The SDSS-GALEX viewpoint of the truncated red sequence in field environments at $z \sim 0$

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ABSTRACT

We combine Galaxy Evolution Explorer GALEX near-ultraviolet (NUV) photometry with a volume-limited sample of local ($0.005 < z < 0.037$) Sloan Digital Sky Survey (SDSS) DR4 galaxies to examine the composition and the environmental dependencies of the optical and ultraviolet (UV)-optical colour–magnitude (CM) diagrams. We find that $\sim 30$ per cent of red-sequence galaxies in the optical CM diagram show signs of ongoing star formation from their spectra having $\text{EW}(\text{H}_\alpha) > 2$ Å. This contamination is greatest at faint magnitudes ($M_r > -19$) and in field regions where as many as three-quarters of red-sequence galaxies are star forming, and as such has important consequences for following the build-up of the red sequence. The NUV $- r$ colour instead allows a much more robust separation of passively evolving and star-forming galaxies, which allows the build-up of the UV-selected red sequence with redshift and environment to be directly interpreted in terms of the assembly of stellar mass in passively evolving galaxies. In isolated field regions, the number density of UV-optical red-sequence galaxies declines rapidly at magnitudes fainter than $M_r \sim -19$ and appears completely truncated at $M_r \sim -18$. These results support the downsizing paradigm whereby the red sequence is assembled from the top down, being already largely in place at the bright end by $z \sim 1$, and the faint end filled in at later epochs in clusters and groups through environment-related processes such as ram-pressure stripping or galaxy harassment.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: luminosity function, mass function – galaxies: stellar content.

1 INTRODUCTION

The most widely studied bimodality in galaxy properties is that observed for their colours, that is the clear separation of galaxies into the red sequence and blue cloud populations (e.g. Strateva et al. 2001). This has the advantage that it is easy to measure, particularly at high redshifts, allowing studies to follow the evolution of the bimodality to $z \sim 1.2$ and beyond (Bell et al. 2004; Willmer et al. 2006).

A number of studies have followed separately the evolution of the red and blue galaxy luminosity functions to $z \gtrsim 1$. There is a little evolution in the number density of massive ($M > 10^{11} M_\odot$) red-sequence galaxies with only a factor of 2 increase in the stellar mass density from $z \sim 1$ to the present day (Bell et al. 2004; Willmer et al. 2006). At lower stellar masses, however, a much more rapid evolution is observed, with the stellar mass density of $M \lesssim 10^{10.3}$ red galaxies dropping by an order of magnitude by $z \sim 0.8$ (Bundy et al. 2006). The red sequence thus appears to be built up from the top down, with the most massive galaxies in place first at $z > 1$, and the faint end incrementally filled in at lower redshifts.

The epoch and rapidity over which the red sequence is assembled is found to be a function of environment. In cluster environments, Tanaka et al. (2005) find no evidence for any significant growth of the red sequence since $z = 0.83$, except for a hint of evolution in the lowest mass bin ($M < 10^{10.5} M_\odot$) between $z = 0.83$ and 0.55. Similarly, De Lucia et al. (2007) find evidence for a deficit of faint [0.1 $\lesssim (U-I)_V \lesssim 0.4$] red-sequence galaxies in 18 EDiSCS clusters at $0.4 < z < 0.8$ with respect to the present-day clusters. They show that the observations are consistent with a simple model whereby these galaxies are formed as the result of blue galaxies in clusters at $z = 0.8$ having their star formation suppressed by the hostile cluster environment. In field environments, the fraction of galaxies on the red sequence is lower than in clusters at all luminosities and all redshifts to $z = 0.8$ (Tanaka et al. 2005), showing that the colour–density relation is already in place at $z = 0.8$. There is also a deficit of faint red-sequence galaxies in field regions, both at $z \sim 0.8$ and...
at the present day, indicating that the assembly of the red sequence is still incomplete in low-density environments.

In Haines et al. 2006, 2007, hereafter Papers I and II, respectively, we presented an analysis of star formation (SF) in galaxies as a function of both luminosity and environment in order to constrain the physical mechanisms that drive the star formation histories of galaxies of different masses. In Paper I, we used the fourth data release of the Sloan Digital Sky Survey (SDSS DR4; Adelman-McCarthy et al. 2006) to investigate the mass dependencies of the SF-density and age-density relations in the vicinity of the Abell 2199 supercluster. For giant galaxies ($M_\ast < -20$), we found gradual age–density and SF–density trends extending to the lowest densities studied, with the clusters dominated by old, passively evolving galaxies while in field regions we found equal fractions of old, passively evolving and young, star-forming galaxy populations which were completely interspersed. In contrast for the dwarf galaxy population ($-19 < M_\ast < -17.8$), we found a sharp transition from the virialized regions of clusters and groups which were still dominated by old, passively evolving galaxies, to outside where virtually all dwarf galaxies were young with ongoing star formation. The few old, passive dwarf galaxies outside of the clusters were always found to reside in poor groups or as a satellite to a massive galaxy.

In Paper II, we extended the analysis to the entire SDSS DR4, finding that in high-density regions 70 per cent of galaxies are passively evolving (EW [Hγ] < 2 Å) independent of luminosity. In the rarefied field, however, the fraction of actively evolving galaxies is strongly luminosity dependent, dropping from 50 per cent for $M_\ast \lesssim -21$ to zero by $M_\ast \sim -18$. Throughout the SDSS DR4 data set, no passively evolving dwarf galaxy is found more than two virial radii from a massive halo, whether that be a cluster, group or massive galaxy.

These results imply fundamental differences in the formation and evolution of giant and dwarf galaxies. A theoretical framework is being developed whereby these differences are related to: (i) the increasing star formation efficiencies and decreasing gas consumption time-scales with galaxy mass resulting from the Kennicutt–Schmidt law (Kennicutt 1998); (ii) the way that gas cools and flows on to the galaxy (Kereš et al. 2005); as well as (iii) active galactic nuclei (AGN) feedback which can effectively quench star formation in massive galaxies (Springel, di Matteo & Hernquist 2005a). The lack of passively evolving dwarf galaxies in isolated field regions implies that internal processes, such as AGN feedback, merging or gas consumption through star formation, are not able to completely shut down star formation in these galaxies. Instead star formation in dwarf galaxies is only terminated once they become satellites in massive haloes, probably through the combined effects of tidal forces and ram-pressure stripping.

In this article, we examine what consequences these differences have on the form of the red sequence in the local Universe, and its variation from within the high-density environments of clusters and groups, to the lowest density regions of the rarefied field. The SDSS and GALEX data sets used are described in Section 2.

In Section 3, we examine the issue of aperture bias on our spectral classification of galaxies (Brinchmann et al. 2004; Kewley, Jansen & Geller 2005). In Section 4, we examine the extent and make-up of the red sequence as a function of environment, based on the $u - r/M_\ast$ colour–magnitude (CM) diagram, considering the issue of the contamination of the red sequence by dusty star-forming galaxies. To resolve these problems in Section 5, we use the GALEX data to obtain near-ultraviolet (NUV)– $r/M_\ast$ CM diagrams in both cluster and field environments. Finally in Section 6, we present our discussion and conclusions. Throughout we assume a cold dark matter cosmology with $\Omega_m = 0.3, \Omega_{\Lambda} = 0.7$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 THE DATA

The galaxy sample is the same as that used and described in Paper II, consisting of 27 753 galaxies in the redshift range $0.005 < z < 0.037$ from the New York University–Value-Added Galaxy Catalog (Blanton et al. 2005a) low-redshift subsample (Blanton et al. 2005b). Incompleteness is a major issue for dwarf galaxies in surveys due to their low surface brightnesses, but Blanton et al. (2005b) show that at least for $M_\ast < -18$ their low-redshift subsample does not suffer from significant ($\gtrsim 10$ per cent) incompleteness due to surface brightness effects.

We use the stellar indices of the Max Planck Institute for Astrophysics/John Hopkins University SDSS DR4 catalogues (Kauffmann et al. 2003), in which the emission-line fluxes are corrected for stellar absorption. In Paper II, we showed that the distribution of the [O III] $\lambda5007$/Hβ diagnostic diagrams of Baldwin, Phillips & Terlevich (1981) as those galaxies lying above the $\sigma$ lower limit of the models defined by Kewley et al. (2001). When either the [O III] or Hβ lines are unavailable (S/N < 3), the two-line method of Miller et al. (2003) is used, with AGN identified as having log([NII] $\lambda6584$/Hα) $>-0.2$.

The local environment of each galaxy is quantified using a variant of the adaptive kernel estimator (Pisani 1996), whereby each $M_\ast < -18$ galaxy is represented by a Gaussian kernel in redshift space, $K(x, z)$, of width 500 km s$^{-1}$ in the radial direction, and whose transverse width is defined by the distance to its third nearest neighbour within 500 km s$^{-1}$. This method is designed (see Paper II for details) to resolve the galaxy’s environment on the scale of its host dark matter (DM) halo, as it is the mass of a galaxy’s 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 its star formation history or morphology (e.g. Lemson & Kauffmann 1999; Kauffmann et al. 2004; Blanton & Berlind 2007). By selecting galaxies with $\rho < 0.5$ Mpc$^{-2}$, a pure field sample is produced with no contamination from group members. In contrast 60 per cent of $\rho > 1$ galaxies lie within the virial radius of a galaxy group.

The launch of the Galaxy Evolution Explorer (GALEX; Martin et al. 2005) has allowed UV photometry to be obtained for a large sample of galaxies from the SDSS, and for this analysis we use both far-ultraviolet (FUV; $\lambda_{\text{eff}} = 1539$ Å, $\Delta \lambda = 268$ Å) and NUV ($\lambda_{\text{eff}} = 2316$ Å, $\Delta \lambda = 732$ Å) imaging from the third GALEX data release (GR3). Passively evolving galaxies at $z \sim 0$ have FUV $- r < 7$ and NUV $- r < 5.5$–6 (Yi et al. 2005), requiring $m_{\text{FUV}} \gtrsim 24.5$ and $m_{\text{NUV}} \gtrsim 23$ imaging to detect all galaxies from our 0.005 $< z < 0.037$ SDSS spectroscopic sample. Hence for the NUV, we consider those GALEX GR3 images from the Medium Imaging Survey (MIS), Nearby Galaxy Survey (NGS) and the publicly available Guest Investigator images which have exposure times $\sim 1$ ks and 5σ depths of $m_{\text{FUV}}, m_{\text{NUV}} \sim 24.5$ (Martin et al. 2005) sufficient to detect the SDSS sources also in the FUV. In total 528 GALEX GR3 NUV images from these surveys overlap with the SDSS DR4 footprint, for a total area of 490.1 deg$^2$. 

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3 APERTURE BIASES IN THE SDSS SPECTROSCOPIC SAMPLE

One of the major concerns of using the fibre-obtained SDSS spectra for nearby galaxy samples, such as those used in Papers I and II, is the effect of aperture biases, due to the spectra being obtained through 3 arcsec diameter apertures rather than over the full extent of the galaxy. Significant radial star formation gradients are possible within galaxies, particularly those undergoing nuclear starbursts or spiral galaxies with prominent passively evolving bulges, that can result in ‘global’ star formation rates (SFRs) extrapolated from spectra containing flux from only the galaxy nucleus being significantly over- or underestimated. Kelly et al. (2005) indicate that SFRs based on spectra obtained through apertures containing less than \( \sim 20 \) per cent of the integrated galaxy flux can be over or underestimated by a factor of \( \sim 2 \), and to ensure the SDSS fibres sample more than 20 per cent requires galaxies to be at \( z > 0.04 \). Clearly in order to use the SDSS data set to study star formation in dwarf galaxies, this is not possible as at \( z = 0.04 \) they are already too faint to be included in the SDSS spectroscopic sample.

In Papers I and II, we are primarily interested in the simple classification of galaxies into passive and star forming, and so the main issue is the number of early-type spiral galaxies which may appear passive from spectra that sample only their bulge, but have also normal star-forming discs. The integrated NUV – r colour gives a robust separation of passive and star-forming galaxies (Salim et al. 2005; Kauffmann et al. 2007; Martin et al. 2007, see Section 5). Hence, we can quantify the level of aperture bias as the fraction of galaxies that are classified as ‘passive’ from their spectra by having EW([H\alpha]) < 2 Å, yet have global UV-optical colours indicative of star-forming galaxies, defined as those with NUV – r < 4 (Wyder et al. 2007).

In Fig. 1, we show the r-band (panel a) and NUV-band (panel b) images of a typical misclassified galaxy from our sample (\( z = 0.0323, M_r = -21.71 \)), with the apertures used to obtain the SDSS spectra indicated by the red circles. The galaxy is a face-on early-type spiral, whose \( r \)-band flux is dominated by a bulge, but also with apparent spiral arms. In the NUV-band image however, this bulge disappears almost completely, while the extended UV-flux from star formation in the disc and spiral arms is now dominant. The reason for the misclassification is clear, the SDSS aperture covers only the central bulge which is passively evolving as apparent from the ‘hole’ in the UV-emission in the nuclear regions, yet misses entirely the extended star-forming regions from the outer disc and spiral arms.

In panel (c), we show the fraction of galaxies misclassified due to aperture effects as a function of absolute magnitude. We find that the level of misclassification due to aperture effects is strongly luminosity dependent, dropping from 8 per cent at \( M_r < -21.0 \) (20 out of 246) to zero for \( M_r > -19.5 \) galaxies. We indicate that aperture biases are significant for \( M_r < -20 \) galaxies, where 7 per cent are spectroscopically classified as passive, yet whose blue-integrated NUV – r colours are indicative of recent star formation.

As expected many of these galaxies appear as face-on spiral galaxies with prominent bulges, whose predominately old and passive stellar populations dominate the flux within the SDSS spectral apertures. In contrast, we find that none of the 1375 \( M_r > -19.5 \) galaxies in
the SDSS sample covered by GALEX UVI photometry are misclassified, indicating that the classification of such low-luminosity galaxies based on their Hα emission as measured through the SDSS fibres is robust against aperture biases. Note that here we are only discussing bias in terms of classifying galaxies as star forming or passive, and the fibre-based SFR estimates of dwarf galaxies may well have significant uncertainties, in particular, for dIrrs which have rather patchy star formation.

We can understand this luminosity dependence for the level of aperture bias as the combination of two effects: (i) more luminous galaxies at the same distance will have larger apparent sizes, and so the fraction of flux covered by the SDSS fibres will be reduced and (ii) low-luminosity galaxies tend to be either late-type spirals or dwarf ellipticals and hence do not have such significant radial gradients in their SFRs. The luminosity function of early-type spirals or dwarf ellipticals and hence do not have such significant radial gradients in their SFRs. The luminosity function of early-type spirals (Sa+bc) for which aperture biases are by far the most important has a Gaussian distribution centred at $M_r = -21.7$ and width $\sigma \sim 0.9$ mag (de Lapparent 2003), and hence are rare at $M_r \gtrsim -20$.

4 THE MAKE-UP OF THE RED SEQUENCE IN OPTICAL SURVEYS

It is broadly assumed that red-sequence galaxies are passively evolving galaxies dominated by old stellar populations formed at $z > 1$, while blue galaxies are star-forming galaxies, whose optical emission is dominated by young stellar populations. However, the optical colours of galaxies do not necessarily fully relate to the underlying star formation history as just described. In particular, galaxies can appear red both because they are passive, but also through high levels of dust extinction produced by starbursts. A much more reliable measure of recent star formation in galaxies than their optical emission, the best measure of recent star formation in galaxies than their optical emission is dominated by young stellar populations. However, the optical colours of galaxies do not necessarily fully relate to the underlying star formation history as just described. In particular, galaxies can appear red both because they are passive, but also through high levels of dust extinction produced by starbursts. A much more reliable measure of recent star formation in galaxies than their optical colour can be made from their spectra, in particular the level of Hα emission (Kennicutt 1998).

In Fig. 2, we look at how the $u - rM_r$ CM diagram is broken up into (i) passively evolving, (ii) star-forming and (iii) AGN components as determined from their spectra. In each panel, the black contours indicate the global bivariate density distribution of $0.005 < z < 0.037$ galaxies in CM space, while each galaxy is weighted by $1/V_{\text{max}}$ where $V_{\text{max}}$ is the maximum volume over which the galaxy could be observed within the survey. For each bin in $u - r$ colour and $M_r$ magnitude, we calculate the relative contribution of passively evolving galaxies (EW [Hα] < 2 Å; not AGN), star-forming galaxies (EW [Hα] > 2 Å; not AGN) and AGN, in panels (a–c), respectively. For each bin in the CM diagram containing at least one galaxy, the box is colour-shaded with increasingly intense red colours indicating higher passive galaxy fractions in that bin. Panels (b) and (c) show the contributions of star-forming galaxies (blue-shaded boxes) and AGN (green-shaded boxes).

The bimodality of galaxy properties in CM space is clear, with a population of red ($u - r \sim 2.4$) galaxies forming the red sequence, and the less luminous ‘blue cloud’ population apparent at $u - r \sim 1.2$. The CM relation of red-sequence galaxies shows the well known slope due to metallicity effects. We apply the method of López-Cruz, Barkhouse & Yee (2004) to estimate the slope and width of the CM relation, using the biweight algorithm (Beers, Flynn & Gebhardt 1990) to estimate the dispersion about the relation (see e.g. Haines et al. 2004). Panel (a) shows that passively evolving galaxies are well confined to the red sequence, with virtually no optically blue ($u - r < 1.6$) passive galaxies, and so considering just the passively evolving galaxies we obtain a best-fitting relation of

$$u - r = 2.291 (0.004) - 0.1191 (0.0114) \times (M_r + 20)$$

shown by the red solid lines in panels a–c), and with a width $\sigma = 0.181$. We identify red-sequence galaxies as those which have colours redder than the black-dashed line, which corresponds to a relation 1.5$\sigma$ bluer than the red sequence, and where equal numbers of passive and star-forming galaxies are observed when averaged over all environments.

In panel (b), we see that virtually all blue galaxies are identified as star forming from their spectra, and hence to a first approximation the correlation between galaxy colour and the current SFR appears good. However, it is also notable that a significant fraction of galaxies with red optical colours ($u - r \gtrsim 2$) are in fact star forming, particularly at the faint end ($-19 < M_r < -17$), where 53 per cent of red-sequence galaxies (i.e. above the dashed line) are spectroscopically classed as star forming. Finally in panel (c), we see that AGN are generally red and confined to the most luminous galaxies in the sample where they make-up ~50 per cent of the galaxy population, this fraction falling to close to zero by $M_r \sim -18$ as shown in Paper II.

Hence, while passive galaxies are red, red galaxies are not necessarily passive. In particular, Davoodi et al. (2006) find that 17 per cent of red-sequence galaxies are dusty, star-forming galaxies (identified by their high 24/3.6 μm flux ratios and Hα emission), while Wolf, Gray & Meisenheimer (2005) find that dusty, star-forming galaxies make-up more than one-third of the red-sequence population, finding them preferentially in the outskirts of clusters. Given that the relative fractions of passively evolving/red and

Figure 2. The global make-up of the $u - rM_r$ CM diagram of galaxies. Contours show the volume-corrected $u - rM_r$ CM diagram, and are spaced logarithmically, the spacing between contours indicating a factor of $\sqrt{2}$ increase in the galaxy density. Panel (a) shows the global fraction of passively evolving galaxies in each bin of $u - r$ colour and $M_r$ magnitude, with increasingly intense red colours indicating higher passive galaxy fractions in a bin (indicated also by the numeric value). Panels (b) and (c) show the contributions of star-forming galaxies (blue-shaded boxes) and AGN (green-shaded boxes). The solid red line indicates the best-fitting CM relation of equation (1), and the dashed line indicates the limit used to separate red sequence and blue cloud galaxies.
Table 1. Fraction of red-sequence galaxies classified as star forming as a function of both environment and luminosity.

| Magnitude range | Gals   | Global fraction (per cent) | Field (ρ < 0.5) (per cent) | Cluster (ρ > 1.0) (per cent) |
|-----------------|--------|---------------------------|---------------------------|-----------------------------|
| All             | 6189   | 31.4 ± 1.1                | 37.2 ± 2.2                | 24.6 ± 1.5                  |
| M_r < −20       | 3068   | 18.1 ± 1.1                | 21.0 ± 2.1                | 14.0 ± 0.4                  |
| −19 < M_r < −17 | 1579   | 51.7 ± 3.1                | 73.0 ± 7.8                | 35.4 ± 3.5                  |

star-forming/blue galaxies of a given luminosity are strongly dependent on local environment, particularly at the faint end (Balogh et al. 2004; Baldry et al. 2006; Paper II), the contamination of the red sequence by star-forming galaxies is also likely to be strongly dependent on environment.

In Table 1, we examine how the fraction of red-sequence galaxies (i.e. above the red dashed lines in Fig. 2) which are spectroscopically classed as star forming varies with both environment and luminosity. Globally, we find that 31 per cent of red-sequence galaxies (with M_r < −17) are star forming, similar to that found by Wolf et al. (2005), but larger than the 17 per cent obtained by Davanord et al. (2006). This difference is most likely due to their sample being biased towards more luminous galaxies than ours, and indeed we find just 18 per cent of M_r < −20 galaxies to be star forming. We find that the contamination of dusty star-forming galaxies is much greater in field regions than in clusters; and in all environments, the contamination is greater at faint magnitudes. We note that most galaxies which are above the red sequence (u − r ∼ 2.8) are in fact star forming, their red colours simply due to dust extinction.

The most notable value in Table 1 is that for −19 < M_r < −17 red-sequence galaxies in field regions, where we find 73 ± 8 per cent to be classed as star forming. This has important consequences for interpreting many of the recent studies for the build-up of the red sequence, both in the local universe and at high redshifts. For example, Baldry et al. (2006) show that in low-density regions the fraction of galaxies belonging to the red sequence is strongly dependent on stellar mass, dropping from ~80 per cent at log M_r ∼ 11.4 to ~5 per cent at log M_r ∼ 9.0. In Paper II, we find that the fraction of passively evolving galaxies drops to precisely zero by M_r ∼ −18 or log M_r ∼ 9.2. Similarly, Tanaka et al. (2005) determine the luminosity function of red-sequence galaxies in field regions, obtaining a Schechter function with a very shallow faint-end slope (α = −0.14), but which appears to flatten out at the faintest magnitudes (−19 < M_r < −17.5) due to a residual population of faint red-sequence galaxies. Our results indicate that around three-quarters of this residual faint red-sequence population in field regions are in fact star-forming galaxies. Hence, if a more robust colour selection could be applied to separate passive and star-forming galaxies, this residual faint red population would largely disappear in field regions (if not entirely).

5 THE GALEX-SDSS VIEW OF THE RED SEQUENCE AT z ∼ 0

The UV photometry from GALEX provides a global measure of star formation that is an order of magnitude more sensitive than optical photometry (e.g. u − r) alone to low levels of recent star formation3 overlaid on otherwise old stellar populations (e.g. Martin et al. 2005; Kauffmann et al. 2007; Martin et al. 2007). Similarly, the NUV − r colour is shown to correlate tightly with the birthrate parameter b (the ratio of the current to past-averaged SFRs; Salim et al. 2005) and the age-sensitive spectral indices d4000 and Hδ (Martin et al. 2007), implying that the star formation history of a galaxy can be constrained from its NUV − r colour alone. Moreover, Salim et al. (2007) show that the combined FUV and NUV photometry can be used to obtain reliable measures of dust-corrected SFRs for star-forming galaxies to an accuracy of 0.2 dex.

To resolve the limitations inherent in separating passively evolving and star-forming galaxies from just their u − r colours, we take advantage of the available GALEX UV data. Fig. 3 shows the global make-up of the NUV − r/M_r CM diagram, breaking it up into its (i) passive-evolving, (ii) star-forming and (c) AGN components, analogously to Fig. 2. The bimodality of galaxy properties in CM space is again apparent, with a robust separation of red and blue galaxies about a colour NUV − r ∼ 4 (see also Wyder et al. 2007) that appears much cleaner than for the optical counterpart.

Passive galaxies (panel a) are well confined to the red sequence, with few showing blue UV-optical colours (NUV − r ≤ 4). We estimate the zero-point, slope and dispersion of the red sequence before using those galaxies classified as passively evolving, obtaining a CM relation of

\[ \text{NUV} − r = 5.393(0.013) − 0.1782(0.0223) \times (M_r + 20) \]

(2)

(shown by the black solid line in panel a) and a dispersion of σ_{NUV-r} = 0.370 ± 0.007, consistent with the 0.3−0.5 mag obtained by Wyder et al. (2007). As before we identify red-sequence galaxies as those which are less than 1.5σ bluer than the CM relation, i.e., that lie above the dashed line.

In panel (b), we see that virtually all blue galaxies with NUV − r < 4 are spectroscopically star forming (except at the very bright end where AGN begin to dominate as shown in panel c). Unlike the optical CM diagram where a significant fraction of red galaxies were also classified as star forming, we see few star-forming galaxies with NUV − r > 5. Indeed, globally we find that just 8 per cent of galaxies belonging to the NUV-optical red sequence are classified as star forming as opposed to 31 per cent of galaxies from the optical red sequence. In Table 2, we report the corresponding fractions of star-forming galaxies among the NUV-optical red-sequence population as a function of both magnitude and environment. In all cases, the contamination of the NUV-optical red sequence by star-forming galaxies is significantly less (by typically a factor of 3−5) than for the optically selected red-sequence galaxies, being ≤10 per cent for all subsamples except for the faint, field galaxy population where 30 per cent appear to be star forming. However, we note that this last result is based on just four star-forming galaxies out of thirteen −19 < M_r < −17 red-sequence galaxies. We thus argue that the position of a galaxy in the NUV − r/M_r CM diagram can be used as a robust classifier of its recent star formation history, efficiently separating passively evolving and star-forming galaxies.

In panel (c), we show that AGN dominate the bright end of the CM diagram, and typically have NUV − r colours that are intermediate between the red sequence and blue cloud, lying in the so-called ‘green valley’. Indeed this preponderance of AGN in the transition zone between the red sequence and blue cloud has been proposed as

3 Where ≤1 per cent of the galaxy’s mass in stars form in the last Gyr.
FUV−optical colours, although they are found only on the lower edge of the red spectroscopically classified as star forming with red FUV-optical colours, due to excess galaxies with intermediate NUV−r colours, while green and magenta triangles indicate AGN with EW [Hα] < 2 Å respectively.

Table 2. Fraction of NUV−r selected red-sequence galaxies classified as star forming as a function of environment and luminosity.

| Magnitude range | Gals | Global fraction (per cent) | Field (ρ < 0.5) (per cent) | Cluster (ρ > 1.0) (per cent) |
|-----------------|------|---------------------------|----------------------------|----------------------------|
| All             | 796  | 8.5 ± 1.3                 | 10.6 ± 4.2                 | 5.8 ± 1.3                  |
| M_r < −20       | 358  | 6.1 ± 1.6                 | 3.3 ± 2.7                  | 5.0 ± 1.9                  |
| −19 < M_r < −17 | 245  | 10.2 ± 2.7                | 31 ± 24                    | 5.0 ± 2.0                  |

5.1 Comparison to FUV and MIR indicators

The FUV is yet more sensitive to recent star formation than the NUV, and traces star formation on time-scales of ∼10^8 yr, while the NUV does the same but for time-scales 5 to 10 times longer. However, galaxies are ∼1 mag fainter in the FUV than the NUV, and so a significant number of SDSS galaxies are not detected in the MIS FUV imaging. Hence, we consider only the deeper DIS images, and in Fig. 4, we show the FUV−r/M_r CM diagram for z < 0.05 SDSS galaxies with DIS FUV imaging. We separate galaxies into star forming (EW[Hα] > 2 Å; shown as blue circles) and passively evolving (EW[Hα] < 2 Å; red squares) galaxies. Galaxies with optical AGN signatures are indicated by green triangles (for those with EW[Hα] > 2 Å) or magenta triangles (EW[Hα] < 2 Å).

As for the NUV, we see a robust separation of passive and star-forming galaxies, with the red sequence dominated by passive galaxies at FUV−r ∼ 7 and the blue cloud of star-forming galaxies at FUV−r ∼ 3. Even in the FUV, however, we see some galaxies spectroscopically classified as star forming with red FUV-optical colours, although they are found only on the lower edge of the red sequence with FUV−r ∼ 6. The separation is only marginally better than that based on the NUV−r colour.

In Fig. 5, we compare the observed NUV−r colour with the ratio of 24 to 3.6 μm infrared (IR) luminosities obtained by the SWIRE IR survey (Lonsdale et al. 2003), matching the z < 0.05 SDSS galaxies with the public SWIRE IRAC + 24 μm band-merged catalogues for the Lockman, ELAIS-N1 and ELAIS-N2 fields. The 24-μm luminosity is known to be a well-calibrated indicator of the SFR (Calzetti et al. 2007), while the 3.6 μm flux can be used to trace the stellar mass distribution of galaxies almost independently of dust obscuration effects. Hence, the 24 to 3.6 μm flux ratio can be considered as a good measure of the specific SFR of a galaxy, and Davoodi et al. (2006) use log (L_{24}/L_{3.6}) = −0.7 to separate star-forming and passive galaxies. We see that the NUV−r colour and F_{24}/F_{3.6} ratio are strongly correlated, and both are directly related to the spectroscopic classification based on the galaxy’s nebular emission: star-forming galaxies have high F_{24}/F_{3.6} ratios and blue NUV−r colours, while passive galaxies have exclusively low F_{24}/F_{3.6} ratios and red NUV−r colours. Most importantly, we see that of the galaxies on the NUV-optical red sequence, only those spectroscopically classified as star forming or AGN have high F_{24}/F_{3.6} ratios, the 24 μm...
emission in the case of the latter produced by dust heated by the AGN rather than star formation. There is no evidence for a population of galaxies with ongoing star formation that is so completely obscured so as not to show any H\alpha emission or UV flux, and so we can gain a robust classification of galaxies into passive and star forming by a combination of SDSS spectra and NUV photometry.

5.2 Environmental trends of the NUV−r CM relation

In Fig. 6, we compare the NUV−rM\_r CM diagrams of galaxies in field (\( \rho < 0.5 \); left-hand panel) and cluster (\( \rho > 1.0 \); right-hand panel) environments. In Paper II, we found that the few passively evolving dwarf galaxies in field regions (\( \rho < 0.5 \)) were always satellites to massive galaxies (\( M_r < -20 \)), and that throughout the SDSS DR4 there were no passively evolving dwarf galaxies \( \gtrsim 2R_{200} \) from a massive halo, whether that be a cluster, group or massive galaxy. Hence to confirm this result, we remove the \( \sim 10 \) per cent of field galaxies that are found within a projected distance of 400kpc and a radial velocity within 300 km s\(^{-1}\) of a \( M_r < -20 \) galaxy. Our resultant field galaxy sample thus excludes galaxies which are satellites within massive haloes; however, it may include galaxies which have had a fly-by encounter with a massive galaxy in the recent past. The NUV-optical red sequence should then represent only those galaxies which have become passive through internal processes such as merging, AGN feedback and gas exhaustion through star formation.

In cluster regions (\( \rho > 1; \) right-hand panel), there is a clear NUV-optical red sequence dominated by passively evolving galaxies that extend to at least the completeness limit of the survey (\( M_r = -18 \)). There appears to be a break in the red sequence at \( M_r \sim -20.5 \), with massive red-sequence galaxies having similar colours (NUV−r \( \sim 5.7 \)) while fainter galaxies become increasingly blue. Similar trends have been seen by Boselli et al. (2005) who find the dichotomy between giant and dwarf red-sequence galaxies to be even stronger when using the FUV-optical or FUV-NIR colours. Wyder et al. (2007), in contrast, find no evidence of a break in the NUV-optical red sequence, fitting it instead by a straight line for \( -23.5 < M_r < -18 \). Fitting separate CM relations to bright (\( M_r < -20 \)) and faint (\( -21 < M_r < -18 \)) passively evolving galaxies, we obtain slopes of \( -0.043 \pm 0.052 \) and \(-0.222 \pm 0.039\), respectively, and hence the break appears significant. Considering now a CM relation with break at \( M_r = -20.5 \), the overall dispersion is reduced slightly to \( \sigma_{\text{NUV}} = 0.345 \pm 0.007 \), with no significant difference between bright and faint magnitudes.

At all luminosities, we see an extended tail of galaxies with bluer colours, being mostly AGN at the bright end and star-forming galaxies at fainter magnitudes. Although many of these galaxies have NUV−r \( \sim 2 \) corresponding to the peak of the blue cloud distribution seen in Fig. 3, a significant fraction are found with transitional colours being in the ‘green valley’ with NUV−r \( \sim 4–5 \). We see no obvious separation between the red sequence and the blue cloud populations in cluster environments.

In the field, however, the dominant feature of the CM diagram becomes the blue cloud population at NUV−r \( \sim 2 \), made up almost entirely of star-forming galaxies, except at the very bright tip (\( M_r \lesssim M_\star \)) where AGN take over. The red sequence is now sparsely populated at all magnitudes and appears truncated below \( M_r \sim -18.5 \).

5.3 The red and blue galaxy luminosity functions

In Fig. 7, we plot the red and blue galaxy luminosity functions (as red and blue symbols, respectively) in both field and cluster environments, based on the galaxies shown in Fig. 6, where the dashed line is used to separate the red and blue galaxy populations. We correct for incompleteness at faint magnitudes by weighting

![Figure 5](https://example.com/figure5.png)

**Figure 5.** NUV−r colour against the ratio of 24 to 3.6 \( \mu \)m luminosity. Solid symbols are as in Fig. 4. Open symbols indicate galaxies not detected in 24 \( \mu \)m at the 450\( m\)y SWIRE limit. The dotted line indicates the MIR cut used to separate star forming and passive galaxies in Davoodi et al. (2006).

![Figure 6](https://example.com/figure6.png)

**Figure 6.** The NUV−rM\_r CM diagram of galaxies in the lowest (\( \rho < 0.5 \)) and highest (\( \rho > 1.0 \)) density environments. Red squares and blue circles indicate passive (EW [H\alpha] < 2 \( \AA \)) and star-forming (EW [H\alpha] > 2 \( \AA \)) galaxies, while green and magenta triangles indicate AGN with EW(H\alpha) > 2 \( \AA \) and EW(H\alpha) < 2 \( \AA \) respectively. The dotted line indicates the completeness limit of the volume covered, while the solid and dashed lines are as in Fig. 3.
each galaxy by 1/Vmax. For each luminosity function (LF), we determine the best-fitting single Schechter (1976) function based on a maximum-likelihood analysis, shown by the black curves. The resultant best-fitting parameters are presented in Table 3, where the reported errors represent the 68.3 per cent confidence limits in α and M*.

We see little sign of variations in the luminosity function of blue galaxies from field to cluster environments, with marginal evidence for an increase in the luminosity of M* from field to cluster environments, but no difference in the faint-end slope. In contrast, the luminosity function of the red-sequence populations in field and cluster environments are inconsistent at >3σ level. In particular, the red-sequence luminosity function in field regions peaks at M_r ∼ −20.5 and drops rapidly at magnitudes fainter than M_r ∼ −18.5, with no red galaxies at M_r > −18. This decline results in a very shallow faint-end slope α = +0.484 ± 0.365, and we are also able to fit the red-sequence field galaxy population equally well by a single Gaussian function with σ = 0.684 ± 0.088 and M'_r = −20.23 ± 0.16 as shown by the dashed curve in Fig. 7.

Table 3. Best-fitting luminosity functions.

| LF parameters       | α            | M*           | ψ            |
|---------------------|--------------|--------------|--------------|
| Field regions (ρ < 0.5, >400 kpc from M_r < 20.0 galaxy) |           |              |              |
| Red                 | +0.484 ± 0.365 | −20.16 ± 0.26 | 49.3         |
| Blue                | −1.078 ± 0.071  | −20.71 ± 0.19 | 163.2        |
| Cluster regions (ρ > 1.0) |           |              |              |
| Red                 | −0.884 ± 0.122  | −21.28 ± 0.25 | 135.9        |
| Blue                | −1.126 ± 0.121  | −21.25 ± 0.28 | 110.3        |

About 30 per cent of red-sequence galaxies in the optical CM diagram show signs of ongoing star formation from their spectra having EW (Hα) > 2 Å. This contamination is greatest at faint magnitudes (M_r > −19) and in field regions where as many as three-quarters of red-sequence galaxies are star forming. This has important consequences for understanding the build-up of the red and blue sequences being interpreted as the hierarchical assembly of star-forming and passively evolving galaxies, as the colour of the galaxy cannot be always reliably related to its star formation history. Instead a significant fraction (and in some cases the majority) of galaxies on the red sequence have star formation histories more in common with the blue cloud population, and appear red simply due to dust, the presence of which is directly related to them having active ongoing star formation.

The effect of the contamination of the faint end of the red sequence by dusty star-forming galaxies is likely to become increasingly important at higher redshifts, where the global SFRs (Noeske et al. 2007; Zheng et al. 2007), and hence the effects of dust extinction are that much higher. This produces a significant overestimation of the amount of stellar mass already in the red sequence at a given epoch, particularly at low masses, and an overestimation of the look-back time by which the stellar mass is assembled in passively evolving galaxies. Similarly, the global amounts of stellar mass and star formation in the blue sequence of star-forming galaxies will be underestimated. These effects could bias the interpretation of studies looking at the evolution of the optically defined red and blue sequences with redshift in terms of the hierarchical assembly and conversion of accreted gas into stars in passive and star-forming galaxies (e.g. Bell et al. 2004), the result of which could be the overestimation of the importance of dry mergers to create the present-day population of passively evolving galaxies.

Instead the NUV − r colour allows a much more robust separation of passively evolving and star-forming galaxies, with a clear red sequence of passively evolving galaxies at NUV − r ≥ 5 and a well-separated blue sequence of star-forming galaxies at NUV − r < 4. We find that globally only 8 per cent of UV-selected red-sequence galaxies are star forming, i.e. one-quarter of the contamination seen in the optical red sequence. By comparing the NUV − r colour with both FUV and Spitzer 24 μm photometry, we confirm this robust separation, finding no evidence for a population of galaxies with star formation that is so heavily obscured so as to not show any Hα emission or UV flux. We thus indicate that through a combination of SDSS spectra and NUV photometry, we can gain a robust classification of galaxies into passive and star forming. This allows the build-up of the UV-selected red sequence with redshift and environment to be directly interpreted in terms of the assembly of stellar mass in passively evolving galaxies (Arnouts et al. 2007; Martin et al. 2007).

We examine the issue of aperture biases on the classification of galaxies from their SDSS fibre-obtained spectra, and confirm the findings of Brinchmann et al. (2004) that a significant fraction of star formation is missed for M_r < −20 galaxies at low redshifts (z < 0.04) due to the fibre sampling only the bulge of the galaxy, resulting in many early-type spirals being misclassified as passive. However, we also show that this is not the case for lower mass galaxies, and the separation of dwarf galaxies (M_r > −19.5) into passively evolving and star forming from their SDSS fibre-obtained spectra as used in Paper II is robust to aperture effects.

In cluster and group environments, the UV-selected red sequence is fully in place to at least M_r = −18. In sharp contrast in isolated field regions (where the majority of galaxies are found), the number density of UV-optical red-sequence galaxies declines rapidly at
magnitudes fainter than $M_r \sim -18.5$ with no galaxies seen fainter than $M_r \sim -18$. This confirms the findings of Paper II that no passively evolving dwarf galaxies are found more than two virial radii from a massive halo, whether that be a group, cluster or massive galaxy. Hence, in these regions the build-up of the red sequence of passively evolving galaxies is incomplete, forming from the top down and being largely absent at $M_r \gtrsim -18.5$. Only internal processes such as merging, supernovae and AGN feedback mechanisms, and gas exhaustion due to star formation can be responsible for completely stopping star formation in these galaxies, and hence cannot be effective in low-mass galaxies (see Paper II, for a discussion) as otherwise passively evolving dwarf galaxies would be ubiquitous. Instead the passively evolving dwarf galaxies that dominate (in terms of numbers) groups and clusters and make up the faint-end of the cluster red sequence must have had their star formation quenched through processes directly related to their environment such as ram-pressure stripping or tidal shocks.

Arnouts et al. (2007) have followed the build-up with redshift of the passive and star-forming galaxy populations as selected from their rest-frame $NUV - r$ colour. They are able to obtain a similarly robust separation of rest-frame UV-selected red- and blue-sequence galaxies to at least $z \sim 1.2$ and probably as early as $z = 2$. They find that the stellar mass density of red-sequence galaxies has increased by a factor of 2 since $z \sim 1.2$, and that this increase can be accounted for entirely by the shutdown of star formation in active galaxies without requiring additional growth through dry mergers, in agreement with the results of Bell et al. (2007) who derive the global star formation contribution of blue and red galaxy populations from ultraviolet and Spitzer 24 μm luminosities.

These results support the downsizing paradigm whereby the red sequence is built-up from the top down, being already largely in place at the bright end by $z \sim 1$ (Bell et al. 2004; Willmer et al. 2006), and the faint-end filled in at later epochs in clusters and groups through environment-related processes such as ram-pressure stripping or galaxy harassment. This filling in of the faint end appears to occur mainly at $z < 1$, and occurs earlier in the richest clusters. Tanaka et al. (2007) find few faint red galaxies in four clumps belonging to a large-scale structure at $z \sim 1.2$ suggesting that the red sequence is truncated within groups at $M^* + 1.5$, whereas by combining several rich clusters at $z \sim 1.2$, Strazzullo et al. (2006) find the red sequence to be fitted by a Schechter function with $\alpha = -0.85$ to at least $M^* + 2.5$. De Lucia et al. (2007) find an increase of a factor of 2 in the dwarf-to-giant ratio of red-sequence galaxies from $z \sim 0.8$ to 0.4, while Stott et al. (2007) find evidence for a further doubling of the dwarf-to-giant ratio since $z \sim 0.5$.

At all epochs to $z \sim 0.8$, Tanaka et al. (2005) find a deficit of faint ($M_r > M^*_r + 1$) red-sequence galaxies in field regions, with respect to cluster and group environments, although their deficits are not as dramatic as presented here due to the use of photometric redshifts and statistical subtraction methods to define the field sample, as well as the use of rest-frame $U - V$ CM diagrams to define the red-sequence population. To obtain clearer results for the field dwarf galaxy population at these redshifts would require a large-scale spectroscopic survey of galaxies to $\sim M^* + 3$ in order to define both the redshifts and environments of each galaxy, something that is within reach of present surveys (e.g. DEEP2, VVDS), at least to $z \sim 0.4$.

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