The different physical mechanisms that drive the star formation histories of giant and dwarf galaxies

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Accepted 2007 July 5. Received 2007 June 18; in original form 2007 March 30

ABSTRACT
We present an analysis of star formation and nuclear activity in galaxies as a function of both luminosity and environment in the fourth data release of the Sloan Digital Sky Survey. Using a sample of 27 753 galaxies in the redshift range 0.005 < z < 0.037 that is ≳ 90 per cent complete to \( M_r = -18.0 \), we find that the H\(_\alpha\) equivalent width, \( \text{EW}(\text{H}\alpha) \), distribution is strongly bimodal, allowing galaxies to be robustly separated into passively evolving and star-forming populations about a value \( \text{EW}(\text{H}\alpha) = 2 \) Å. In high-density regions ∼70 per cent of galaxies are passively evolving independent of luminosity. In the rarefied field, however, the fraction of passively evolving galaxies is a strong function of luminosity, dropping from 50 per cent for \( M_r \sim -21 \) to zero by \( M_r \sim -18 \). Indeed for the lowest luminosity range covered (∼18 < \( M_r < -16 \)) none of the ∼600 galaxies in the lowest-density quartile is passively evolving. The few passively evolving dwarf galaxies in field regions appear as satellites to bright (∼\( L^* \)) galaxies. We find a systematic reduction of ∼30 per cent in the H\(_\alpha\) emission from dwarf (∼19 < \( M_r < -18 \)) star-forming galaxies in high-density regions with respect to field values, implying that the bulk of star-forming dwarf galaxies in groups and clusters are currently in the process of being slowly transformed into passive galaxies. The fraction of galaxies with the optical signatures of an active galactic nucleus (AGN) decreases steadily from ∼50 per cent at \( M_r \sim -21 \) to ∼0 per cent by \( M_r \sim -18 \) closely mirroring the luminosity dependence of the passive galaxy fraction in low-density environments. This result reflects the increasing importance of AGN feedback with galaxy mass for their evolution, such that the star formation histories of massive galaxies are primarily determined by their past merger history. In contrast, the complete absence of passively evolving dwarf galaxies more than ∼2 virial radii from the nearest massive halo (i.e. cluster, group or massive galaxy) indicates that internal processes, such as merging, AGN feedback or gas consumption through star formation, are not responsible for terminating star formation in dwarf galaxies. Instead the evolution of dwarf galaxies is primarily driven by the mass of their host halo, probably through the combined effects of tidal forces and ram-pressure stripping.

Keywords: galaxies: active – galaxies: clusters: general – galaxies: dwarf – galaxies: evolution – galaxies: stellar content.

1 INTRODUCTION
It has been known for decades that local galaxies can be broadly divided into two distinct populations (e.g. Hubble 1926, 1936; Morgan 1958; de Vaucouleurs 1961). The first are red, passively evolving, bulge-dominated galaxies dominated by old stellar populations that make up the red sequence, and the second make up the ‘blue cloud’ of young, star-forming, disc-dominated galaxies (e.g. Strateva et al. 2001; Blanton et al. 2003b; Kauffmann et al. 2003a,b; Baldry et al. 2004; Driver et al. 2006; Mateus et al. 2006).

It has also long been known that the environment in which a galaxy inhabits has a profound impact on its evolution in terms of defining both its structural properties and its star formation histories (SFHs) (e.g. Hubble & Humason 1931). In particular, passively evolving spheroids dominate cluster cores, whereas in field
regions galaxies are typically both star forming and disc-dominated (Blanton et al. 2005a). These differences have been quantified through the classic morphology–density (Dressler 1980) and star formation (SF)–density relations (Lewis et al. 2002; Gómez et al. 2003). However, despite much effort (e.g. Treu et al. 2003; Balogh et al. 2004a,b; Gray et al. 2004; Kauffmann et al. 2004; Tanaka et al. 2004; Christlein & Zabludoff 2005; Rines et al. 2005 Baldry et al. 2006; Blanton, Berlind & Hogg 2006; Boselli & Gavazzi 2006; Haines et al. 2006a,b; Mercurio et al. 2006; Sorrentino, Antonuccio-Delogo & Rifatto 2006; Weimann et al. 2006a,b; Mateus et al. 2007), it still remains unclear whether these environmental trends are: (i) the direct result of the initial conditions in which the galaxy forms, whereby massive galaxies are formed earlier preferentially in the highest overdensities in the primordial density field, and have a more active merger history, than galaxies that form in the smoother low-density regions; or (ii) produced later by the direct interaction of the galaxy with one or more aspects of its environment, whether that be other galaxies, the intracluster medium (ICM), or the underlying dark matter (DM) distribution (e.g. tidal stripping). Several physical mechanisms have been proposed that could cause the transformation of galaxies through interactions with their environment such as ram-pressure stripping (Gunn & Gott 1972), galaxy harassment (Moore et al. 1996), and suffocation (also known as starvation or strangulation) in which the diffuse gas in the outer galaxy halo is stripped preventing further accretion on to the galaxy before the remaining cold gas in the disc is slowly consumed through SF (Larson, Tinsley & Caldwell 1980).

The morphologies and SFHs of galaxies are also strongly dependent on their masses, with high-mass galaxies predominately passively evolving spheroids, and low-mass galaxies generally star-forming discs. A sharp transition between these two populations is found about a characteristic stellar mass of $\sim 3 \times 10^{10} M_{\odot}$, corresponding to $\sim M_* + 1$ (Kauffmann et al. 2003a,b). This bimodality implies fundamental differences in the formation and evolution of high- and low-mass galaxies. The primary mechanism behind this transition appears to be the increasing efficiency and rapidity with mass of the SFHs and gas-consumption time-scales longer than the Hubble time ($z > 2$). Further contributions to cosmic downsizing and the observed bimodality in galaxy properties could come from the way gas from the halo cools and flows on to the galaxy (Kereš et al. 2005; Dekel & Birnboim 2006) and which affects its ability to maintain SF over many Gyr, in conjunction with feedback effects from supernovae and active galactic nuclei (AGN) (e.g. Springel, di Matteo & Hernquist 2005; Croton et al. 2006). These mechanisms which can shut down SF in massive galaxies allow the hierarchical CDM model to reproduce very well the rapid early formation and quenching of stars in massive galaxies (e.g. Bower et al. 2006; Hopkins et al. 2006b, 2007b; Birnboim, Dekel & Neistein 2007). In particular, the transition from cold to hot accretion modes of gas when galaxy haloes reach a mass of $\sim 10^{12} M_{\odot}$ (Dekel & Birnboim 2006) could be responsible for the observed sharp transition in galaxy properties with mass.

If the evolution of galaxies due to internal processes is effectuated earlier and more rapidly with increasing mass, then this would give less opportunity for external environmental processes to act on massive galaxies. Moreover, low-mass galaxies having shallower potential wells are more susceptible to disruption and the loss of gas due to external processes such as ram-pressure stripping and tidal interactions. This suggests that the relative importance of internal and external factors on galaxy evolution and on the formation of the SF–, age– and morphology–density relations could be mass-dependent, in particular the relations should be stronger for lower mass galaxies. Such a trend has been observed by Smith et al. (2006) who find that radial age gradients (out to $R_{200}$) are more pronounced for lower mass ($\sigma < 175 \text{ km s}^{-1}$) cluster red-sequence galaxies than their higher mass subsample.

The environmental trends of fainter galaxies ($M_r > M_r + 1$) have generally been examined using galaxy colours as a measure of their SFH. Whereas the colour of massive galaxies becomes steadily redder with increasing density, a sharp break in the mean colour of faint galaxies is observed at a critical density corresponding to $\sim R_{200}$ (Gray et al. 2004; Tanaka et al. 2004). In a photometric study of galaxies in the environment of the Shapley supercluster core, we found that the fraction of faint ($M_r + 2 < M_r < M_r + 6$) red galaxies dropped from $\sim 90$ per cent in the cluster cores to $\sim 20$ per cent by the virial radius (Haines et al. 2006a), while the shape of the faint end of the red galaxy luminosity function changes dramatically with density inside the virial radius (Mercurio et al. 2006).

In Haines et al. (2006b, hereafter Paper I) we investigated the possible mass dependency of the age–density and SF–density relations by comparing the global trends with environment for giant ($M_r < -20$) and dwarf ($-19 < M_r < -17.8$) galaxies in the vicinity of the $z = 0.03$ supercluster centre on the rich cluster A2199, the richest low-redshift ($z < 0.05$) structure covered by the Sloan Digital Sky Survey (SDSS) fourth data release (DR4) spectroscopic data set.
A strong bimodality was seen in the mean stellar age-\(M_\star\) distribution about a mean stellar age of 7 Gyr, with a population of bright (\(L^\star\)) galaxies \(\sim 10\) Gyr old, and a second population of fainter galaxies dominated by young (\(\lesssim 3\) Gyr) stars, while a clear age-density distribution was identified for both giant and dwarf subsamples. We confirmed the findings of Smith et al. (2006) that the age-density relation is stronger for dwarf galaxies, while the critical density at which the ages increase markedly is higher for dwarf galaxies, occurring at values typical of the cluster virial radius. In the highest-density regions, we found that \(\gtrsim 80\) per cent of both giant and dwarf subsamples were old (>7 Gyr). However, whereas the fraction of old giant galaxies declines gradually with decreasing density to the global field value of \(\sim 50\) per cent, that of dwarf galaxies drops rapidly, tending to zero for the lowest-density bins. Identical trends with density were independently observed when passive galaxies were identified from their lack of H\(\alpha\) emission.

Looking directly at the spatial distribution of galaxies in the vicinity of the supercluster, in field regions the giant population shows a completely interspersed mixture of both young and old populations, indicating that their evolution is driven primarily by their merger history rather than direct interactions with their environment. In contrast, the mean stellar ages of dwarf galaxies were strongly correlated with their immediate environment: those passively evolving or old dwarf galaxies found outside the rich clusters were always found within poor groups or as a satellite to an old, giant (\(\gtrsim L^\star\)) galaxy. No isolated old or passively evolving dwarf galaxies were found.

In this paper, we extend the study to cover the entire SDSS DR4 footprint, creating a volume-limited sample of \(\sim 28,000\) galaxies with \(0.005 < z < 0.037\) that is \(\gtrsim 90\) per cent complete to \(M_\star = -18 (M^\star + 3.2)\). We re-examine the arguments of Paper I taking advantage of this much larger data set to provide quantitative measures of the environmental dependencies on SF in galaxies and in particular how these vary with the galaxy mass/luminosity. We attempt to disentangle the different contributions to the SF–density relation caused by physical mechanisms internal to the galaxy (e.g. AGN feedback) and those caused by the direct interaction of the galaxy with its surroundings (for a review of how the diverse mechanisms leave different imprints on the environmental trends, see e.g. Treu et al. 2003).

In Section 2, we describe the data set used, the classification of galaxies, and the measures used to remove any biases due to aperture effects and the complex survey geometry, while in Section 3 we describe the adaptive kernel method used to define the local galaxy density. In Section 4, we quantify how the fraction of passively evolving galaxies depends on both environment and mass/luminosity, while in Section 5 we examine the ongoing effects of environment on galaxies that are still forming stars. In Section 6, we examine which aspects of environment are most important for defining the SFH of galaxies in field regions, in particular whether the presence of a nearby galaxy of a particular mass has any role in SF being truncated in a galaxy. In Section 7, we quantify the fraction of galaxies having AGN signatures as a function of both luminosity and environment, and examine the possible connection between AGN feedback and the shut-down of SF in galaxies. In Section 8, we compare our results with predictions from the semi-analytic models of Croton et al. (2006). In Section 9, we discuss the possible physical mechanisms that can affect SF in galaxies and produce the observed environmental trends, and finally in Section 10 we present a summary of our results and conclusions. Throughout we assume a concordance \(\Lambda\)CDM cosmology with \(\Omega_M = 0.3, \Omega_{\Lambda} = 0.7\) and \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\).
continuum fitting code was adopted that was optimized to work with SDSS data in order to recover also the weak features of the spectra and to account for the Balmer absorption (Tremonti et al. 2004). The library of spectra templates are composed of single stellar population models following the assumption that the SFH of a galaxy is made up of a set of discrete bursts. The models are based on the new population synthesis code of Bruzual & Charlot (2003) which incorporates a spectral library covering the 3200–9300 Å range and with high resolution (3 Å) matching the SDSS data. The templates span a wide set of ages and metallicities. After a Gaussian convolution of the templates in order to match the stellar velocity dispersion of each galaxy, the best-fitting model is constructed by performing a non-negative least-squares fit with the dust extinction values $A_{\lambda}$ of K03 and the $\lambda^{-0.7}$ attenuation law of Charlot & Fall (2000). K03 use the amplitude of the 4000-Å break (as defined in Balogh et al. 1999) and the strength of the H$\delta_A$ absorption line as diagnostics of the stellar populations of the galaxies, from which maximum-likelihood estimates of the $z$-band mass-to-light ratios are made. These in conjunction with the $z$-band absolute magnitude and the dust attenuation $A_{\lambda}$ yield the stellar mass $M$ of each galaxy.

The stellar mass estimates of K03 are only available for galaxies in the range $14.5 < r < 17.77$. For the remainder of the galaxies, we use the same technique as Baldry et al. (2006) who estimate the stellar mass-to-light ratio of each galaxy from its $u - r$ colour, using the analysis of Bell & de Jong (2001) who show that for models of star-forming disc galaxies with reasonable metallicities and SFHs, the stellar mass-to-light ratios correlate strongly with the colours of the integrated stellar populations. Briefly, for each 0.05-mag bin in $u - r$ we determine the median value of $M/L$ for those galaxies with stellar mass estimates by K03 and, linearly interpolating between bins, create a relation between the $u - r$ colour and its stellar mass-to-light ratio. This relation is then used to estimate stellar masses for the remaining galaxies from their $r$-band luminosity and $u - r$ colour.

### 2.2 Aperture biases

Throughout this paper, we quantify the current SF and nuclear activity in our sample of galaxies from their spectral indices, in particular their H$\alpha$ emission. One possible cause of bias in estimating the SFR of galaxies in our sample is due to the galaxy spectrum being obtained through a 3-arcsec-diameter aperture rather than over the full extent of the galaxy. Significant radial SF gradients are possible within galaxies, particularly those undergoing nuclear starbursts or spiral galaxies with a prominent passively evolving bulge, that can result in the ‘global’ SFR being significantly over- or underestimated based on spectra containing flux dominated by the galaxy nucleus. Kewley, Jansen & Geller (2005) indicate that SFRs based on spectra obtained through apertures covering less than 3 arcsec can result in the ‘global’ SFR being significantly over- or underestimated, and where possible refer to comparable studies performed using samples limited to redshifts where aperture effects are much reduced (e.g. Gómez et al. 2003; Balogh et al. 2004a; Tanaka et al. 2004). Throughout this paper, we indicate the possible effects of aperture biases on our results.

#### 2.3 The completeness of the catalogue

The completeness (i.e. the fraction of galaxies brighter than the SDSS spectroscopic magnitude limit of $r = 17.77$ that have been spectroscopically observed resulting in good redshifts) of our catalogue is strictly influenced by the following three factors:

(i) The dimension of the fibres which prevents two objects closer than 55 arcsec from being observed. Roughly, 6 per cent of the objects are not spectroscopically observed for this reason (Blanton et al. 2003a).

(ii) The blending of bright galaxies with saturated stars. Bright galaxies which overlap saturated stars are flagged themselves as saturated and hence will not be targeted spectroscopically. As one goes to fainter magnitudes the blending goes down as the area covered by the galaxy decreases. The fraction of galaxies not targeted for spectroscopy for this reason rises from 1 per cent overall to 3 per cent at the bright end of the galaxy sample ($r < 15$) (Strauss et al. 2002).

(iii) The selection criteria set by LRC are broader than those of the selection algorithm used to target galaxies for the spectroscopic SDSS survey (Strauss et al. 2002).

The pronounced incompleteness of the spectroscopic catalogue at the bright end may bias the detection and characterization of low-z groups of galaxies, since the most-luminous objects of these structures are not included. To cope with this deficiency, we have matched the photometric catalogue of SDSS with the NASA/IPAC Extragalactic Data base (NED). For all the objects with a positive match, we have associated the SDSS ugriz photometry with the erably smaller ($\lesssim 20$ per cent) and a simple scaling of the fibre SFR by the $r$-band flux, as done by Hopkins et al. (2003), is perfectly acceptable.

In a subsequent paper (Haines, Gargiulo & Merluzzi 2007, hereafter Paper III), we perform a complementary analysis of the same volume-limited sample combining the SDSS $r$-band photometry with GALEX near-ultraviolet (NUV) imaging to obtain integrated measures of recent SF in $\sim 15$ per cent of our galaxies. A comparison of the integrated NUV $- r$ colours with the SDSS fibre spectral indices allows us to quantify the effects of aperture bias within our sample. We find that for $M_r < -20$ galaxies aperture biases are significant with $\sim 7$ per cent of galaxies classified as passive [equivalent width EW(H$\alpha$) $< 2$Å] from their spectra yet also having blue colours (NUV $- r < 4$) indicative of recent SF. As expected, many of these galaxies appear as face-on spiral galaxies with prominent bulges. This fraction drops to zero at fainter magnitudes ($M_r \gtrsim -19.5$) as the SDSS fibres cover a greater fraction of the galaxies, while lower luminosity galaxies tend to be either late-type spirals or dwarf ellipticals. The luminosity function of early-type spirals (Sa+b) for which aperture biases are by far the most important has a Gaussian distribution centred at $M_r \sim -21.7$ and width $\sigma \sim 0.9$ mag (de Lapparent 2003), and hence are rare at $M_r \gtrsim -20$.

We thus indicate that SFR estimates for $M_r > -20$ galaxies in our sample based on H$\alpha$ fluxes obtained through the SDSS fibres should be reasonably robust against aperture biases. In the case of $M_r < -20$ galaxies where aperture biases are important, we limit our analysis to that based on the simple separation of passive and star-forming galaxies, and where possible refer to comparable studies performed using samples limited to redshifts where aperture effects are much reduced (e.g. Gómez et al. 2003; Balogh et al. 2004a; Tanaka et al. 2004). Throughout this paper, we indicate the possible effects of aperture biases on our results.
corresponding redshift from NED and calculated the absolute magnitudes. There are a total of 803 galaxies added this way to our catalogue with 0.005 < z < 0.037 and r < 17.77. Their contribution is largest at bright magnitudes where the 202 r < 14.5 galaxies from NED make up ~8 per cent of the catalogue. We do not have the spectral indices for the galaxies taken from NED, and so they are only used here in defining the local environment of the LRC galaxies.

Despite the contribution from NED, our improved spectroscopic catalogue is still incomplete. To compute the completeness, assuming that in the catalogue all the objects with spectra are correctly classified, it is first necessary to check the classification of the objects without spectra. From a first visual check on the limited sample of bright galaxies (r < 14.5) with no spectra we found many objects such as saturated stars and satellite tracks classified as galaxies. To remove these objects from our photometric catalogue in the most automatic way, we have compared their flags with those of known galaxies (i.e. with redshifts) looking for some peculiar differences. From this comparison we have noted that, differently from galaxies, all the saturated stars have the flags SATURATED, SATUR_CENTER and the great part of those due to satellite tracks have the flag EDGE (Stoughton et al. 2002). After removing the objects with these flags, we have performed a visual inspection of a subsample of galaxies in the range 14.5 < r < 17.7 which were not targeted for spectroscopy. In this subsample, we found that the photometric pipeline sometimes fails the detection, recognizing non-existent objects. Real r < 17.7 galaxies should be clearly detected also in at least the g, i and z images, whereas this should not be the case for non-existent objects, and hence to exclude these objects we have only selected galaxies as having g, i, z < 21 and r < 17.77 the last limit due to the selection criteria of the SDSS spectroscopic survey. Finally, in the photometric catalogue we also found a small percentage (~1 per cent) of stars classified as galaxies and of badly deblended objects. Since no particular flag characterizes them and it being impossible to reject these by hand, we have left these objects in the catalogue, their influence on determining the completeness being negligible.

To compute the completeness of this CLEANEEd catalogue, we have followed the prescription of Blanton et al. (2003a) based on the algorithm used by SDSS to locate the plates and to assign the fibres. This procedure places on the area covered by the survey a set of 1.49° radius circles (defined tiles) so as to maximize the number of available fibres. The intersection between the tiles and the survey region defines a set of spherical polygons. The union of all the polygons that could have been observed by a unique set of tiles is called ‘sector’. These sectors are the regions over which we have computed the completeness, C, as the fraction of galaxies in the cleaned photometric catalogue that have good redshifts.

3 DEFINITION OF ENVIRONMENT

To study how the evolution of galaxies is related to their local environment, we first need to define the environment by means of the local number density of M_i < -18 galaxies.

To compute the local number density ρ(x, z), we use a variant of the adaptive kernel estimator (Silverman 1986; Pisani 1993, 1996) where each galaxy i with M_i < -18 is represented with an adaptive Gaussian kernel σ_i(x, z) in redshift space. Differently from Silverman (1986) and its previous applications to astronomical data (e.g. Haines, Campusano & Clowes 2004a; Haines et al. 2004b, 2006a) in which the kernel width σ_i is iteratively set to be proportional to r_i^{-1/2}, we fix the radial width to 500 km s^{-1} and the transverse width σ_i to (8/3)^{1/2} D_i, where D_i is the distance of the third nearest neighbour within 500 km s^{-1}, a limit which includes ~99 per cent of physical neighbours (as determined from the Millenium simulation considering the three nearest galaxies in real space) and minimizes the contamination of background galaxies. The choice of D_i was made to maximize the sensitivity of the density estimator to poor groups containing as few as four galaxies, while the (8/3)^{1/2} smoothing factor was added to reduce the noise of the estimator, so that in ‘field’ regions σ_i ≈ D_i which, as shown in Appendix A and Table A1, appears the optimal value for the smoothing length-scale.

The choice both of the method and of the kernel dimensions is designed to resolve the galaxy’s environment on the scale of its host DM halo, as it is the mass of its host halo and whether the galaxy is the central or a satellite galaxy, that is believed to be the dominant factor in defining its global properties such as SFH or morphology (e.g. Lemson & Kauffmann 1999; Kauffmann et al. 2004; Yang et al. 2005; Blanton et al. 2006). In the case of galaxies within groups or clusters, the local environment is measured on the scale of their host halo (0.1–1 Mpc), while for galaxies in field regions the local density is estimated by smoothing over its five to 10 nearest neighbours or scales of 1–5 Mpc.

For each galaxy i the local galaxy density is defined as

\[ \rho_i(x, z) \propto \sum_j \eta_{ij} \exp \left\{ -\frac{1}{2} \left( \frac{D_{ij}}{\sigma_i} + \left( \frac{v_i - v_j}{500 \text{ km s}^{-1}} \right)^2 \right) \right\} , \tag{1} \]

where \( \eta_{ij} = C_i^{-1}(2\pi)^{-3/2} \sigma_i^{-2} \) is the normalization factor, \( D_{ij} \) is the projected distance between the galaxies i and j, \( v_i \) is the recession velocity of galaxy i, and the sum is over all galaxies with \( M_j < -18 \). Note that we also calculate the local galaxy density for galaxies fainter than \( M_i = -18 \).

We have performed a number of tests of the efficiency of this density estimator, in particular with regard to identifying group and isolated field galaxies, by applying the estimator to the public galaxy catalogues from the Millennium simulation (Springel et al. 2005c), and comparing it to other estimators based on the nearest-neighbour algorithm as applied by Balogh et al. (2004b, hereafter BB04) and Baldry et al. (2006, hereafter BB06). These tests are described in detail in Appendix A, and confirm that the estimator is at least as efficient as any variant of the nearest-neighbour algorithm for the same data set. In particular the estimator is very sensitive to the presence of even poor groups containing as few as four galaxies, the result being that selecting galaxies with \( \rho < 0.5 \text{ Mpc}^{-2} \) (500 km s^{-1})^{-1} a pure field sample is produced, with no contamination from group members. In contrast 90 per cent of \( \rho > 4 \) galaxies lie within the virial radius of a galaxy group or cluster, while those galaxies in the transition regions between groups and field environments (\( r \sim R_{vir} \)) have densities in the range \( 1 \lesssim \rho \lesssim 4 \).

Fig. 1 shows the resultant r-band luminosity-weighted density map for galaxies with \( M_i < -18 \) over the redshift range 0.023 < z < 0.037 for the whole SDSS DR4 North Galactic Cap region. For comparison, the red box indicates the 12 × 12-deg² region containing the A2199 supercluster that was analysed in Paper I. The adaptive kernel estimator used has the advantage of being able to be used as a group-finder (e.g. Bardelli et al. 1998; Haines et al. 2004a), by identifying groups and clusters as local maxima in the galaxy density function \( \rho(x, z) \), and as demonstrated in Appendix A all groups and clusters having four or more \( M_i < -18 \) galaxies in the SDSS DR4 catalogue will be marked by local maxima in the density map of Fig. 1. To put this in perspective, we are sensitive to environments comparable to the Local Group (which contains four
Figure 1. Luminosity-weighted density map of $M_r < -18$ galaxies over the redshift range $0.023 < z < 0.037$ over the entire SDSS DR4 North Galactic Cap region. The isodensity contours are logarithmically spaced, the spacing between each contours indicating a factor of $\sqrt{2}$ increase in the $r$-band luminosity-weighted local density. The red box indicates the $12^\circ \times 12^\circ$ region containing the $z = 0.03$ A2199 supercluster analysed in Paper I.

$M_r < -18$ galaxies: Milky Way, Large Magellanic Cloud, M 31 and M 33) and the other nearby groups (the M81, Cen A/M 83 and Maffei groups; Karachentsev 2005). Such poor groups represent the preferential major-merger mass-scale ($M_{\text{halo}} \sim 10^{12} M_\odot$ for galaxies of stellar mass $\sim 10^{10} - 10^{11} M_\odot$ (Hopkins et al. 2007a).

4 THE BIMODALITY IN EW(H$\alpha$) AND ITS DEPENDENCE ON LUMINOSITY AND ENVIRONMENT

One of the best understood and calibrated indicators of the SFR in galaxies is the H$\alpha$ nebular emission-line, whose luminosity is directly proportional to the ionizing radiation from massive ($> 10 M_\odot$) short-lived ($< 20$ Myr) stars, and hence the H$\alpha$ emission provides a near-instantaneous measure of the current SFR (Kennicutt 1998). Fig. 2 shows the EW(H$\alpha$) distribution of $M_r < -18.0$ galaxies in the redshift range $0.005 < z < 0.037$ from the SDSS DR4 spectroscopic data set. The $x$-axis is scaled as $\sinh^{-1}$ EW(H$\alpha$): this results in the scale being linear at EW(H$\alpha$) $\approx 0$ Å where measurement errors dominate, and logarithmic for EW(H$\alpha$) $\gtrsim 10$ Å allowing the lognormal distribution of EWs for star-forming galaxies to be conveniently displayed.

We exclude galaxies showing an AGN signature, as their H$\alpha$ emission may be dominated by emission from the AGN rather than SF. AGN are defined using the [N II]$\lambda 6584$/H$\alpha$ versus [O III]$\lambda 5007$/H$\beta$ diagnostics of Baldwin, Phillips & Terlevich (1981) as lying above the $1\sigma$ lower limit of the models defined by Kewley et al. (2001). When either the [O III]$\lambda 5007$ or H$\beta$ lines are unavailable (S/N $< 3$), the two-line method of Miller et al. (2003) is used, with AGN identified as having $\log([N II]_{\lambda 6584}/H\beta) > -0.2$. We also exclude those galaxies without an H$\alpha$ measurement.

The distribution is clearly bimodal, with two approximately Gaussian distributions: one that is narrow and centred at EW(H$\alpha$) $\sim 0.2$ Å, corresponding to passively evolving galaxies with little or no ongoing SF; and another that is wider and centred at EW(H$\alpha$) $\sim 20$ Å, corresponding to galaxies currently actively star forming. Mid-way between these two distributions, there are, relatively speaking, very few galaxies, and we identify the dividing line between passive and star-forming galaxies as being EW(H$\alpha$) $= 2$ Å, that corresponds approximately to the minimum in the distribution between the two peaks. Note that this value is different to that used in the studies of Balogh et al. (2004a, hereafter B04) and Tanaka et al. (2004, hereafter T04) who use EW(H$\alpha$) $= 4$ Å to separate passive and star-forming galaxies, but is the same as used by Rines et al.
(2005, hereafter R05). The lower value, however, appears justified empirically from Fig. 2, and is sufficiently large that even for the faintest galaxies ($r \sim 17.77$) the limit still represents a $4\sigma$ detection in $H\alpha$, the median uncertainty in EW($H\alpha$) only reaching 0.5 Å by $r = 17.77$. The inclusion of galaxies with optical AGN signatures would tend to fill in the gap in the bimodal distribution, their $H\alpha$ EWs typically in the range 0.5–10 Å (median = 1.56 Å).

The left-hand panel of Fig. 3 shows how the bimodality in EW($H\alpha$), and hence the ongoing SFR of galaxies, depends on both luminosity and environment. Each coloured curve shows the fraction of passively evolving galaxies ($EW(H\alpha) < 2$ Å) as a function of local density for a particular luminosity range as indicated. The lowest luminosity bin ($-18 < M_r < -16$) is far from complete, and is biased heavily towards galaxies close to the bright magnitude limit, but the environmental trends should be representative of those galaxies slightly fainter than $M_r = -18$. Galaxies that lie very close to the edge of the SDSS DR4 footprint are likely to have biased density estimates, and so galaxies that are within 2 Mpc or $\sigma_v$ Mpc, whichever is smaller, of the survey boundary are excluded from all further analyses. This results in a final sample of 22 113 galaxies.

At the highest densities ($\rho \gtrsim 5$), corresponding to the centres of galaxy clusters or groups, passive galaxies dominate for the entire luminosity range studied, with $\sim 70$ per cent of galaxies being passive independent of luminosity. At lower densities in contrast the fraction of passive galaxies depends strongly on luminosity. Even at densities comparable to those seen at the virial radius of groups/clusters, the fraction of $M_r \gtrsim -20$ galaxies that are passive has dropped to $\sim 20$ per cent or lower, while that of brighter galaxies has dropped only slightly. The luminosity dependence is greatest for the lowest-density regions corresponding to field environments well beyond the environmental influence of galaxy clusters or groups. Here the fraction of passive galaxies drops from $\sim 50$ per cent for $M_r \gtrsim -21$ galaxies to $\sim 0$ per cent for $M_r \gtrsim -19$ in the lowest luminosity bin ($-18 < M_r < -16$) the passive galaxy fraction has dropped to precisely zero in the lowest-density regions. In fact, there are no passive galaxies in the lowest-density quartile, corresponding to $\sim 600$ galaxies in total.

These results can be compared with the analysis of BB04 who show in their fig. 2 the fraction of red sequence galaxies as a function of both environment and $r$-band luminosity using data from SDSS DR1. As here, BB04 find that $\sim 70$ per cent of galaxies in their highest density bin belong to the red sequence. However, in their lowest-density bin, the luminosity dependence is somewhat less than presented here, dropping from $\sim 35$ per cent for $-22 < M_r < -21$ to $\sim 8$ per cent for $-19 < M_r < -18$.

The right-hand panel of Fig. 3 repeats the analysis using stellar mass ($M$) instead of $r$-band luminosity. Essentially the same results are obtained, with passive galaxies dominating in high-density regions independent of stellar mass, while in low-density regions the fraction of passively evolving galaxies depends strongly on stellar mass, dropping from $\sim 30$ per cent at $M \sim 10^{10.8} M_\odot$ to zero by $M \sim 10^{10.2} M_\odot$. We note that for stellar masses below $10^{10.2} M_\odot$ we are no longer volume-limited introducing a selection bias, whereby passively evolving galaxies are more likely to be missed by the $r = 17.77$ magnitude limit than star-forming galaxies of the same mass and at the same distance.

BB06 have performed a very similar analysis of the same SDSS DR4 data set, examining how the fraction of red sequence galaxies varies as a function of both environment and stellar mass (their fig. 11a). They consider a much larger volume than our analysis, resulting in a significantly larger sample, particularly at the high-mass end, allowing them to follow the environmental trends for stellar mass bins to log $M = 11.6$. BB06 use a different approach to K03 to calculate the mass-to-light ratios of the galaxies based on the $u - r$ colour only, but they use the same initial mass function, and as shown in fig. 5 of BB06 obtain stellar masses that on average are within 0.1 dex of one another. The global trends are qualitatively the same, with red sequence galaxies dominating in high-density environments independently of stellar mass, while in the lowest-density environments the fraction of red sequence galaxies is a strong function of stellar mass. This latter trend

![Figure 3](https://academic.oup.com/mnras/article-abstract/381/1/7/994952/38117772/fig3.png)

**Figure 3.** The fraction of passively evolving galaxies ($EW(H\alpha) < 2$ Å) as a function of both local density and luminosity (left-hand panel) or stellar mass (right-hand panel). Each coloured curve corresponds to a different luminosity/stellar mass bin as indicated. Each density bin contains 150 galaxies. The grey shaded region indicates the typical densities found for galaxies near the virial radius ($0.8 \lesssim r/R_{vir} \lesssim 1.2$) of groups or clusters in the Millennium simulation (see fig. A1).
extends to the higher stellar masses studied by BB06, falling from \( \sim 100 \) per cent at \( \log M \sim 11.6 \) to 5 per cent by \( \log M \sim 9.0 \). However, for the same stellar mass bin, the red sequence fractions of BB06 in low-density regions are systematically \( \sim 10 \) per cent higher than the passive galaxy fraction from our analysis.

Although the trends shown here in Fig. 3 are similar to those of BB04 and BB06, as discussed above there are some important differences. In particular, we find that for \( M_r > -18.0 \) or \( M \lesssim 10^{9.2} M_\odot \) there are no passively evolving galaxies in the lowest-density bins, whereas for the same stellar mass/luminosity ranges both BB04 and BB06 find that 5–10 per cent of the galaxies belong to the red sequence in their lowest-density bin. This difference has important consequences for the conclusions that can be drawn from the data (see Section 9). What is the cause of this remnant population of faint red galaxies in low-density environments, that disappears in our analysis? First, as discussed previously, the local density estimator used in BB04 and BB06 is not completely able to separate group and field galaxies, so that even for the lowest-density bin considered \( \sim 5 \) per cent of the galaxies are group members, the majority of which lie on the red sequence at all luminosities. Secondly, not all red sequence galaxies are passively evolving: a significant fraction are known to be star forming, and appear red due to high levels of dust extinction. In an analysis of the SDSS main sample galaxies covered by infrared imaging from the SWIRE survey, Davoodi et al. (2006) find that 17 per cent of red sequence galaxies are dusty star-forming galaxies (identified by their high 24 \( \mu \)m to 3.6 \( \mu \)m flux ratios and H\( \alpha \) emission), while Wolf, Gray & Meisenheimer (2005) find that dusty star-forming galaxies constitute more than one-third of the red sequence population in the A901/2 supercluster region.

Conversely, due to the SDSS spectra being obtained through 3′ diameter fibres, the region covered may only cover the central bulge region of nearby large galaxies, resulting in galaxies appearing passive despite having normal star-forming discs. As discussed earlier (Section 2.2) based on a comparison of the SDSS and GALEX NUV photometry of \( \sim 15 \) per cent (4065 galaxies) of our low-redshift sample we find that \( \sim 8 \) per cent (20 out of 246) of bright \( (M_r < -21) \) galaxies are classified as passive yet have blue UV-optical colours (NUV - \( r \) < 4) indicative of normal star-forming galaxies (Paper III). This fraction drops steadily with magnitude (being 2.5 per cent for \( -21 < M_r < -20 \) galaxies), falling to zero (0 out of 1375) for galaxies at \( M_r > -19.5 \). We find no significant variation of these fractions with environment. We thus indicate that the passive galaxy fractions obtained for the higher luminosity/mass bins are overestimated due to aperture effects, but that those for the lower luminosity galaxies \( (M_r > -20) \) are robust against aperture biases.

5 STAR-FORMING GALAXIES

If star-forming galaxies at the present day are affected by environmental mechanisms when they move from low- to high-density regions, we should see a signature of this transformation which depends on the relevant time-scale. In particular, if the dominant environmental mechanism produces a gradual (\( \gtrsim 1 \) Gyr) decline in SF when galaxies become bound to groups or clusters (e.g. suffocation), then star-forming galaxies in dense regions should show systematically lower SFRs or EW(H\( \alpha \)). On the other hand, if the dominant environmental mechanism suppresses SF in galaxies on a very short time-scale, then we should not expect any significant changes in the EW(H\( \alpha \)) distribution of star-forming galaxies, since the galaxies will quickly become classed as passive and hence not contribute to the EW(H\( \alpha \)) distribution. In the previous studies of B04 and T04 the distributions of EW(H\( \alpha \)) of giant \( (M_r < M^* + 0.1) \) star-forming (EW[H\( \alpha \)] > 4 \( \AA \)) galaxies show no dependence on local density, while R05 found no difference in the EW(H\( \alpha \)) distributions of star-forming galaxies inside the virial radius, in infall regions \((1 < (r/R_{200}) < 5)\) or in field regions. From these results they imply that few giant galaxies can be currently undergoing a gradual decline in SF due to environmental processes. However, when considering fainter galaxies with \( M^* + 1 < M < M^* + 2 \) T04 found the EW(H\( \alpha \)) of star-forming galaxies to be slightly smaller in dense regions, a result taken to be a signature of the slow truncation of SF in faint galaxies.

5.1 H\( \alpha \)-density relation for star-forming galaxies

Following B04 and T04, we show in Fig. 4 the EW(H\( \alpha \)) distribution of star-forming galaxies as a function of local density for three luminosity ranges: \( M_r < -20 \) (red dashed lines) which can be compared with the results of B04 \((M_B < -20.2; M_r < -21.3)\) or the bright sample of T04 \((M_r < -20.3)\); \(-19 < M_r < -20 \) (green dot–dashed lines) which is comparable to the faint sample of T04; and \(-18 < M_r < -19 \) (blue solid lines). In each case, star-forming galaxies are defined as having EW(H\( \alpha \)) > 2 \( \AA \) as throughout this paper. Note that both B04 and T04 use EW(H\( \alpha \)) > 4 \( \AA \), but using this value instead makes no noticeable difference to the results. We also exclude here those galaxies classified as AGN. As observed in previous studies, there is no apparent dependence on density for the EW(H\( \alpha \)) distribution for galaxies with \( M_r < -20 \). In contrast, the trends for lower luminosity galaxies show a significant drop in EW(H\( \alpha \)) with increasing density, most of the drop occurring within the range 0.5 \( \lesssim \rho \lesssim 2 \) which represents the transition between galaxies inside and outside bound structures. The significance of the trends are measured using the Spearman rank correlation test and reported in Table 1. Whereas the EW(H\( \alpha \)) distribution of \( M_r < -20 \) star-forming galaxies shows no correlation with local density

![Figure 4](https://academic.oup.com/mnras/article-abstract/381/1/7/994952/1)
\( \rho \), significant anti-correlations are found for the \(-20 < M_r < -19\) and \(-19 < M_r < -18\) star-forming galaxy populations at the 5 and 10\( \sigma \) level, respectively.

We do not expect aperture biases to have any significant effects on the environmental trends presented here, as we observe no dependencies on local galaxy density for the distribution of SDSS fibre aperture covering fractions in any of the luminosity ranges. Similarly we find no environmental trends for the fraction of the early-type spiral galaxies classified as passive from their SDSS spectra yet having blue NUV\( - r \) colours. The only possible effect could be a systematic underestimation of the H\( \alpha \) emission in the \( M_r < -20 \) luminosity bin, but our results for this bin are fully consistent with the comparable trends obtained by T04 and B04 based on galaxy samples at 0.03 < \( z \) < 0.065 and 0.05 < \( z \) < 0.095, respectively, where aperture effects should not be important (Kewley et al. 2005).

To see exactly how the distribution of EW(H\( \alpha \)) changes with environment, Fig. 5 shows the EW(H\( \alpha \)) distribution of galaxies in high (\( \rho > 1.0 \); red histogram) and low (\( \rho < 0.5 \); blue dashed histogram) density environments for three luminosity ranges, corresponding to \( M_r < -20 \) (left-hand panel), \(-20 < M_r < -19 \) (middle) and \(-19 < M_r < -18 \) (right). The vertical red and blue dotted lines indicate the median values of star-forming galaxies (EW[H\( \alpha \)] > 2 \( \AA \)).

The bimodal character of the EW(H\( \alpha \)) distribution is apparent in both the high- and low-density environments for each of the luminosity ranges studied. The two environmental dependencies described in Figs 3 and 4 can both be seen when comparing the EW(H\( \alpha \)) distributions for the high- and low-density environments.

First, a global shift in the relative fractions of star forming and passively evolving galaxies is apparent. The two histograms have been normalized so that distributions of the star-forming galaxies appear to have approximately the same height. As a result, the relative increase in the fraction of passively evolving galaxies from low- to high-density environments is clear. This relative increase is strongly dependent on luminosity, rising from about a factor of 2.5–3 for luminous (\( M_r < -20 \)) galaxies to a factor of \( \sim 20 \) for the dwarf (\(-19 < M_r < -18 \)) galaxy population.

The second effect can be seen as a global shift in the EW(H\( \alpha \)) distribution of the star-forming galaxies from high- to low-density environments. In each environment and luminosity range, the EW(H\( \alpha \)) distribution of the star-forming galaxies can be well described as being log-normal (and hence appearing as a Gaussian distribution in the figure). However, whereas there is no apparent difference in the high- and low-density distributions for luminous (\( M_r < -20 \)) star-forming galaxies, at lower luminosities, the high-density EW(H\( \alpha \)) distributions are systematically shifted to lower values than their low-density counterparts. The level of this shift is quantified by comparison of the median values of the distribution, while the significance of the differences between the two distributions are estimated through application of the non-parametric Kolmogorov–Smirnov and Wilcoxon–Mann–Whitney \( U \)-tests, the results of which are shown in Table 1. These results confirm that while the EW(H\( \alpha \)) distribution of the high- and low-density \( M_r < -20 \) galaxy populations are fully consistent with one another, for the lower luminosity samples the null hypothesis that the high- and low-density star-forming populations have the same EW(H\( \alpha \)) distribution is rejected at very high significance levels. For the \(-19 < M_r < -18 \) sample, the H\( \alpha \) emission from star-forming galaxies in high-density environments is systematically lower by \( \sim 30 \) per cent with respect to their low-density counterparts.

The H\( \alpha \) emission (and hence SF) must be suppressed in a significant fraction of galaxies when they fall into a cluster or group for the first time. However, for these galaxies to remain classified as star forming, this suppression must act over a long period of time, to allow a significant fraction of galaxies to be seen in the process of

Table 1. Comparison of the EW(H\( \alpha \)) distributions in high (\( \rho > 1.0 \)) and low (\( \rho < 0.5 \)) density environments.

| Magnitude range | Median EW(H\( \alpha \)) (\( \AA \)) | Probability (Kolmogorov–Smirnov) | U-test (\( \sigma \)) | Spearman rank correlation \( \rho \) |
|-----------------|----------------------------------|----------------------------------|---------------------|----------------------------------|
| \( M_r < -20 \) | 15.19                            | 14.66                            | 0.464               | 0.07                            |
| \(-20 < M_r < -19\) | 20.23                           | 16.58                            | \( 2 \times 10^{-6} \) | 5.26                            |
| \(-19 < M_r < -18\) | 22.85                           | 16.48                            | \( 6 \times 10^{-25} \) | 11.27                           |

Figure 5. A comparison of the EW(H\( \alpha \)) distributions for galaxies in high- (\( \rho > 1.0 \); red histogram) and low-density (\( \rho < 0.5 \); blue dashed histogram) regions for three luminosity ranges, corresponding to \( M_r < -20 \) (left-hand panel), \(-20 < M_r < -19 \) (middle) and \(-19 < M_r < -18 \) (right-hand panel). The vertical scale corresponds to the number of galaxies per bin in the high-density histogram, while the low-density histogram has been scaled to allow comparison of the distribution of star-forming galaxies. The red and blue dotted lines indicate the median values of star-forming galaxies (EW[H\( \alpha \)] > 2 \( \AA \)) in the high- (red) and low-density (blue) regions.
transformation into passively evolving galaxies. If we assume that the 
Hα emission of galaxies declines exponentially with time as they are being transformed, and that the rate at which galaxies are 
transformed remains constant, the EW(Hα) of galaxies which are 
currently in the process of being transformed but are still classed as 
star forming, will drop from ~20 to 2 Å, with an average of ~8 Å. 
Hence, star-forming galaxies in the process of transformation will 
have on average ~40 per cent of their emission prior to their being 
transformed. To produce a global systematic reduction of ~30 per 
cent in the Hα emission would then require ~50 per cent of the dwarf 
star-forming galaxies in high-density regions to be in the process 
of being transformed into passive galaxies. Given that, as discussed 
previously, as many as 30–40 per cent of galaxies in the high-density 
sample do not lie within the virialized regions of a cluster or group, 
this suggests that the vast majority of dwarf star-forming galaxies in 
groups or clusters are currently in the process of being transformed 
into passive galaxies.

5.2 SFR-density relation for star-forming galaxies

The current SFR of a galaxy can be estimated from its Hα flux 
through the calibration given by Kennicutt (1998):

\[
\text{SFR} \left( M_\odot \text{ yr}^{-1} \right) = \frac{L(\text{H}\alpha)}{1.27 \times 10^{20} \text{ W}}. 
\]

(2)

Before applying this calibration, it is necessary to correct for the 
effects of dust obscuration and account for the effects of emission 
loss by virtue of the spectra being obtained through a fibre whose 
aperture may be significantly smaller than the galaxy. The obscuration 
correction is measured by the Balmer decrement, estimated by 
measuring the ratio of the stellar absorption-corrected Hα and Hβ 
line fluxes, and assuming case B recombination and the obscuration 
curve of Cardelli, Clayton & Mathis (1989). The aperture correction 
is quantified as the ratio of the observed r-band Petrosian flux and 
the continuum flux at the wavelength of Hα within the fibre aperture. 
A full discussion of these corrections and the use of Hα line 
emission as a SFR indicator in SDSS data is given in Hopkins et al. 
(2003) where the explicit calculation used is given as equation B2. 
Moustakas, Kennicutt & Tremonti (2006) compare the integrated 
SFRs estimated from the Hα flux using the above procedure with 
those estimated from IRAS infrared data and find the two estimates 
consistent with a precision of ±70 per cent and no systematic offset, 
confirming that the extinction-corrected Hα luminosity can be used 
as a reliable SFR tracer, even for the most dust-obscured systems. 
Using the above calibration and corrections, we plot in Fig. 6 the 
median SFR of star-forming galaxies as a function of local density 
for galaxies in the luminosity range ~20 < M_r < ~19 (green dot-
dashed line) and ~19 < M_r < ~18 (blue solid line). As discussed 
in Section 2.2, aperture effects will strongly bias the estimates of 
SFRs made using the method of Hopkins et al. (2003) for the most-
massive galaxies in our sample and so we do not plot the results 
for M_r < ~20 galaxies. To allow the effect of high-density envi-
nronments on SF to be measured, each curve is normalized to the 
median SFR of ‘field’ (ρ < 0.5) star-forming galaxies in the same 
luminosity range.

The environmental trends in SFR broadly match those shown ear-
lier in Fig. 4 for the EW(Hα) distribution of star-forming galaxies, 
confirming that those trends do indeed reflect changes in the global 
SFR with environment, and are not due to variations in dust ob-
scuration or aperture biases. These trends are quantified in Table 2 
which compares the median SFRs of star-forming galaxies in high-
and low-density environments for both luminosity ranges, as well as 
estimates the significance of any differences. The most significant 
result (~6σ) is the observed systematic drop of ~20 per cent in the 
median SFR of dwarf (~19 < M_r < ~18) star-forming galaxies in 
high-density regions with respect to field galaxies. In both luminos-
ity bins there appears a systematic drop in SFR for densities greater 
than 1 Mpc^{-2}, which suggests that SF is suppressed in a significant 
fraction of galaxies when they infall for the first time into a cluster 
or group.

As discussed earlier we do not expect aperture biases to be im-
portant for galaxies in these luminosity bins. Moreover we find 
no dependencies on local galaxy density for the fraction of galaxy 
flux covered by the SDSS fibre apertures in either luminosity 
bin.

As a final check to confirm that aperture effects are not behind 
the observed environmental trends in EW(Hα) and SFRs, we re-
peat the analyses using galaxy u − r colours as a measure of their 
current/recent SF. The u − r colours are determined over ap-
ertures defined by the Petrosian radius, and hence represent an in-
tegrated measure of a galaxy’s SFH. The resultant trends in the median 
\text{u − r} colour with local density for each of the luminosity ranges are 
presented in Fig. 7.

For each of the three luminosity ranges star-forming galaxies be-
come increasingly redder with density. The strength of the trend 
increases with decreasing luminosity from 0.07 mag for ~21 < 
M_r < ~20 galaxies to ~0.2 mag for M_r > ~20 galaxies. Almost 
identical trends were observed by BB04 for galaxies selected as star 
forming by their u − r colour. In the case of the two lower luminos-
ity ranges (M_r > ~20) the bulk of the change in u − r colour with 
density occurs at ρ > 1, as seen for the trend in SFR of Fig. 6. 
These trends are fully consistent with those seen in the Hα emission 
and SFR, confirming that the previous trends are not the result of 
aperture effects.

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Table 2. Comparison of the SFRs of star-forming galaxies in high ($\rho > 1.0$) and low ($\rho < 0.5$) density environments.

| Magnitude range of galaxies | Median SFR ($M_\odot$ yr$^{-1}$) | Probability (Kolmogorov–Smirnov) | $U$-test |
|-----------------------------|---------------------------------|----------------------------------|----------|
| $-20 < M_r < -19$           | 0.496                           | 0.443                            | 0.0079   | 2.30     |
| $-19 < M_r < -18$           | 0.191                           | 0.157                            | $7 \times 10^{-9}$ | 6.52     |

Figure 7. The dependence of the $u - r$ galaxy colour on local density for star-forming galaxies with EW(H$\alpha$) > 2 Å. The red dashed lines represent giant galaxies ($M_r < -20$), the green dot-dashed lines represent galaxies with $-20 < M_r < -19$, while the blue solid lines represent dwarf galaxies ($M_r > -19$). The thick and thin lines show, respectively, the median and interquartile values of the distribution. The median lines are accompanied by $1\sigma$ error limits estimated by bootstrap resampling and include the measured errors in $u - r$. Each bin contains 300 galaxies.

6 WHICH ASPECTS OF ENVIRONMENT DEFINE THE SF–DENSITY RELATION?

To this point we have examined the environmental dependence on SF in galaxies using densities measured by smoothing over the nearest 5–10 galaxies. This has allowed us to describe the effects of the group and cluster environments on the galaxies. It is also possible that galaxies are affected by the presence of individual neighbouring galaxies, for example through disturbance from tidal forces.

In particular, we wish to re-examine for the much larger volume covered by the SDSS data set the long noted morphological segregation of dwarf galaxies in the local ($\lesssim 30$ Mpc) neighbourhood, whereby dwarf ellipticals are confined to groups, clusters and satellites to massive galaxies, while dwarf irregulars tend to follow the overall large-scale structure without being bound to any of the massive galaxies (Binggeli, Tarenghi & Sandage 1990; Ferguson & Binggeli 1994).Einasto et al. (1974) first noted this segregation when comparing the spatial distribution of dwarf companions to our Galaxy and the nearby massive spirals M 31, M 81, and M 101. He found a striking separation of the regions populated by dE and dIrr galaxies with dEs confined to being close satellites to the primary galaxies, and dIrr found at larger distances. In Paper I, we found no isolated passively evolving dwarf galaxy, always finding them gravitationally bound to clusters/groups or as satellites of $\gtrsim L^* $ field galaxies, differently from star-forming field dwarfs which appeared randomly distributed throughout the region.

In this context, we wish to look at the effects of neighbouring galaxies on the SFHs of field galaxies ($\rho < 0.5$), that is, those not in groups or clusters for which other processes may well dominate. There are two main physical mechanisms whereby a neighbouring galaxy could affect SF in another galaxy, tidal interactions, and ram-pressure stripping caused by the passage of the galaxy through the gaseous halo of its neighbour. In both of these mechanisms, the mass/luminosity of both the central galaxy (i.e. that which is being acted on) and the neighbouring galaxy are important for defining the strength of the effect on the central galaxy, in particular the greater mass-ratio between the neighbouring galaxy and the central galaxy, the stronger the effect is likely to be. To measure the effect of both the central and neighbouring galaxy masses, we split both the central and neighbouring galaxies into bins of luminosity. It is also important that we take out the effect of the large-scale ($\gtrsim 1$ Mpc) galaxy density from the equation, as galaxies in higher density regions will naturally have closer neighbours than lower density regions. To measure the effect of the presence of a neighbouring galaxy on the SFH of the central galaxy we compare the distances to the nearest neighbour (within a certain luminosity range) for passively evolving and star-forming central galaxies that have the same mass/luminosity and the same large-scale environment (i.e. their local densities are the same). If the presence of a neighbouring galaxy is important for causing the central galaxy to become passive, we would expect passively evolving central galaxies to have nearer neighbours (within a certain luminosity range) than star-forming galaxies of the same luminosity and large-scale environment.

In Fig. 8, the distribution of distances between passively evolving (EW[H$\alpha$] < 2 Å; red histograms) and star-forming (EW[H$\alpha$] > 2 Å; blue dashed histograms) central galaxies in field regions ($\rho < 0.5$) and their nearest neighbours are compared for both different magnitude ranges of central galaxies (in order of increasing luminosity from left to right as indicated) and different magnitude ranges of neighbouring galaxies (in order of increasing luminosity from top to bottom as indicated).

As a consequence of the SF–density relation, even in field regions passively evolving galaxies will on average be in higher density regions than star-forming galaxies of the same luminosity, and hence on this basis alone would be expected to have closer neighbours on average. To remove this bias, we normalize the density distribution of the star-forming galaxies to that of the passively evolving galaxies. This is done by splitting the galaxies into ten density bins of equal logarithmic width (0.2 dex) in the range $0.01 < \rho < 1$ and for each bin $j$ identify a weight $\omega_j = N_\text{passive}^j / \sum N_\text{passive}^j$, where $N_\text{passive}^j$ and $N_\text{SF}^j$ are the total number of passive and star-forming galaxies in that density bin. Each star-forming galaxy belonging to density bin $j$ is then given the corresponding weight $\omega_j$. The resulting...
weighted population of star-forming galaxies has the same density distribution as their passive counterparts. The blue-dashed histograms then represent the distribution of distances to the nearest neighbour for the star-forming galaxies where each galaxy $i$ is represented by its corresponding weight $w_i$.

For each of the panels in Fig. 8 corresponding to a particular luminosity range for central and neighbouring galaxies, we estimate the significance of any differences between the distributions of the distance to the nearest neighbours of passive and star-forming galaxies (the red and blue histograms) using the Kolmogorov–Smirnov test. The results of these are indicated in the top-right of each panel, with significant differences ($P_{KS} < 0.01$) highlighted by red boxes.

Looking at the histograms in the last two columns (corresponding to central galaxies with $M_r < -19$) we see that the distributions of distances to the nearest neighbours of any luminosity range are the same for the passively evolving and star-forming galaxies. This implies that the SFHs of $M_r < -19$ galaxies are not significantly affected by the presence of individual galaxies in their immediate neighbourhoods, and instead it is only the global large-scale environment (as measured here by $\rho$) to which their SFRs are correlated. Equally if we look at the histograms in the top four rows (corresponding to neighbouring galaxies with $M_r > -20.5$) the distance distribution to the nearest neighbours are the same for passively evolving and star-forming central galaxies of any luminosity range. Hence, SF in galaxies (at least for $M_r \lesssim -16$) is not significantly affected by the presence of neighbouring galaxies with $M_r \gtrsim -20$.

The only luminosity combinations of central and neighbouring galaxies that show any significant difference ($P_{KS} < 0.01$) between the distance distribution to the nearest neighbours of the passive and star-forming central galaxies are the two lower left-hand panels corresponding to low-luminosity central galaxies ($M_r > -19$) that have bright ($M_r < -20.5$) neighbours. In both these panels we see that passively evolving dwarf galaxies ($M_r > -19$) are much more likely to have a nearby bright ($M_r < -20.5$) neighbour within

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**Figure 8.** The distributions of distances to the nearest neighbouring galaxy within a specific luminosity range (in order of increasing luminosity from top to bottom as indicated) for $\rho < 0.5$ passive (red line) and star-forming (blue dashed line) central galaxies also within a specific luminosity range (in order of increasing luminosity from the left-hand to right-hand side as indicated). The probabilities that the two histograms are taken from the same distribution according to the Kolmogorov–Smirnov test are indicated in the top right-hand side of each panel.
~500 kpc than would a star-forming galaxy of the same luminosity and having the same global environment (as measured with \( \rho \)). This implies that massive galaxies can influence the SFH of neighbouring dwarf galaxies, presumably orbiting as satellites, by causing them to become stop forming stars.

We re-illustrate these effects in Fig. 9 where we plot the fraction of central passive (red solid line) and star-forming (blue dashed line) galaxies that have one or more neighbours within 0.5 Mpc belonging to a fixed magnitude range. Each panel corresponds to a different magnitude range of central galaxies as before, while each point corresponds to one of the six magnitude ranges of neighbouring galaxies of Fig. 8, the central value of which is indicated along the x-axis. The fractions of passive and star-forming giant galaxies with a neighbour within 0.5 Mpc are quite similar for every magnitude range of surrounding systems; not only, but the common fractions are quite constant independently of the luminosity of neighbouring galaxies. These observations show that both passive and star-forming massive galaxies have no preferences about their neighbours suggesting a uniform distribution for these systems. Different results are found for dwarf galaxies with a neighbour within 0.5 Mpc are different from those found for their star-forming counterparts. The latter show a similar behavior with the field giants having, on average, no preference for neighbours of a particular luminosity. On the contrary, the fraction of passive field dwarfs with a close-by galaxy strongly increases with the luminosity of the neighbour, underlining that these systems, as was first pointed out by Einasto et al. (1974), are not uniformly distributed but are commonly found close to massive galaxies. This trend is also present, even if in a less strong way, for \( -19 < M_r < -16 \) central galaxies and disappears at brighter magnitudes.

These results suggest that the mechanisms transforming giants and dwarfs from star-forming to passive systems are different. The quite uniform spatial distribution of passive field giant galaxies underlines the negligible influence of any environmental interactions in stopping SF for these systems, while the frequent presence of nearby massive galaxies to passive field dwarf galaxies is a clear indication of the fundamental impact of massive galaxies on SF in nearby dwarf systems.

Out of the 252 passively evolving dwarf galaxies in the lowest luminosity bin \(( -18 < M_r < -16 )\) 48 are in regions with \( \rho < 0.5 \). Of these 48, 34 were found to have bright \(( M_r < -20 )\) galaxies within \( \sim 500 \) kpc and \( \sim 500 \) km s\(^{-1} \), 24 of which were within \( \sim 200 \) kpc and \( \sim 200 \) km s\(^{-1} \). No further neighbours are identified if the magnitude limit is extended from \( M_r < -20 \) to \( M_r < -19 \). A further nine galaxies were identified as not actually being passively evolving dwarfs, either having apparent H\(_\alpha\) emission not identified by the MPA/JHU pipeline, appearing blue, or having bad photometry which made the galaxy appear much fainter than it actually was.

Only five passively evolving dwarf galaxies appear to be isolated, being 0.8–1.2 Mpc from the nearest bright galaxy. However, looking a little further out we find that all five appear to lie in the infall regions of galaxy groups at around 1.5–2 virial radii from the group centres, as indicated in Table 3. The centres and redshifts of each of the groups were identified as maxima in the luminosity-weighted galaxy density distribution, and the cluster velocity dispersions and virial radii determined as in Girardi et al. (1998) based on the galaxy radial velocities within 2 Mpc and 3\( \sigma_v \) of the cluster centre.

Although the first galaxy lies some 2.5 Mpc from MKW 8, this cluster is part of a larger structure which extends for \( \sim 7 \) Mpc around the ‘isolated’ passive dwarf galaxy. It seems reasonable to assume this structure is still in the process of assembly, and hence the dwarf galaxy may have been left behind or thrown out by a previous interaction between the structures. The remaining nearby clusters are rather more isolated and regular, and so it seems less likely that the other four dwarf galaxies were thrown out by cluster interactions. The most likely mechanism for these galaxies to have become passive is that in the past their orbits took them through their regions of galaxy groups at around 1.5–2 virial radii from the group centres, as indicated in Table 3. The centres and redshifts of each of the groups were identified as maxima in the luminosity-weighted galaxy density distribution, and the cluster velocity dispersions and virial radii determined as in Girardi et al. (1998) based on the galaxy radial velocities within 2 Mpc and 3\( \sigma_v \) of the cluster centre.

| Table 3. Candidate isolated passively evolving dwarfs and possible associated groups. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| RA, Dec. (J2000) | \( \zeta \) | \( M_r \) | \( d_{cl} \) (Mpc) | Group name | Reference | \( N_{gal} \) | \( \mu_{nu} \) (km s\(^{-1} \)) | \( R_{nu} \) (Mpc) | \( T_X \) (keV) | \( \log(L_X) \) (erg s\(^{-1} \)) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 14:37:13.70, +02:28:35.9 | 0.0255 | -17.67 | 2.56 | MKW 8 | 1.2 | 147 | 0.0267 | 492 | 1.56 | 3.03 | 41.98 |
| 12:00:26.60, +01:40:07.6 | 0.0209 | -17.32 | 1.46 | MKW 4 | 1.2 | 99 | 0.0199 | 428 | 1.25 | 1.83 | 41.96 |
| 12:00:37.72, +02:08:47.9 | 0.0201 | -17.61 | 1.41 | MKW 1 | 1.2 | 99 | 0.0199 | 428 | 1.25 | 1.83 | 41.96 |
| 15:14:04.35, +03:24:04.9 | 0.0297 | -17.82 | 0.76 | WBL 236 | 3.4 | 24 | 0.0219 | 324 | 0.96 | 41.76 |
| 09:47:15.48, +37:03:07.1 | 0.0223 | -17.62 | 1.83 | MKW 8 | 1.2 | 147 | 0.0267 | 492 | 1.56 | 3.03 | 41.98 |

References: (1) Rines & Diaferio (2006), (2) Popesso et al. (2004), (3) White et al. (1999), (4) Mahdavi & Geller (2004).
neighbouring group/cluster, whereupon they became passive through ram-pressure stripping and/or tidal interactions. From cosmological N-body simulations Mamon et al. (2004) find that infalling galaxies on radial orbits can bounce out of the clusters, reaching maximum clustercentric distances of between 1 and 2.5 virial radii. The main difficulty is to understand why these galaxies have not been able to start forming stars again once they are no longer affected by the cluster environment. In particular, while these galaxies may have been completely stripped of gas while in the cluster, outside gas recycling from stellar mass loss should be able to produce enough gas to be detectable (e.g. Jungwiert, Combes & Palous 2001) and subsequently allow SF to restart after a few Gyr, although Grebel, Gallagher & Harbeck (2003) suggest that ram-pressure from the passage of the galaxy through the low-density IGM may be sufficient to strip the stellar mass loss as it is recycled. It would be interesting to confirm whether these isolated dwarfs are truly passively evolving or whether they have any detectable H I.

7 THE CONNECTION WITH ACTIVE GALACTIC NUCLEI

In recent years observations have shown that at the heart of most if not all massive galaxies is a supermassive black hole (SMBH) (for a review see Ferrarese & Ford 2005), and it has become increasingly clear that the evolution of the galaxy and the central black hole are strongly interdependent. This is manifested most clearly by the tight correlations between the mass of the central SMBH and the global properties of their host galaxies, such as the stellar mass of the bulge component (MBH = 0.0014 ± 0.0004MBulge; Haring & Rix 2004), the stellar velocity dispersion (Gebhardt et al. 2000; Ferrarese & Ford 2005), and the host bulge Sersic index (Graham & Driver 2007). The scatter in the black hole masses around these relations are only of the order of 0.3 dex.

Silk & Rees (1998) suggested that these correlations arise naturally through the self-regulated growth of SMBHs through accretion triggered by the merger of gas rich galaxies. Tidal torques produced by the merger channel large amounts of gas on to the central nucleus fuelling a powerful starburst and rapid black hole growth, until feedback from accretion is able to drive quasar winds and expel the remaining gas from the remnant galaxy. Hydrodynamical simulations of gas rich galaxy mergers incorporating SF, supernova feedback and black hole growth (Springel et al. 2005a) confirm this picture, reproducing the observed MBH − σ relation (di Matteo, Springel & Hernquist 2005). Springel et al. (2005a) show that the presence of the central SMBH has a strong impact on the remnant galaxy, producing passively evolving spheroidal galaxies (Springel, di Matteo & Hernquist 2005b) consistent with the observed scaling relations (Robertson et al. 2006) and whose gas is heated by the quasar winds forming the observed X-ray emitting haloes (Cox et al. 2006), whereas the remnant galaxies in models without SMBHs continued to form stars at a non-negligible rate.

Given the tight correlation between the mass of the central SMBH and that of the host galaxy, we should expect the effects of AGN feedback to be strongly dependent on galaxy mass, being reduced or even negligible for low-mass galaxies. Springel et al. (2005b) find that for merging galaxies with σ = 80 km s−1 the effects of black hole growth on the remnant are negligible, the spheroids that form remaining gas rich with ongoing SF. Indeed in low-mass galaxies SMBHs may not form at all during mergers. The rapidity of the gas accretion on to the central object depends on the depth of the potential well of the host galaxy, and in low-mass galaxies the accreting gas may have time to fragment and form stars, preventing further dissipation and collapse of the gas (Haehnelt, Natarajan & Rees 1998). Indeed most (50–80 per cent) dwarf galaxies (MBH ≳ −18) appear to host central compact stellar nuclei, regardless of their morphological class (Côte et al. 2006; Rossa et al. 2006), the masses of which scale with the mass of their host galaxy, following the same correlation as that observed for SMBHs (Ferrarese et al. 2006; Wehner & Harris 2006).

In recent years there have been significant advances in the theoretical framework in understanding galaxy evolution, in particular the ability of semi-analytic models to reproduce the global properties observed in the current large scale surveys such as the SDSS. One large problem that the theoreticians have been facing is reproducing the observed break and exponential cut-off in the luminosity function at the bright end along with the observation that most massive galaxies are passively evolving, and have been for many Gyr. These massive galaxies have haloes of X-ray emitting hot gas, which without constant energy injection should cool through radiative losses on to the galaxy, fuelling further SF (Mathews & Brighenti 2003). However, no evidence of this cooling gas is observed, and AGN feedback has often been put forward as a means of supplying energy to the hot gas, and preventing it from cooling. Croton et al. (2006) have developed semi-analytic models which include AGN feedback to prevent this gas cooling on to massive galaxies, which have been able to successfully reproduce the exponential cut-off in the bright end of the luminosity function and the fact that most massive galaxies are quiescent and dominated by old stars. It is important to note that the feedback considered here is low-level AGN activity, the fraction of gas that is in thermal equilibrium with the DM halo.

To examine the possible role of AGN feedback in terminating SF in galaxies, Fig. 10 shows how the AGN fraction depends on both luminosity and environment. Each coloured curve shows the fraction of galaxies classified as AGN from their location in the [N ii]λ6584/Hz versus [O iii]λ5007/Hβ diagnostic diagram (Baldwin et al. 1981) as a function of local density for a particular luminosity range as indicated. We note that these diagnostics are not sensitive to type 1 AGN with broad-line emission; however, these are mostly limited...
show that the presence of even a low-luminosity AGN with $10^5 < L[\text{O III}] < 10^6 \, L_\odot$ would perturb the emission-line ratios enough to be detected in 93 per cent of dwarf galaxies classified as star forming.

Although the biases due to S/N effects, dust-obscuration, aperture effects, emission from star-forming regions etc are likely to affect the ability to detect AGN in galaxies, the observed trend with luminosity is very strong, and appears broadly consistent with expectations from the tight correlation between the mass of the central SMBH and the host bulge component. At the lowest luminosities, the predicted mass of the central black hole (if there is one at all) is too low to be able to power an AGN detectable in the optical spectrum. With increasing galaxy luminosity, the typical mass of the central SMBH increases (Ferrarese & Ford 2005), becoming increasingly capable of powering an AGN detectable in the optical spectrum, resulting in the AGN fraction increasing with luminosity.

A comparison between Figs 3 and 10 finds a remarkable match between the fraction of passive galaxies in low-density environments and the AGN fraction for all of the luminosity bins covered. In these regions, environment-related processes such as galaxy harassment or ram-pressure stripping are not effective, and their SFHs are dependent only on mechanisms internal to the galaxy, such as their merger history and feedback processes. The strong correlation between the fraction of AGN and passive galaxies in these regions suggests a direct connection, with galaxies becoming passive through AGN feedback, and appears consistent with the current model of the coevolution of AGN and galaxies (e.g. Springel et al. 2005a; Hopkins et al. 2006a, b, 2007b).

8 COMPARISON WITH SEMI-ANALYTIC MODELS

To better understand the physical mechanisms that contribute to the observed different environmental trends of galaxies with luminosity, we compare our results with those produced by the semi-analytic models of Croton et al. (2006, hereafter C06). These are implemented on top of the Millennium Run N-body simulation, currently the largest DM simulation of the concordance ΛCDM cosmology with $\sim 10^{10}$ particles in a periodic box $500 \, h^{-1} \, \text{Mpc}$ on a side, giving a mass resolution of $8.6 \times 10^9 \, h^{-1} \, \text{Mpc}$ (Springel et al. 2005c). DM haloes and subhaloes are identified as having 20 or more bound particles, their merging trees constructed, which are subsequently used to populate the haloes and subhaloes with galaxies according to the prescriptions described in C06. For each galaxy there are four components: stars, cold gas in the disc, hot gas in the halo, and the central SMBH. The two novel features of the C06 model are: (i) the modelling of gas infall from the halo on to the cold disc, which occurs either through rapid cooling primarily in low-mass galaxies, or cooling from a static halo of hot gas heated by accretion shocks, the dominant process in massive galaxies; and (ii) its inclusion of the growth of black holes, and their subsequent effects on the cold and halo gas in the galaxy. These effects are two-fold, during galaxy mergers a certain fraction of the cold gas is accreted by the black hole, although any resultant energy released such as quasar winds are not modelled, while instead low-level accretion of the hot gas in the halo on the black hole is also described and results in energetic ‘radio mode’ feedback which can prevent the further cooling of gas from the halo.

As described in Appendix A the resultant galaxy properties are used to create a mock SDSS redshift catalogue, and the local density for each galaxy estimated in the same manner. As in the mock catalogues we do not have information regarding the Hα emission from
each galaxy, we instead define galaxies as being passive if they are both red (a − r > 2.2) and have a current specific SFR (SFR/\m_\odot) less than 10 per cent that of the median value of star-forming galaxies (\sim\times10^{-10} h^{-1} \m_\odot \text{ yr}^{-1}/\m_\odot).

Fig. 11 shows the resultant fraction of passively evolving galaxies as a function of both local density and luminosity. Each coloured curve corresponds to a different luminosity bin as indicated, and are analogous to those for the SDSS data set shown in Fig. 3 allowing a direct comparison. There are several important discrepancies between the model predictions and the SDSS data, which indicate areas where the models do not accurately describe the physical processes which define whether galaxies are still forming stars or not.

The most notable difference is that the much smaller apparent luminosity dependence in the fractions of passively evolving galaxies in low-density regions from the C06 models in comparison to those observed in the SDSS data. Whereas the passive galaxy fraction increases from \sim2−8 per cent to \sim30 per cent from the lowest to the highest luminosity bins in the models, in the SDSS data set the increase over the same luminosity range is from 0 per cent to \sim50 per cent. As in these low-density regions environmental processes should not be important, the differences must be due to the models treatment of internal feedback processes that truncate and regulate SF in galaxies. The discrepancies appear greatest for the most massive galaxies where AGN feedback should be the most important mechanism for truncating SF in galaxies, and so this suggests that the prescription for AGN feedback in the C06 model is not efficient enough, the most likely cause of this being the neglect of feedback from quasar winds.

There is also a discrepancy at the low-luminosity end, with fewer passively evolving dwarf galaxies observed than predicted by the models. While in the SDSS data the passive galaxy fraction continues to fall with luminosity until it reaches zero at \m_\* \sim18, in the models there appears no luminosity dependence for galaxies fainter than \m_\* \gtrsim−20.5, in any environment. The C06 model predicts that 6.1 ± 0.3 per cent of \sim18 < \m_\* < −19 galaxies in field regions (\rho < 0.2) should be passively evolving, a factor of \sim3 greater than the 1.9 ± 0.3 per cent observed in the SDSS data set.

Three-quarters of these galaxies in the C06 model are satellites to \m_\* < −20 galaxies, indicating that this excess most likely related to how the C06 model deals with the evolution of satellite galaxies. In the C06 model, as in most semi-analytic models, when a galaxy becomes a satellite within a more massive halo, it instantly loses the gas from its halo to that of its host, ‘suffocating the galaxy’, and consequently uses up the remainder of its cold gas until it is no longer able to continue forming stars (Larson et al. 1980). This finding of too many passively evolving dwarf galaxies in low-density environments suggests that the incorporation of ‘suffocation’ into the model is too efficient, terminating SF in galaxies too rapidly once they become satellites. This is confirmed by Weinmann et al. (2006b) who split galaxies in the SDSS and C06 catalogues into satellite and central galaxies, and find that in the C06 model catalogues just \sim20 per cent of \m_\* \sim−18 satellite galaxies are blue, much lower than the \sim60 per cent observed in the SDSS data.

Bekki, Couch & Shioya (2001, 2002) performed N-body and hydrodynamical simulations following the effects of the cluster environment on the gaseous halo of an infalling \L^* spiral galaxy, and found that for a cluster of mass \sim10^{14} \m_\odot, the combination of the cluster tidal field and ram-pressure was able to efficiently strip \sim80 per cent of the halo gas over a period of 1–2 Gyr. The stripping should be more rapid for lower mass galaxies. Balogh, Navarro & Morris (2000) elaborated the model of Larson et al. (1980), indicating that the gradual decline in SF on the \sim3 Gyr time-scales predicted by suffocation could reproduce the Butcher–Oemler effect and the observed gradual SF density relations extending well beyond the cluster virial radius (e.g. Lewis et al. 2002; Treu et al. 2003). By simply assuming the Schmidt-Kennicutt law, Balogh et al. (2000) obtain a relation for the decline in SF where no further gas accretion is possible, as

\[ \text{SFR}(t) = \text{SFR}(0) \left(1 + \frac{3}{2.2} \frac{t}{t_c}\right)^{-3.5} \m_\odot \text{ yr}^{-1}, \]

where SFR(0) is the initial SFR, and \( t_c \approx 2.2[SFR(0)/\m_\odot \text{ yr}^{-1}]^{1/29} \text{ Gyrs} \) is the characteristic gas consumption time-scale, including the effects of gas recycling. For a typical \L^* spiral galaxy with SFR(0) \sim5 \m_\odot \text{ yr}^{-1}, we obtain \( t_c \sim 1.4 \text{ Gyrs} \), resulting in the galaxy taking \sim4 Gyrs to become passive (SFR(t)/SFR(0) \sim 0.1), a time-scale consistent with the cluster spiral population in \sim0.4 clusters becoming passive by \z = 0.

Applying equation (3) instead to a typical field dwarf galaxy with \m_\* \sim−18 and SFR(0) \sim0.2 \m_\odot \text{ yr}^{-1} \text{ We obtain } t_c \sim 3.5 \text{ Gyrs}, resulting in the galaxy taking \sim10 Gyrs to become passive, consistent with their observed gas depletion time-scales of \sim20 Gyrs (van Zee 2001). Hence, even if deprived of further gas accretion through suffocation, SF in dwarf galaxies occurs at a sufficiently low rate that they are unlikely to have consumed all their gas and become passive by the present day if they are acted on only by the mild stripping envisaged in suffocation.

If suffocation alone is unable to terminate SF in the dwarf satellites of massive galaxies, then a stronger form of gas stripping is required. Mayer et al. (2001, 2006) show that dwarf spiral galaxies orbiting a Milky Way type galaxy can suffer significant mass loss and have their entire gas content removed or used up in a starburst, transforming them into passive dwarf ellipticals over a period of \sim5 Gyrs through the combination of tidal shocks and ram-pressure stripping if their orbits take them within \sim50 kpc of the primary. Such a behaviour is difficult to model within a cosmological simulation such as that of C06, in particular as the tidal forces acting on the dwarf satellites change rapidly along their orbits, such that
the SFHs and evolutions (in terms of mass loss) of dwarf satellites could be very strongly affected by even small variations in their orbits (Kravtsov, Gnedin & Klypin 2004; Sales et al. 2007).

Looking at the possible effect of the Millennium simulation neglecting tidal stripping on the satellite population, we find an overabundance of faint satellite galaxies around massive field galaxies in the models in comparison to the SDSS data. In particular for each $M_\star < -20$ field galaxy we observe on average $0.125 \pm 0.007 < 19 < M_\star < -18$ galaxies that lie within 250 kpc and 500 km s$^{-1}$ of it (i.e. that are probable satellites), whereas in the C06 model we find on average 0.195 ± 0.004. A certain fraction of these galaxies will in fact be interlopers, and should be subtracted from this analysis. We estimate the number of interlopers as the number of dwarf ($-19 < M_\star < -18$) galaxies found around a dwarf galaxy which has no $M_\star < -20$ galaxy within 1 Mpc and 1000 km s$^{-1}$, so that neither of the dwarf galaxies is a satellite, obtaining a value of $0.083 \pm 0.003$ per galaxy. This takes into account the natural clustering of dwarf galaxies, independent of the presence of nearby giant galaxies. An alternate estimate for the number of interlopers can be made by assuming that interlopers are distributed evenly over the volume covered, and so in this case we would expect 0.019 dwarf galaxies within the volume around each $M_\star < -20$ galaxy. Considering the contamination from interlopers to be between these two values, we estimate the excess dwarf satellites in the Millennium simulation to be 65–167 per cent.

9 DISCUSSION

Using a volume-limited sample of galaxies from the SDSS DR4 spectroscopic data set, we have examined the SF activity of galaxies as a function of both luminosity and environment, the main results of which are summarized in Fig. 3. In high-density regions, the bulk of galaxies are passively evolving independent of mass. Many processes could contribute to terminating the SF in these galaxies, either internal to the galaxy or related to the hostile cluster environment, making it difficult to identify those which are most important. To gain insights into the relative importance of these different mechanisms, we instead focus on galaxies in low-density regions for which we can be sure that their SFHs have not been influenced by cluster-related processes (thanks to our robust separation of cluster and field populations). Hence, the SFHs of these galaxies can only be influenced by internal mechanisms such as merging, gas consumption through SF and AGN feedback.

We find that the fraction of passively evolving galaxies in field regions drops steadily from $\sim 50$ per cent at $M_\star \lesssim -21$ to zero by $M_\star \sim -18$. This implies that internal mechanisms are not responsible for the formation of passively evolving dwarf galaxies, while they become increasingly important with mass and galaxies for driving their SFHs. This would be consistent with the increasing early and rapid conversion of gas into stars for more massive galaxies resulting from the Kennicutt–Schmidt law ($\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.4 \pm 0.1}$; Kennicutt 1998; Schmidt 1959), which has been shown to hold over several orders of magnitude of gas density, in conjunction with the appearance of a critical gas density below which SF does not occur (Martin & Kennicutt 2001). Hydrodynamical simulations of the formation of massive $\sim M^*$ field galaxies show that passively evolving elliptical galaxies can be produced without recourse to major mergers or feedback mechanisms consuming their gas in a short burst ($\lesssim 2$ Gyr) of SF at $z \geq 2$ (Chiosi & Cararro 2002; Naab et al. 2007). In dwarf galaxies instead SF occurs very inefficiently resulting in gas consumption time-scales much longer than the age of the Universe (van Zee 2001) and global SFRs that have remained approximately constant since $z \sim 3$ (Panter et al. 2006). These simulations and the observed studies of the global decline in SF since $z \sim 1$ through downsizing (Heavens et al. 2004; Noeske et al. 2007a,b) suggest that gas exhaustion through SF may play a dominant role in the global evolution of SF.

This does not appear to be the complete answer, in particular it does not explain the wide variety of SFHs seen in field $\sim M^*$ galaxies (Paper I), where completely interspersed mixtures of young and old galaxies (in terms of their stellar populations) are found. This instead suggests that some stochastic processes play a role in determining the SFHs of massive galaxies, the most natural being their hierarchical assembly through mergers and the resultant growth of SMBHs and subsequent AGN feedback effects (Hopkins et al. 2006a,b, 2007b). Moreover we find a close mirroring of the increase in AGN fraction with galaxy luminosity to that observed for the passive galaxies in field regions, suggesting a direct connection between nuclear activity and galaxies becoming passive, reflecting the increasing importance of AGN feedback with galaxy mass for their evolution.

9.1 Massive galaxies affected by merging

In the case of massive galaxies ($M \gtrsim 10^{10.3} M_\odot; M_\star \lesssim -20$), we confirm the recent results on the environmental dependence of SF (Lewis et al. 2002; Gómez et al. 2003; T04; R05), finding gradual trends for the fraction of passively evolving bright galaxies with environment that extend to the lowest densities studied (Section 4). Furthermore we find that this correlation with the local density is independent of the presence or absence of individual neighbouring galaxies (Section 6). R05 find that the fraction of passively evolving galaxies depends on the local density, and this dependency is the same for galaxies in different types of global environment (within the cluster virial radius, in infall regions, and the field), while T04 find no dependence on system richness for galaxies residing in groups with $\sigma > 200$ km s$^{-1}$. In Section 5, we also find that the distribution of EW(He$\alpha$) of massive galaxies with current SF shows no dependence on local density in agreement with the results obtained by B04, T04 and R05. These results together indicate a limited role for mechanisms specific to cluster environments on the termination of SF in massive galaxies, in particular excluding mechanisms which result in a gradual decline in the SFR of infalling galaxies. SF in massive galaxies is terminated rapidly (on time-scales $\lesssim 1$ Gyr) through processes that depend only marginally on the local density and/or occur at high redshifts such that ongoing transformations are rare.

This early cessation of SF in massive passively evolving galaxies and the independence of the SFHs on the global cluster environment, point towards the evolution of massive galaxies being driven primarily by internal mechanisms and their merger history (Hopkins et al. 2007b). The environmental trends are then defined by the initial conditions in which galaxies form, whereby massive galaxies are formed earlier preferentially in the highest overdensities in the primordial density field (Maulbetsch et al. 2007), and have a more active merger history (Gottlöber, Klypin & Kravtsov 2001), than those that form in the smoother low-density regions. This implies the environmental trends should be imprinted early on in the massive galaxy population, as is observed with the morphology–density and colour–density relations being already largely in place by $z \sim 1$ (Smith et al. 2005; Cooper et al. 2006), and possibly apparent even at $z \gtrsim 2$ (Quadri et al. 2007).

This rapid formation of massive galaxies and the early shutdown of SF is produced naturally in the monolithic collapse model,
where the deep potential wells allow for rapid and efficient conversion of the gas into stars according to the Kennicutt–Schmidt law (Chiosi & Carloo 2002) in a short burst ($\lesssim 2$ Gyr) of SF at $z \gtrsim 2$.

While the monolithic collapse model appears at odds with the hierarchical growth of structures produced in $\Lambda$CDM models, Merlin & Chiosi (2006) are able to reproduce the same qualitative SFHs for massive galaxies within a hierarchical cosmological context, most of the merging of substructures occurring early in the galaxy life ($z > 2$). This so-called ‘revised monolithic’ scheme is consistent with the observed rapid evolution and growth of massive galaxies through merging at $z \gtrsim 1$ (Conselice 2006), and the mild evolution in the number density of massive ($M_* \gtrsim 10^{10.5} M_\odot$) red galaxies to $z \sim 1$ (Bell et al. 2004; Willmer et al. 2006) and beyond (Glazebrook et al. 2004; Cirasuolo et al. 2006; Renzini 2006). Equally the observed bimodality in the colour distribution of galaxies at $z \sim 1.2$ (Bell et al. 2004; Willmer et al. 2006) implies that SF must be truncated rapidly and completely in massive galaxies at $z \gtrsim 1.5$ or even earlier (Kriek et al. 2006). Given the short gas-consumption time-scales of massive galaxies, to maintain SF to the present day would require massive galaxies to continuously accrete fresh gas from their surroundings (Larson et al. 1980). However, massive galaxies in haloes of mass $\gtrsim 6 \times 10^{11} M_\odot$ stable virial shocks form which heat inflalling gas to the virial temperature, significantly reducing the accretion rate on to the galaxy, and making the gas vulnerable to feedback effects such as AGN (Dekel & Birnboim 2006). Indeed in many massive galaxies further accretion of gas may be completely shut down, resulting in the subsequent termination of SF without the need for further quenching mechanisms such as mergers or AGN feedback (Birnboim et al. 2007).

In Section 7, we determined the fraction of galaxies with optical AGN signatures as a function of both luminosity and environment. We find the AGN fraction to be independent of local density for galaxies of a given luminosity for $M_* < -18$. In contrast the AGN fraction is strongly luminosity dependent, increasing from $\sim 0$ per cent at $M_* \sim -18$ to $\sim 50$ per cent by $M_* \sim -21$ in a way that closely mirrors the luminosity dependence of the passive galaxy fraction in low-density environments. These results suggest that the ability of a galaxy to host an AGN depends only on its mass, as would be expected from the tight $M_{BH} - \sigma$ relation (Ferrarese & Ford 2005), while the strong correlation between the fractions of galaxies hosting AGN and being passive suggests a direct connection between nuclear activity and a galaxy becoming passive. This appears consistent with the current models of the coevolution of AGN and galaxies (e.g. Springel et al. 2005a; Hopkins et al. 2006a,b, 2007b), and reflects the increasing importance of AGN feedback with galaxy mass for their evolution, and its increasing efficiency in permanently shutting down SF, by expelling gas from the galaxy through quasar winds (di Matteo et al. 2005) and/or preventing further cooling of gas from the surrounding halo (C06).

It seems impossible for environmental processes to be able to shut off SF in massive galaxies at such an early epoch as required: ram-pressure stripping for example is unlikely to be efficient until later epochs ($z \lesssim 1$) once the dense cluster ICM has had time to build up (Kapferer et al. 2007), while both galaxy harassment and suffocation take several Gyr to terminate SF in galaxies, and simply have not had time to act. Moreover, even in field regions where these processes are not efficient, massive, passively evolving galaxies are seen to be in place at $z > 1$, with only slight differences observed in the mean stellar ages and mass-to-light ratios of galaxies in diverse environments (Thomas et al. 2005; Smith et al. 2006; van Dokkum & van der Marel 2007).

Although the formation of passively evolving early-type galaxies through merging largely took place at $z \gtrsim 1$, there is evidence indicating this process is continuing at lower redshifts. Early-type galaxies that are currently passively evolving, but with remnant young (1–4 Gyr) stellar populations or E+A spectra indicating $\lesssim 1$ Gyr old stars, are preferentially located in low-density environments or poor groups, where low-velocity interactions should be most frequent (Goto 2005; Nolan, Raychaudhury & Kabín 2007). The fraction of blue, spiral galaxies in clusters is also observed to drop rapidly from $z \sim 0.5$ to $z \sim 0$ – the Butcher–Oemler effect – while many spiral galaxies in local clusters show strong evidence of being transformed now by ram-pressure stripping (e.g. Solanes et al. 2001; Koopmann & Kenney 2004; van Gorkom 2004).

As discussed in Section 8, the mechanism of suffocation was proposed by Larson et al. (1980) to explain the Butcher–Oemler effect, by stripping the extended gas reservoirs of recently accreted spiral galaxies in clusters at $z \sim 0.4$, slowly transforming them by the present day into passively evolving galaxies by exhausting their remaining gas supplies through SF. However, suffocation should not change the morphology or radial profiles of the spiral galaxies, turning them into anemic spirals (van den Bergh 1976) rather than the SOs whose numbers in clusters have increased rapidly since $z \sim 0.4$ mirroring the decline of cluster spirals (Dressler et al. 1997; Desai et al. 2007).

Instead, studies of spiral galaxies in the Virgo cluster find that a much larger fraction of them have truncated Hα and H I radial profiles (52 per cent) than appear simply anemic (6–13 per cent) with globally reduced SF and gas densities (Koopmann & Kenney 2004). Similarly, Vogt et al. (2004) find a significant fraction of spirals with asymmetric Hα profiles and H I rotation curves in nearby rich clusters. It is difficult for suffocation to produce these truncated or asymmetric Hα and H I profiles, and instead it appears more likely that a process such as ram-pressure stripping actively removes the gas from the outside-in, and Boselli et al. (2006) show that ram-pressure stripping is able to reproduce the observed radial profiles. This outside-in removal of the gas should also produce inverted colour gradients in which the inner regions of the galaxy are bluer than the outer regions, as SF is truncated earlier in the periphery than the core of the galaxy, an effect which has been observed for the Virgo spiral NGC 4569 (Boselli et al. 2006).

These truncated spiral galaxies are mostly confined to the inner 1–1.5 Mpc of the Virgo cluster, that is within the virial radius, although there are some well outside the virial radius (Koopmann & Kenney 2004). All of the asymmetric spiral galaxies are located within 1 h$^{-1}$ Mpc of the cluster centres with the truncation of the H I and Hα emission preferentially along the leading edge (Vogt et al. 2004). These results are more consistent with the effects of ram-pressure stripping which should only affect massive galaxies within the cluster cores ($\lesssim 0.3 R_{vir}$; Roediger & Hensler 2005), although the H I deficient spiral galaxies are observed to be on highly elliptical radial orbits (Solanes et al. 2001), those truncated or asymmetric galaxies at $0.3 \lesssim (r/R_{vir}) \lesssim 1.5$ could have recently passed through the cluster core (Mamon et al. 2004).

The few anemic spirals with globally reduced Hα and H I emission are generally found further from the cluster centres than truncated galaxies, half of them are outside the virial radius (Koopmann & Kenney 2004), while Goto et al. (2003) find that passive spirals in the SDSS are generally found in the outskirts of clusters at 1–10 R_{vir}. It could then be that these galaxies are the natural results of suffocation, and may represent an early phase of evolution from spirals to passively evolving S0s. The finding of significant numbers of truncated spiral galaxies in clusters, implies that the complete...
removal of gas and transformation into passively evolving galaxies does not occur rapidly, at least in Virgo-like clusters. This appears inconsistent with our finding of no environmental dependence in the Hα emission of bright star-forming galaxies, as that implies the transformation is either rapid or occurs at high redshift. One plausible explanation could be due to our measuring the Hα emission from a confined region in the galaxy centre rather than the entire disc, and that SF within the truncation radius is relatively unaffected, until the galaxy orbit brings it sufficiently close to the cluster centre that the remaining gas is completely stripped, rapidly terminating SF across the galaxy.

9.2 Dwarf galaxies affected by their environment

In Section 4, we showed that the make-up of the dwarf galaxy population varies strongly with environment. Whereas in galaxy groups and clusters the bulk of dwarf galaxies are passively evolving, as the local density decreases the fraction of passively evolving dwarfs drops rapidly, reaching zero in the rarefied field. Indeed for the lowest luminosity range covered (−18 < M_B < −16) none of the ∼600 galaxies in the lowest-density quartile are passively evolving.

In Section 6, we examined in detail the immediate environment of those few passively evolving dwarf galaxies in field regions, finding them very strongly clustered around bright (M_B ≤ −20.5) galaxies. Almost without exception those passively evolving galaxies outside groups and clusters appear to be satellites bound to massive galaxies. This association of passively evolving dwarf galaxies as satellites within more massive haloes is consistent with the analysis of Zehavi et al. (2005) of the dependence of the galaxy two-point correlation function on luminosity and colour. They find that whereas the overall amplitude of clustering decreases monotonically with magnitude over −23 ≤ M_B ≤ −18, the clustering of red galaxies on ≤ 1 Mpc scales is strongest for M_B > −19. They are able to describe these results using halo occupation distribution (HOD) models in which the faint red galaxies are nearly all satellites in high-mass haloes.

These results confirm and significantly extend the long noted morphological segregation of dwarf galaxies in the local (∼30 Mpc) neighbourhood, with dwarf ellipticals (dEs) confined to groups, clusters and satellites to massive galaxies, while dwarf irregulars (dIrrs) tend to follow the overall large-scale structure without being bound to any of the massive galaxies (Einasto et al. 1974; Ferguson & Binggeli 1994). Here dwarf ellipticals (dEs) are generally defined as galaxies with −18 ≤ M_B ≤ −14 having smooth, symmetrical surface brightness profiles implying no spiral structures or star-forming regions, and typically have very low HI mass fractions, and hence we identify these galaxies with our passively evolving dwarf galaxies, although there are galaxies which are classed as dEs but have recent SF in their central regions; (e.g. NGC 205, Mateo 1998).

The morphological segregation of dwarf galaxies was first noted by Einasto et al. (1974) who compared the spatial distributions of dwarf companions to our Galaxy and the nearby massive spirals M 31, M 81 and M 101. They found a striking separation of the regions populated by dE and dIrr galaxies with a well-defined line of segregation which had a strong luminosity dependence, with more luminous dEs constrained to smaller regions around the primary galaxy. They argued that tidal effects would be insufficient to produce this segregation and that a dense corona of halo gas around massive galaxies is necessary to strip the gas from the satellites as they move through the corona (Gunn & Gott 1972). In the Local Group, the only dwarf ellipticals are M 32, NGC 147, NGC 185 and NGC 205, all of which are satellites of M 31, while three of the five dwarf irregulars of comparable brightness (NGC 6822, IC 6822 and WLM) are free-floating within the Local Group potential (e.g. Mateo 1998; van den Bergh 1999). Beyond the Local Group, there are no known isolated dE galaxies within 8 Mpc (Karachentsev et al. 2004).

In a survey covering 900 deg² Binggeli et al. (1990) identify 179 dwarf galaxies, and claim that ‘in the field there are virtually no isolated dEs, and that the few dEs outside gravitationally bound systems are close satellites to massive giants’. They find just one good candidate for an isolated dE, #179 in their dwarf catalogue. The reported location of this galaxy is covered by the SDSS, but no galaxy is found there, and it appears most likely to correspond to a z = 0.08 Sa galaxy 1 arcmin distant.

Dwarf ellipticals (including here dSphs) in contrast are the most numerous galaxy type in clusters, although unlike the field or within groups only a small fraction appear bound to massive galaxies (Ferguson 1992), the rest follow the general cluster potential. However, the ratio of dEs to giants is much greater in clusters than in groups or the field, and so not all cluster dEs can be accounted for by the accretion of ‘field’ dEs (Conselice, Gallagher & Wyse 2001).

This clear segregation of passively evolving dwarf galaxies places strong constraints on their formation and evolution, in particular as to the physical mechanisms that could cause them to cease forming stars. Most importantly, unlike massive galaxies for which their build-up through mergers appears fundamental in determining their SFH, we can rule out merging as a formation mechanism for passively evolving dwarfs.

Galaxy merging is a stochastic process which occurs independently of the large-scale environment (≳1 Mpc) of a galaxy (Hopkins et al. 2007a). This means that mergers take place in all environments¹ even in voids, as has been observed for interacting pairs (Alonso et al. 2006). This results in merger remnants being ubiquitous, as predicted by Hopkins et al. (2007a), and observed in the spatial distribution of post-starburst galaxies (Goto 2005; Hogg et al. 2006). This is most clearly demonstrated with the presence in all environments of passively evolving, massive galaxies with old stellar populations, which in field regions make up >50 per cent of the total population of massive galaxies, forming an equal inter-spersed mixture with younger star-forming galaxies (figs 3 and 4 from Paper I).

Hence, dwarf galaxies which have undergone major mergers should also be ubiquitous, as Conselice (2006) shows that they have undergone on average about the same number of major mergers as massive galaxies since z ~ 3 (albeit at later epochs), yet we find no passively evolving galaxies among the ∼600 – 18 < M_B < −16 dwarfs in the lowest-density quartile. In addition, mergers cannot explain the observed strong segregation of dwarf galaxies. In particular the presence of a massive galaxy should not affect the merging efficiency of a dwarf galaxy, or the observation that most dwarf star-forming galaxies in clusters are in the process of being transformed into passively evolving galaxies, an environment where mergers are now strongly inhibited.

The ineffectiveness of mergers to permanently shut down SF in dwarf galaxies can be understood in the context of the current theoretical framework of galaxy evolution. Springel et al. (2005a) show through hydrodynamical simulations of mergers that although both models with and without black holes produce strong starbursts during the mergers followed by a decline in SF, in those models without

¹ Except in relaxed, rich clusters where encounter velocities are much higher than the internal velocity dispersions of galaxies, preventing their coalescence (Aarseth & Fall 1980).
black holes the remnants continue to form stars at a non-negligible rate. Given that the growth of central black holes during galaxy mergers is strongly regulated by the mass of the host galaxy, in low-mass galaxies the resultant black holes (if indeed there is one at all), based on the $M_{\text{BH}}-\sigma$ relation (Ferrarese & Ford 2005), are too small to power the quasar winds which would expel the remaining gas and shut down SF, as occurs in more massive systems. Indeed for merging galaxies with $\sigma = 80 \text{ km s}^{-1}$, Springel et al. (2005b) show that the effects of black hole growth are minimal on SF in the remnant galaxy, and the galaxy does not become passive as a result of the merger. Moreover, most dwarf galaxies ($M_\odot \gtrsim -18$) appear to host central compact stellar nuclei rather than a central SMBH (Côté et al. 2006), consistent with our observation that the AGN fraction of galaxies falls too close to zero by $M_\odot \sim -18$ (Section 7). Even if a significant fraction of the available gas in the remnant is used up during the starburst, the intrinsic low SF efficiency of low-mass galaxies and regulatory effects of supernovae feedback, plus the continuous infall and cooling of fresh gas from the halo along filaments (Keres et al. 2005), ensures that the remaining gas is unlikely to be exhausted. Finally, the quasi-continuous low-level AGN activity that C06 suggest could inhibit cooling of gas from the diffuse hot gaseous halo of massive galaxies and prevent subsequent SF in them, has in contrast little effect against the clumpy nature of the gas infalling along filamentary structures on to the dwarf merger remnants.

In Section 5, we find a significant anti-correlation (10σ) between the EW(Hα) of dwarf star-forming galaxies and their local density, producing a systematic reduction of $\sim 30$ per cent in the Hα emission in high-density environments with respect to field values. We argue that this implies that the bulk of star-forming dwarf galaxies in groups and clusters are in the process of being slowly transformed into passive galaxies over long time-scales ($\gtrsim 1$ Gyr), and is thus suggestive of suffocation (Balogh et al. 2000).

However, as discussed in Section 8 the long gas consumption time-scales predicted from Equation 3 and observed by van Zee (2001) imply that even if deprived of further gas accretion through suffocation, SF in dwarf galaxies occurs at a sufficiently low rate that they are unlikely to have consumed all their gas by the present day. In low-mass dwarf galaxies ($M_\odot \lesssim 10^8 M_\odot$) as gas collapses and stars form, the resultant feedback from supernovae is able to drive out the remaining gas, temporarily shutting off SF, until the gas is able to cool and restart SF, resulting in episodic bursts of SF every $\sim 300$ Myr (Stinson et al. 2007). In more massive dwarf galaxies, such as those studied here, SN feedback appears too inefficient to power galactic winds that could expel the remaining gas from dwarf galaxies, even during starbursts (Mac Low & Ferrara 1999; Marcolini et al. 2006). Instead it seems that SF in dwarf galaxies appears strongly regulated and rather resilient over long time-scales. This quasi-continuous SF in dwarf galaxies seems to have been maintained since early epochs, as the global SFRs of galaxies with $M_\odot < 3 \times 10^{10} M_\odot$ have remained approximately constant since $z \sim 3$ (Panter et al. 2006).

A further difficulty for dEs being produced as the result of suffocation is that it does not affect the galaxy structurally, and so we should expect the surface brightness and luminosity to decrease in parallel as the stellar population evolves passively. However, the surface stellar mass densities of passively evolving dwarf galaxies are $0.5 \text{ dex higher}$ than their star-forming counterparts of the same stellar mass (Kauffmann et al. 2003b). Hence, if SF in dIrr galaxies were to simply be stopped, as in suffocation, the resultant surface densities would be too low in comparison to present-day dEs (Grebel et al. 2003). Equally, the metallicity of dIrrs are too low for their luminosity as compared with dEs, for them to be simply transformed by becoming passive (Grebel et al. 2003), while suffocation provides no means for the rotationally supported dIrrs to lose their angular momentum to become the dEs where little or no signs of rotation ($\lesssim 5 \text{ km s}^{-1}$) are seen.

If gas cannot be exhausted through SF, expelled by supernovae feedback during starbursts, or prevented from infalling and cooling through AGN feedback, the end of SF and gas removal in dwarf galaxies must come from external mechanisms, such as ram-pressure or tidal interactions (Marcolini et al. 2006).

When galaxies pass through the dense ICM of clusters or the gaseous haloes of massive galaxies they feel an effective ram-pressure which, if able to overcome the gravitational attraction between the gas and the disc, is able to effectively strip the gas from the disc (for a review see van Gorkom 2004), according to the Gunn & Gott (1972) condition $\rho_{\text{ICM}} v_\parallel^2 > 2\pi G \Sigma \Sigma_{\text{gas}}$, which has been shown to hold approximately from hydrodynamical simulations (e.g. Marcolini, Brighenti & D’Ercole 2003). Hence, ram-pressure stripping should be more effective for lower mass, low surface brightness galaxies, galaxies on more eccentric orbits, and galaxies in richer environments (Hester 2006), such that while for massive galaxies ram-pressure stripping is only effective in the cores of rich clusters, dwarf galaxies can be completely stripped of their gas even in poor groups (Marcolini et al. 2003).

Moore et al. (1996) proposed that cluster spirals could be disrupted by ‘galaxy harassment’, whereby repeated close ($\sim 50$ kpc) high-velocity ($> 1000 \text{ km s}^{-1}$) encounters with massive galaxies and the cluster’s tidal field cause impulsive gravitational shocks that damage the fragile discs of late-type discs, transforming them over a period of Gyr into spheroids. While $\sim L^*$ spirals are relatively stable to the effects of harassment, suffering little or no mass loss, low surface brightness dwarf spirals with their shallower potentials may suffer significant mass losses (up to 90 per cent) of both their stellar and DM components during harassment (Moore et al. 1999), resulting in remnants resembling dwarf ellipticals (Mastropietro et al. 2005).

Dwarf spiral galaxies orbiting as satellites to massive galaxies may also be transformed into passively evolving dEs through tidal interactions with the primary galaxy and ram-pressure stripping as they pass through its gaseous halo. Mayer et al. (2001) show that dwarf spirals orbiting a Milky Way type galaxy on eccentric orbits taking them within 50 kpc of the primary experience tidal shocks during their pericentre passages, that can cause significant mass loss (mostly of the outer gaseous halo and DM, but also of the stellar disc), formation of bar instabilities that channel gas inflows triggering nuclear starbursts, and loss of angular momentum, resulting in their transformation over a period of $\sim 5$ Gyr into an early-type dwarf. Mayer et al. (2006) indicate that while tidal stirring of discy dwarf galaxies can transform them into remnants that resemble dEs after a few orbits, ram-pressure stripping is required to entirely remove their gas component. Kravtsov et al. (2004) show that many dwarf satellites of Milky Way type galaxies have undergone significant mass loss through tidal stripping, and are able to reproduce the observed morphological segregation of dE and dIrr galaxies (Einasto et al. 1974), in which the dEs are those that have suffered significant tidal stripping.

As discussed above star-forming, late-type dwarf galaxies in clusters, groups or bound to massive galaxies can be transformed into dEs through a combination of ram-pressure stripping and tidal interactions. This is supported by the finding of significant populations of dEs in the Virgo cluster having blue central regions caused by recent or ongoing SF (Lisker et al. 2006), significant amounts...
(≥10⁷ M⊙) of H i gas (Conselice et al. 2003), or clear disc features including spiral arms, bars or significant velocity gradients, with rotational velocities similar to dwarf irregulars of the same luminosity, and anisotropy parameters (v/σ_a ≥ 1) indicating stellar kinematics dominated by rotation rather than random motions (van Zee, Skillman & Haynes 2004). These populations are found predominantly in the cluster outskirts and some have flat distributions of radial velocities, suggesting that they have been recently accreted by the cluster or are on high angular momentum orbits and therefore never go through the cluster core, while normal, non-rotating dEs are concentrated in the cluster core or in high-density clumps (Conselice et al. 2003; van Zee et al. 2004; Lisker et al. 2007). In a similar H i study, this time of 11 dIrrs in the Virgo cluster, Lee, McCall & Richer (2003) find that five of them are gas deficient by a factor of ≥10 with respect to field dIrrs at comparable oxygen abundances, and this gas deficiency correlates approximately with the X-ray surface brightness of the ICM. These gas-poor dIrrs have typical colours and luminosities of normal field dIrrs, indicating that their SF has not yet been affected, and suggesting that they have only recently encountered the ICM for the first time. In the Coma cluster Caldwell et al. (1993) and Poggianti et al. (2004) find that whereas bright post-starburst galaxies with k+a spectra are largely absent, there is a significant population of faint galaxies (M_r ≥ −18.5) with k+a spectra, which appear associated with substructures in the ICM, the galaxies lying close to the edges of two infalling structures. This strongly suggests that the interaction with the ICM could be responsible for rapidly quenching the SF in these galaxies, possibly after a starburst. These observations all point towards the ongoing transformation of late-type dwarf galaxies into passively evolving dwarf ellipticals.

10 SUMMARY AND CONCLUSIONS

We present an analysis of SF in galaxies as a function of both luminosity and environment, in order to constrain the physical mechanisms that drive the SFHs of galaxies of different masses. In particular we wish to distinguish between mechanisms that are internal to the galaxy such as AGN feedback, gas consumption through SF and merging, and those related to the direct interaction of the galaxy with its surroundings including ram-pressure stripping and galaxy harassment.

For this analysis we use the NYU-VAGC low-redshift galaxy catalogue (Blanton et al. 2005c) taken from the SDSS DR4 spectroscopic data set. Using a sample of 27 753 galaxies in the redshift range 0.005 < z < 0.037 that is ≥90 per cent complete to M_r = −18.0 we quantify the environment of each galaxy using an adaptive kernel method that for galaxies in groups or clusters resolves the local density on the scale of their host halo, while in field regions smooths over its 5–10 nearest neighbours. We use Hα-emission as a gauge of the current SF in the galaxies and find that the EW(Hα) distribution of galaxies is strongly bimodal, allowing them to be robustly separated into passively evolving and star-forming populations about a value EW(Hα) = 2 Å. Aperture effects can strongly bias the estimates of SFRs based on spectra obtained through fibres which cover less than ~20 per cent of the integrated galaxy flux, as is the case for SDSS spectra of galaxies in the redshift range of our sample (Kewley et al. 2005). For the massive galaxies in our sample with M_r < −20 we confirm that aperture effects are important finding a significant fraction of galaxies (mostly face-on spirals with prominent bulges) which are classified as passive from their spectra, but whose blue integrated NUV − r colours indicate recent SF (Paper III). Throughout this paper, we thus quantify and take full account of the effects of aperture biases on our results for the bright galaxies in our sample. For the dwarf galaxy population which represents our primary interest in this paper, we find that aperture biases should not affect our results, in agreement with Brinchmann et al. (2004), due primarily to the absence of faint early-type spirals.

In the case of massive galaxies (M ≥ 10^{10.5} M⊙; M_r ≤ −20) we find only gradual trends of SF with environment, the fraction of passively evolving galaxies increasing gradually with local density from ~50 per cent to ~70 per cent in high-density regions, the trend extending to the lowest-density regions studied, well beyond the effects of cluster-related processes. For these galaxies only the large-scale galaxy density appears important for defining its SFH, and not its immediate neighbours or even whether it is within a cluster or group, implying that cluster-related processes are not the primary mechanisms by which massive galaxies become passive.

The SFHs of massive galaxies appear to be predefined by the initial conditions in which they form, whereby in high-density regions they are likely to form earlier and have more active merger histories than those in low-density regions, resulting in the observed gradual SF–density relations.

In contrast, the SFHs of dwarf galaxies (M ~ 10^{9.2} M⊙; M_r ~ −18) are strongly dependent on their local environment, the fraction of passively evolving galaxies dropping from ~70 per cent in dense environments, to ~0 per cent in the rarefied field. Indeed for the lowest luminosity range covered (~18 < M_r < −16) none of the ~600 galaxies in the lowest-density quartile is passively evolving. The few passively evolving dwarfs in field regions are strongly clustered around bright (≥L^∗) galaxies, and throughout the SDSS sample we find no passively evolving dwarf galaxies more than ~2 virial radii from a massive halo, whether that be a cluster, group or massive galaxy. This limit of around 2–3.5 virial radii corresponds to the maximum distance from a cluster or massive galaxy that a galaxy can rebound to having previously been subhaloes within massive haloes (Mamon et al. 2004; Diemand, Kuhlen & Madau 2007), and so it seems reasonable to believe that all passively evolving dwarf galaxies are or have been satellites within a massive DM halo.

Our finding that passively evolving dwarf galaxies are only found within clusters, groups or as satellites to massive galaxies indicates that internal processes or merging are not responsible for terminating SF in these galaxies. Instead the evolution of dwarf galaxies is primarily driven by the mass of their host halo, probably through the combined effects of tidal forces and ram-pressure stripping. We find a significant anti-correlation (10r) between the EW(Hα) of dwarf (−19 < M_r < −18) star-forming galaxies and local density, producing a a systematic reduction of ~30 per cent in the Hα emission in high-density regions with respect to field values. We argue that this implies that the bulk of star-forming dwarf galaxies in groups and clusters are currently in the process of being slowly transformed into passive galaxies. The transformation of dwarf galaxies solely through environmental processes results in the wide variety of SFHs observed in the local dwarf galaxy population (Mateo 1998).

Examining the fraction of passively evolving galaxies as a function of both luminosity and local environment, we find that in high-density regions ~70 per cent of galaxies are passively evolving independent of luminosity. In the rarefied field, whereby environmental related processes are unlikely to be effective, the fraction of passively evolving galaxies is a strong function of luminosity, dropping from 50 per cent for M_r ≤ −21 to zero by M_r = −18. This strong luminosity dependence of the fraction of passive galaxies in field regions reflects with the systematic trend with increasing galaxy mass for SFHs to be driven by internal mechanisms as opposed to environmental processes. This transition from
environmentally to internally driven SFHs is likely due to a combination of factors.

(i) The increasing efficiency and rapidity with which gas is converted into stars for more massive galaxies, resulting in gas-consumption time-scales for massive galaxies that are much shorter than the Hubble time.

(ii) The mode for the accretion and cooling of fresh gas on to the galaxy from its surroundings. When galaxy haloes reach a mass of $\sim 10^{12} \, M_\odot$ expanding shocks heat infalling gas to the virial temperature of the halo, producing a stable atmosphere of hot, diffuse gas which is vulnerable to feedback effects that can prevent the gas from cooling on to the galaxy (Kereš et al. 2005; Dekel & Birnboim 2006).

(iii) AGN feedback in the form of quasar winds which can expel the remaining gas from a galaxy and/or the quasi-continuous low-level AGN activity that prevents cooling of the diffuse atmosphere of hot gas in massive galaxies. The observed parallelled increasing fractions of AGN and passive field galaxies with luminosity supports the importance of AGN feedback in shutting down SF in galaxies, a process which should become increasingly efficient with galaxy mass as the result of the tight $M_{\text{BH}}-\sigma$ relation.

(iv) The increased susceptibility of low-mass galaxies to disruption by environmental effects such as tidal shocks and ram-pressure stripping due to their shallow potential wells.

The combined effect of these processes is to produce the observed bimodality in the global properties of galaxies about a characteristic mass of $\sim 3 \times 10^{10} \, M_\odot$ (K03). However, given that several models that treat each of these processes in diverse ways are qualitatively able to reproduce this bimodality (Menci et al. 2005; Bower et al. 2006; C06; Cattaneo et al. 2006; Birnboim et al. 2007), it will be difficult to quantify the relative importance of the mechanisms for driving the SFHs of galaxies, although Hopkins et al. (2007b) show some observational tests that could distinguish between these models.

ACKNOWLEDGMENTS

The authors thank Ivan Baldry, Agatino Rifatto and Eelco van Kampen for reading a draft version of this paper, and the referee for useful comments regarding this work. CPH acknowledges the financial supports provided through the European Community’s Human Potential Program, under contract HPRN-CT-2002-0031 SISCO. AM acknowledges the INAF – Osservatorio Astronomico di Capodimonte for a grant. AG thanks her PhD supervisor Massimino Capaccioli.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration (NASA), the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

This research has made use of the NASA/IPAC Extragalactic Data base (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

The Millennium Run simulation used in this paper was carried out by the Virgo Supercomputing Consortium at the Computing Centre of the Max-Planck Society in Garching. The semi-analytic galaxy catalogue is publicly available at http://www.mpa-garching.mpg.de/galform/agnpaper.

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APPENDIX A: TESTING OF THE DENSITY ESTIMATOR

We test the efficiency of this density estimation algorithm, by applying it to the public galaxy catalogues from the Millennium simulation (Springel et al. 2005c; C06). These simulations cover a (500 h−1 Mpc)3 volume producing a galaxy catalogue complete to $M_r = −17.4$, containing some 9 million galaxies, for which positions, peculiar velocities, absolute magnitudes in each of the SDSS filters, stellar masses are all provided. From this, we consider 61 981 $M_r < −18$ galaxies from a subregion of volume 200 × 200 × 100 Mpc3. We estimate the local density of each galaxy in physical space, ρ(3D), by applying the adaptive kernel method, representing each galaxy by a spherically symmetric Gaussian kernel whose width is equal to the distance to its fifth nearest neighbour. Galaxy groups and clusters are identified through a percolation analysis using a friends-of-friends algorithm with a linking length equal to 0.2 times the mean interparticle separation. For each group containing four or more members, the velocity dispersion ($σ_v$) and virial radius ($R_{vir}$) are calculated following Girardi et al. (1998). For each galaxy we combine the position and peculiar velocity in the z-direction to create a redshift, producing a volume-limited redshift catalogue, to which we apply exactly the same adaptive kernel method as for the SDSS data, representing each galaxy by a Gaussian kernel of transverse width defined by the distance to its 3rd nearest neighbour within 500 km s−1 and of width 500 km s−1 in the radial/redshift direction. The resultant distribution of local galaxy densities, ρ, is shown in the left-hand panel of Fig. A1 by the solid black lines.

To examine the efficiency of this density estimator in identifying galaxies within groups, the red filled histogram shows the density distribution of galaxies that were identified by the percolation analysis to belong to a group containing four or more members. Alternatively, the green-dashed histogram shows the density distribution of those galaxies within the virial radius of a group containing four or more galaxies. In both cases, the observed local galaxy density of group galaxies is strongly biased to high densities with $ρ > 1$, while no group galaxy has $ρ < 0.5$. The yellow hatched histogram shows the density distribution of those galaxies in the transition regions between group and field environments having $0.8 < ρ/R_{vir} < 1.2$. Galaxies in these transition regions have local densities in the range $1 < ρ < 4$. Finally, the blue short-dashed histogram shows those galaxies in isolated field regions more than two virial radii from the nearest group, and hence are unlikely to have encountered the group environment during their evolution or be affected by group/cluster-related physical processes. As expected, they are observed to have low local densities with $ρ ≲ 1$.
The left-hand panel of Fig. A1 demonstrates the efficiency of this density estimator in identifying group and isolated field galaxies, in particular the latter. By selecting galaxies with $\rho < 0.5$ we can be sure of obtaining a sample of field galaxies, the vast majority (>97 per cent) at $>2r_{\text{vir}}$, and with no contamination from any galaxies belonging to groups or clusters, even those containing as few as four galaxies. Considering instead those galaxies with $\rho < 1.0$, >95 per cent still have $>2r_{\text{vir}}$, while only 0.7 per cent lie within the virial radius of a group. In contrast, ~60 per cent of $\rho > 1.0$ and ~90 per cent of $\rho > 4$ galaxies are at $<r_{\text{vir}}$.

For comparison, the right-hand panel of Fig. A1 shows the same density distributions of field and group galaxies brighter than $M_r = -18$ using the nearest neighbour algorithm as applied by BB04 and BB06 who estimate the local density on the basis of the projected distance to the fifth nearest neighbour that is brighter than $M_r = -20$ and has a radial velocity within 10 000 km s$^{-1}$ of each galaxy. The overall density distributions are quite similar, as although there are three times fewer $M_r < -20$ galaxies than $M_r < -18$ galaxies, the recession velocity range over which the projected density is estimated is quadruple that used for the adaptive kernel estimator (2000 km s$^{-1}$ instead of 500 km s$^{-1}$). The most important difference between the two estimators is the much broader density distribution of group galaxies (red filled histogram) for the nearest neighbour algorithm, corresponding to $\Sigma_5 \simeq 0.1$, ~5 per cent of the galaxies are group members, and hence could have been affected by group-related environmental processes. Equally, $\Sigma_5$ does not appear very sensitive to the position of a galaxy within a halo, as is apparent by the densities of those galaxies at and around the virial radius of groups being a wide range of values of $\Sigma_5$ and peaking at a mid-range value for galaxies within groups, rather than that obtained from the adaptive kernel approach where galaxies near the virial radius have generally the lowest densities of those galaxies in groups. The value of $\Sigma_5$ is instead most sensitive to the mass of the nearest massive halo, rather than whether a galaxy is inside or outside that halo.

To fairly compare the efficiency of the adaptive kernel estimator against nearest neighbour approaches, we restated the nearest neighbour algorithm using the same $M_r < -18$ data sets, varying the numbers of neighbours used over the range 3–10, and the velocity range used to select neighbours from 400 to 1000 km s$^{-1}$. We define the efficiency of the density estimators in two ways: first in terms of the rank correlation between the observed projected density and the actual physical three-dimensional galaxy density $\rho(3D)$; and secondly its sensitivity to the position of the galaxy within a halo, as measured by the correlation with the distance $r$ do the nearest massive halo (containing four or more galaxies) scaled by the virial radius $r_{\text{vir}}$. We measure the strengths of these correlations through the Spearman rank correlation test as presented in Table A1. First, varying the numbers of neighbours used to estimate the local density, we find that $\Sigma_5$ is the most sensitive to the actual physical local density $\rho(3D)$, while $\Sigma_10$ is the most sensitive to the position of the galaxy within the halo (for neighbours within 500 km s$^{-1}$). Secondly, varying the velocity range over which neighbours are selected, we find that a range of 400 km s$^{-1}$ is most sensitive to the physical density, while a range of 600 km s$^{-1}$ is the most sensitive to the position of the galaxy within the halo. These confirm that using a range of 500 km s$^{-1}$ is the optimal general purpose value for estimating the local density of galaxies (at least for samples extending to $M_r = -18$, while the commonly used value of 1000 km s$^{-1}$ is much less efficient due to contamination of projected background galaxies.

Comparing our adaptive kernel estimator to the nearest neighbour algorithm, we find that it is always more sensitive to the position of the galaxy within a halo, and is only marginally less efficient than the optimal choice of parameters for the nearest neighbour algorithm ($\Sigma_5$). The adaptive kernel estimator we have adopted is at least as efficient as any comparable nearest neighbour algorithms, and is particularly sensitive to the position of a galaxy within a halo, which is likely to be the most important aspect of the environment in terms of affecting its evolution (Lemson & Kauffmann 1999).

In comparison, we note that the particular algorithm used by BB04, BB06 is significantly less sensitive to both the $\rho(3D)$ and the position of the galaxy within the host halo (last row of
Table A1. Comparison of efficiencies of density estimators.

| Method used | Number of neighbours | Magnitude limit | Velocity range (km s\(^{-1}\)) | Spearman rank correlation \(\rho(3 \, \text{D})\) | \(r/R_{\text{vir}}\) |
|-------------|----------------------|-----------------|-------------------------------|---------------------------------|-----------------|
| AK          | 3                    | \(M_r < -18\)   | 500                           | **0.891**                       | -0.800          |
| NN          | 3                    | \(M_r < -18\)   | 500                           | 0.849                           | -0.744          |
| NN          | 5                    | \(M_r < -18\)   | 500                           | **0.896**                       | -0.774          |
| NN          | 8                    | \(M_r < -18\)   | 500                           | 0.890                           | -0.786          |
| NN          | 10                   | \(M_r < -18\)   | 500                           | 0.877                           | **0.789**       |
| NN          | 5                    | \(M_r < -18\)   | 1000                          | 0.856                           | -0.766          |
| NN          | 5                    | \(M_r < -18\)   | 800                           | 0.872                           | -0.772          |
| NN          | 5                    | \(M_r < -18\)   | 600                           | 0.889                           | **0.775**       |
| NN          | 5                    | \(M_r < -18\)   | 500                           | 0.896                           | -0.774          |
| NN          | 5                    | \(M_r < -20\)   | 400                           | **0.898**                       | -0.766          |
| NN          | 5                    | \(M_r < -20\)   | 1000                          | 0.785                           | -0.741          |

Table A1). These differences reflect the practical issue of the density of information used to characterize the environment of a galaxy. By measuring the local environment using just \(M_r < -20\) galaxies, the density of information is much sparser, making it that much less sensitive to effects on the scales of poor groups, which may contain three or less \(M_r < -20\) galaxies. However, a volume of the universe can be covered that is a factor of 10 larger than that which is possible using our approach which is limited by the necessity of being complete to \(M_r = -18\), and indeed for galaxies brighter than \(\sim M^*\), our analysis of their environmental trends is strongly limited by the small sample size. In addition, in the volume covered by our analysis, the only rich structures (with \(\sigma_v \gtrsim 500\, \text{km s}^{-1}\)) are the supercluster associated with the rich cluster Abell 2199 studied in Paper I, and Abell 1314, limiting our ability to follow the environmental trends to the highest densities.

The adaptive kernel method has the added advantage of being able to be used as a group-finder (e.g. Bardelli et al. 1998; Haines et al. 2004a), by identifying groups and clusters as local maxima in the galaxy density function \(\rho(x, z)\). A comparison of the groups identified in the Millennium simulation from a percolation analysis finds that all such groups containing four or more members are marked as clear local maxima in the luminosity-weighted density maps. Unlike group finding algorithms based on a percolation analysis, the adaptive kernel approach is also able to efficiently define substructures that are the natural consequence of the hierarchical merging of galaxy groups and clusters.

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