, tidal heating facilitated by our shorter-
lived bar will be therefore less efficient than that dem-
strated in pure collisionless simulations, such as those of
Kazantzidis et al. (2011) who assumed the early and com-
plete removal of gas in their models of dSph formation from
10^7 M_☉ progenitor discs.

Our approach to modelling a range of harassment sce-
narios by other satellites (Section 3.3) does not highlight any
significant systematic variation to this evolution. A similar
result was found by Villalobos, De Lucia & Murante (2014)
for more massive satellites, although their explicit modelling
of a live group halo introduced the concept that other satel-
ites can indirectly mitigate satellite transformation by in-
fact modifying the mutual group potential and the associ-
ated satellite orbits.

We assert therefore that for a given infall trajectory,
dwarf satellite transformation is to first order dependent on
time resident within the group halo. The concurrent sup-
pression of SF facilitated by group tidal mechanisms is ineff-
cient, but an inverse correlation in the dwarf quenched frac-
tion with mass (Wheeler et al. 2014) is consistent with the
earlier infall times for lower mass satellites (De Lucia et al.
2012; Wetzel et al. 2013), which would experience a smaller
dynamical friction timescale in the lower mass hosts to which
they are preferentially accreted at higher z (e.g. Jiang et al.
2008).

This assumes however that we have properly charac-
terised the tidal interaction history of a 10^9 M_☉, satel-
life i.e. the incidence of major mergers, which we do not
model in detail but which can significantly disrupt the stel-
lar system (and form a slow rotating system; Fig. 9) is
low. If adopting the definition of a major merger utilised
by Rodriguez-Gomez et al. (2015) (e.g. with mass ratio >
0.25), and integrating their estimated merger rate for this
stellar mass which they deduce from the tracking of sub-
halo merger trees in the Illustris cosmological-scale simu-
lation, we find up to 25 percent of such systems, a minority,
will be involved in a major merger since z = 2. This is
consistent with most slow rotating systems, whose forma-
tion is linked with major mergers, being more massive sys-
tems than considered here (≥ 10^{10.5} M_☉; Emseleenn et al.
2011), and whose mergers rate are higher for all z. Moreover, bright dwarves corresponding to our $10^9 \, M_\odot$ system are least likely among all dwarves to have been pre-processed and accreted as a satellite to a group-mass host (e.g. Wetzel, Deason & Garrison-Kimmel 2014), a process during which mergers/strong tidal interactions are feasible (Gnedin 2003).

The tidal model of the group presented in this study is similar to that of Bekki & Couch (2011), who demonstrated the transformation of spirals to S0s in response to recent findings that S0s are preferentially formed in ($\sigma < 750$ kms$^{-1}$) groups (Willman et al. 2009; Just et al. 2010). This supports the role of tidal interactions in their formation, as opposed to the hydrodynamical ISM-ICM interactions which are expected to be dominant in higher-$\sigma$ environments. The long transition timescale conveyed by our satellites is consistent with the continuous growth in S0 numbers since intermediate redshifts (Just et al. 2010), while the significant reduction in $\lambda_B$ and $\varepsilon$ (Fig. 9) is consistent with tidal mechanisms being essential in their formation (as opposed to being simply faded spirals, e.g. van der Wel et al. 2010; Maltby et al. 2015).

We stress however that we do not reproduce the classic morphology of S0 in our studies, one discrepancy being the lasting spiral/tidal arm structures in our Tidal simulations (in addition to the ongoing SF which we discuss further in Section 4.2). The inability of our group environment to consistently form S0s is qualitatively in agreement with their being typically more massive than the stellar mass range considered here, as implied by their luminosity functions (e.g. Kelvin et al. 2014). Furthermore, the $S0$ number fraction peaks in group systems with velocity dispersions of 600-700 kms$^{-1}$ (Just et al. 2010), which are nominally far more massive, and quite likely to have accreted from, poor $10^{13} \, M_\odot$ groups with $\sigma \simeq 150$ kms$^{-1}$ (McGee et al. 2009).

Instead, our Tidal simulations yield systems which are, morphologically and kinematically, characteristic of dwarf S0s. Unlike S0s, these systems are distinguished from the dE classification in which they are often subsumed by a two-component fit to their light profile and, saliently, evidence of a disc including spiral structure (Sandage & Binggeli 1984; Aguerri et al. 2005).

Our simulations also convey how tidal influences within a $10^{13} \, M_\odot$ group will be accompanied with ongoing starbursts that are increasingly concentrated in the disc centre due to gas infall facilitated by tidal torques, bar dynamics and an enhanced Q in the outer disc. Optically, this would replicate the blue cores found among 70 percent of the dE/dS0 galaxies of the Ursa Major cluster by Pak et al. (2014), with the dS0 subsample exhibiting the most blue $g-i$ colours for a given magnitude (in a range $-18 < M_i < -9$). Since this cluster possesses no significant evidence of ongoing ram pressure stripping, $H$ I-deficiency, they hypothesize that these galaxies represent satellites in transition, whose evolution is primarily driven by tidal interactions. This is supported by a correlation in the frequency of dEs/dS0s with the dynamical state/virialisation of their respective subgroups (see also Tully & Trentham 2008), and a systematically more blue colour compared with their counterparts in the Virgo cluster (the latter exhibiting strong evidence of ram pressure stripping; Chung et al. 2007). Our earlier assertion that the bright dwarves modelled here are least efficiently transformed by group tidal mechanisms is also intriguingly supported by a statistically-significant (at the $3\sigma$ level) absence of dEs in a range $-18 < M_i < -17$ that closely corresponds to our considered stellar mass.

### 4.2 A comparison of group quenching mechanisms with previous studies

Our simulations indicate that the tidal mechanism acting within an idealised group (e.g. harassment, stripping) cannot consistently quench a bright dwarf satellite, in which case the environmental processes that dominate the formation of quiescent systems (Wetzel et al. 2013), in particular those in the dwarf mass regime (Geha et al. 2012), hinge upon the interaction of the satellite with the intra-group medium. A need to characterise its efficiency is highlighted by increasing evidence that $10^{12-13} \, M_\odot$ hosts are the building blocks of larger environments, and where quenching mechanisms appear to commence (McGee et al. 2009; Rafieferantsoa et al. 2015).

Our assumption of the instantaneous removal of a $10^9 \, M_\odot$ satellites’ hot gaseous corona by the group ICM is broadly consistent, albeit conservative, with respect to previous studies which explicitly model this phenomenon and find it almost complete within a Gyr (Kawata & Mulchaey 2008; Bekki 2009). This is supported observationally by the apparent suppression in satellites on their first infall to groups (Rasmussen, Ponman & Mulchaey 2006), and even up to several $\tau_{\text{vir}}$ from group centres (Rasmussen et al. 2012). The suppression of SF by the shutting off of cold mode gas accretion predicted to contribute $\geq 50$ percent to the SFR of bright dwarves (Sanchez Almeida et al. 2015) is supported further by recent cosmological simulations that highlight how the SF of galaxies is determined by this external gas source prior to infall (Rafieferantsoa et al. 2015). Following accretion to halos $< 10^{14} \, M_\odot$, Rafieferantsoa et al. demonstrate how the $H$ I-richness of galaxies traces the sSFR, implying the starvation of the satellite on a timescale of several Gyr.

Various studies espouse a similar timescale during which the SFR declines in an exponential manner since infall, with $e$-folding timescales inferred to be of order 1-3 Gyr (Wang et al. 2007; McGee et al. 2009; De Lucia et al. 2012) but which in practice can vary widely depending on respective satellite and host masses (Bekki 2014). This lies broadly in accordance with the predominantly secular consumption of extant disc gas in our Tidal simulations irrespective of triggered starbursts (Fig. 6), which proceeds according to a SF model that matches a dependence on gas surface density for analogous metal-poor dwarf galaxies (Bigiel et al. 2008). The low SF efficiency with respect to e.g. the Kennicutt-Schmidt relation (Fig. 4) is thus demonstrated to match the slow transition to an inactive status..

An alternative two-stage mode of suppression was recently introduced by Wetzel et al. (2013), who compare the SFR of satellites with a statistical parametrization of central galaxy SFRs in the SDSS DR 7 (with a completeness limit lying slightly above our stellar mass at $10^9.7 \, M_\odot$). Their analysis indicates that the suppression of SF in dwarf satellites can be delayed by more than 4 Gyr after infall (during which the build up of new stellar mass is substantial, of order 50 percent), followed by a rapid decline in SFR with
timescale < 1 Gyr. Their conclusion that these satellites are accreted with enough cold gas to sustain the SFR prior to infall is not supported by our simulations, although we have adopted an initial gas fraction ($f_{\text{gas}}$) implied by observations for this stellar mass ($\sim 1$; Popping, Behroozi & Pee 2014). This may underestimate the total associated gas, which has recently demonstrated for infalling satellites of the Illustris simulation to be in the range $f_{\text{gas}} = 2 - 8$ (Sales et al. 2015).

We do note however a qualitative agreement in this two-stage satellite quenching with our ram pressure simulations (Section 3.4). Fig. 13 conveys a high sustained SFR (for several Gyr) in the Ram/ z = 1/ Overdensity simulation, before the available gas is exhausted and/or the local ram pressure at pericentre passage is sufficient to effectively quench the satellite within 5 Gyr of first virial crossing. This triggering of SF at the ICM-ISM interface, with simultaneous stripping in the outer disc, contributes to the concentration of SF at its centre where the restoring force is largest (Bekki 2014). A similar enhancement in SFR and a truncation in the feedback, compared to field counterparts, was noted in analyses of Virgo cluster spirals (Koopmann & Kenney 2004; Koopmann, Haynes & Catinella 2006). This phenomenon is not limited to dense environments, as revealed by the observation of both a starburst on the leading edge and rapid gas loss via ram pressure stripping in the trailing tail of a late-type satellite of a poor group by (Rasmussen, Ponnam & Mulchaey 2006). On the other hand, an analysis by Rasmussen et al. (2012) of SF rates among the constituents of 23 local galaxy groups finds only 1 to 10 percent of group galaxies exhibiting evidence of starbursts; instead, the net effect on SF, with respect to their field sample, is a suppression by $\sim 40$ percent at group-centric distances up to $2r_{vir}$.

A sustained triggering of SF is limited to a model in which we assume a locally overdense ICM, which recent large-scale hydrodynamical simulations predict infalling satellites to preferentially lie within, with the corresponding quenching timescale in group hosts less than the first orbital period (Bahe & McCarthy 2015; Cen, Pop & Bahcall 2014). However, their results, implying the complete quenching of the $10^{10-1.5}$ population of satellites of $10^{11-13.5}$ $M_\odot$ groups within 4 Gyr contrast sharply with those of Wheeler et al. (2014), who adopt mock observations from the Millennium-II simulation and establish the long quenching timescales ($\geq 6 - 7$ Gyr) that motivated this paper. At present, we emphasise that these cosmological simulations utilise baryonic particle masses of order $10^8 h^{-1} M_\odot$ (corresponding to a resolution of only $\sim 100$ particles for a stellar mass of $10^9 M_\odot$). Nonetheless, we identify some promising agreement with our better refined model that encourages further refinement.

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