

The ultraviolet upturn in field luminous red galaxies at $0.3 < z < 0.7$

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ABSTRACT

We derive the evolution of the ultraviolet upturn colour from a sample of field luminous red galaxies at $0.3 < z < 0.7$ with $-24 < M_r < -21.5$. No individual objects are securely detected, so we stack several hundred galaxies within absolute magnitude and redshift intervals. We find that the colour of the ultraviolet upturn (in observed $NUV - i$ which is approximately equivalent to the classical $FUV - V$ at the redshifts of our targets) does not change strongly with redshift to $z = 0.7$. This behaviour is similar to that observed in cluster ellipticals over this same mass range and at similar redshifts, and we speculate that the processes involved in the origin of the UV upturn are the same. The observations are most consistent with spectral synthesis models containing a fraction of a helium rich stellar population with abundances between 37 per cent and 42 per cent, although we cannot formally exclude a contribution due to residual star formation at the ~ 0.5 per cent level (however, this appears unlikely for cluster galaxies that are believed to be more quenched). This suggests that the ultraviolet upturn is a primordial characteristic of early-type galaxies at all redshifts and that an unexpected nucleosynthesis channel may lead to nearly complete chemical evolution at early times.

Key words: stars: horizontal branch – galaxies: evolution – galaxies: formation.

1 INTRODUCTION

The ultraviolet (UV) upturn is the observed excess flux at $\lambda < 3000$ Å in the spectral energy distributions of early-type galaxies (ETGs) above the predictions of conventional stellar population synthesis models. These models predict that such galaxies should instead be very dark at these wavelengths, given their high metallicities and old ages (e.g. see reviews by O’Connell 1999; Yi 2008). Typical colours in $FUV - V$ for these ETGs (where FUV is a ~ 600 Å wide band centred at 1500 Å) are 1.5–2 mag bluer than those expected from a stellar population formed at $z = 4$, with solar metallicity and star-formation e-folding time (τ) of 0.3 Gyr. This model accurately reproduces the observed colours longwards of ~ 3000 Å (effectively all optical-IR colours) of ETGs to within a few per cent, even at young ages (e.g. Bruzual & Charlot 2003; Conroy, Gunn & White 2009; Conroy & Gunn 2010). The UV upturn therefore points to some incompleteness in our understanding of the stellar populations of ETGs.

There is now a broad consensus that the sources of the UV excess light in spheroidal systems are blue horizontal branch (HB) stars (e.g. Greggio & Renzini 1990; Dorman, Rood & O’Connell 1993; Dorman, O’Connell & Rood 1995; Brown 2004). These objects are directly observed in the bulge of M32 (Brown et al. 2000b) and provide (although unresolved) most of the UV flux in M31’s bulge (Rosenfield et al. 2012). The FUV spectra of a few nearby ellipticals taken by the *Hopkins Ultraviolet Telescope* flown on

the Space Shuttle are consistent with a 25 000 K blackbody (the underlying old stellar population produces negligible flux in this regime), as produced by an extended HB (Brown et al. 1997). Similarly, the UV spectral energy distributions for ETGs in Coma and Abell 1689 derived by Ali et al. (2018a,b) are also a best fit by single blackbodies of relatively high temperatures, with the flux and effective temperature depending on galaxy mass. The UV spectral properties of these galaxies are also broadly inconsistent with those expected from alternate sources such as young stars (Vazdekis et al. 2016; Salvador-Rusiñol et al. 2020) or intermediate mass white dwarfs (Ferguson & Davidsen 1993; Werle et al. 2020).

However, blue HB stars are not normally produced in old, metal-rich stellar populations (e.g. Catelan 2009). For such stars to evolve to the blue HB requires either an increased stellar mass loss (revealing the hotter inner layers of the stellar envelopes) during the first ascent of the red giant branch or an He-enriched chemical composition. An increase in mass loss for metal rich stellar populations as proposed by Yi, Demarque & Kim (1997) is not observed in our Galaxy across more than 3 dex in metallicity (Miglio et al. 2012; McDonald & Zijlstra 2015; Williams et al. 2018). Han, Podsiadlowski & Lynas-Gray (2007) and Hernández-Pérez & Bruzual (2014) instead propose that mass loss occurs within close binaries, as the stellar envelopes are stripped by angular momentum transfer as one of the stars expands beyond its Roche lobe. As already pointed out by Smith, Lucey & Carter (2012), this cannot easily account for the observed trend where more massive and more metal rich galaxies have bluer UV upturns (Burstein et al. 1988; Ali et al. 2018a). Neither can this model explain the strong radial gradients within galaxies in the UV upturn colour

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and their dependence on M_{g_2} strength (Carter et al. 2011; Jeong et al. 2012). Petty et al. (2013) show that the observed colour gradients are consistent with an increase in the fraction of blue HB stars towards the centres of galaxies by around 25 per cent. This would imply that binaries would have to be both more frequent and tighter (to explain the bluer colours) as a function of radius (and M_{g_2} strength), a process that appears to require considerable fine-tuning.

Tantalo et al. (1996) and Chung, Yoon & Lee (2011, 2017) argue for the presence of a minority population of He rich stars that can evolve to the blue HB even at high metallicities. This occurs because the lifetimes of He rich stars are shorter, allowing for lower mass stars to evolve at the same time (with a correspondingly thinner stellar atmosphere over the nearly constant mass core). Unlike other proposed sources of the UV upturn, these stars have clear counterparts in our Galaxy, namely the multiple populations of globular clusters producing anomalously blue HBs (Gratton, Carretta & Bragaglia 2012; Bastian & Lardo 2018). The radial gradients observed by Carter et al. (2011), Jeong et al. (2012), and Petty et al. (2013) could then be produced by a radial gradient in He abundance, especially if this is produced by earlier stellar populations (as is observed in galactic globular clusters). Indeed, the UV upturn and the multiple populations in globular clusters could be manifestations of the same phenomenon albeit in different environments, or the He rich stars may be produced within metal-rich globular clusters as well (Goudfrooij 2018; Chung et al. 2020)

Each of these explanations imply different predictions as to the evolution and environmental dependence of the UV upturn, and these can be used to discriminate between them. Ali et al. (2019) and Phillipps et al. (2020) carried out the first comparison of UV upturn properties across a wide range of environments at low redshifts, ranging from clusters to groups and the more isolated field, and they found no evidence of any strong environmental dependence. This suggests that the UV upturn is an intrinsic property of ETGs originating at early times and argues against a component from residual star formation as the UV upturn is independent of local galaxy density, which otherwise affects star formation properties elsewhere, including residual star formation in ETGs – Crossett et al. 2014.

Most studies of the evolution of the UV upturn were originally limited to bright cluster galaxies, out to relatively moderate redshifts (Brown et al. 1998, 2000a, 2003; Ree et al. 2007; Donahue et al. 2010; Boissier et al. 2018), although Atlee, Assef & Kochanek (2009) studied the evolution of field ETGs out to $z = 0.6$ by stacking objects. These found evidence for only moderate to no evolution out to $z = 0.6$, which does not provide strong evidence for either model discussed above. Le Cras et al. (2016) used spectroscopic indices on stacked spectra of bright LRGs from the BOSS survey and found that the strength of the UV upturn declines at $z > 0.6$, nearly disappearing at $z = 1$, while Ali et al. (2018b,c) observed that the UV upturn does not evolve in clusters to $z = 0.55$ but then its colour becomes significantly redder at $z = 0.7$. Ali et al. (2021) show that the $NUV - r$ colour of cluster ETGs is also consistent with the presence of an UV upturn to $z = 0.6$ but this component largely disappears at $z = 0.95$. This is an evidence of evolution in the UV upturn (although Lonoce et al. 2020 claim a detection of the UV upturn in a $z = 1.4$ galaxy, albeit from a single spectral line at the 2σ level) with redshift. Only models with a He-rich subpopulation are able to reproduce the whole evolutionary trend in the colour of the UV upturn. From this, Ali et al. (2018a,b,c) and Ali et al. (2021) estimate that ETGs would have to contain a population (about ~ 10 per cent by mass) of stars with $Y > 0.42$ formed at $z > 3$, to explain the behaviour and strength of the UV upturn as a function of redshift. This level of He enrichment is

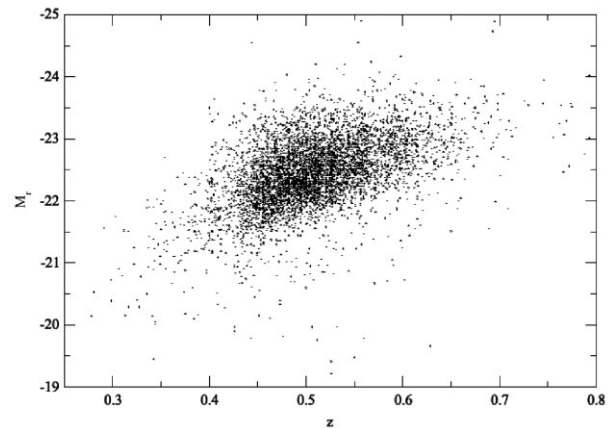


Figure 1. The magnitude and redshift distribution of the LRG sample used in this paper.

similar to that observed in the more extreme multiple populations in globular clusters in our Galaxy.

Here, we extend this analysis to field ETGs at $0.3 < z < 0.7$ to compare evolutionary trends across different environments and further refine the modelling of the UV upturn population. In the next section, we describe the data and our analysis. The results are presented and discussed in Section 3. We adopt the latest cosmological parameters from Planck Collaboration (2020). All magnitudes quoted are in the AB system.

2 DATA AND PHOTOMETRY

Our data set consists of luminous red galaxies (LRGs) with $i < 19.8$, colour selected from the SDSS DR1 (Abazajian et al. 2003) according to the prescriptions of Eisenstein et al. (2001) and for which new spectroscopy was obtained within the 2SLAQ survey (Cannon et al. 2006) using the 2 degree field spectrograph (Lewis et al. 2002) on the 3.9m *Anglo-Australian Telescope*. The targeted galaxies span the redshift range $0.3 < z < 0.8$ and the sample is approximately 90 per cent complete. Within this sample of 15 000 galaxies, we have selected for our analysis only those objects where the best-fitting spectroscopic template is the SDSS LRG template of Eisenstein et al. (2003), which are most likely to be fully quiescent ETGs showing (if they resemble their counterparts in clusters at these redshift) the UV upturn. Inspection of the SDSS images confirms the nature of these objects as typically E/S0 galaxies. One caveat is that these field LRGs are likely to dwell within environments significantly less rich than clusters and more typical of the general field, such as small and poor groups (Tal et al. 2012, 2013).

We have then selected those galaxies having observations in the GALEX archive (Martin et al. 2005; Morrissey et al. 2005; Morrissey et al. 2007); we restricted our search to objects with exposure times in the NUV band (corresponding approximately to the rest-frame FUV at the redshifts of our sample) > 1000 s and within 39.6 arcmin of the centre of each of the GALEX circular tiles, to avoid the noisier region around the rim of each field. This leaves a total of 6094 galaxies in our sample. In Fig. 1, we plot the absolute M_r magnitude (calculated using the conventional cosmological parameters and with $k + e$ corrections from a Conroy et al. 2009; Conroy & Gunn 2010 model with formation redshift of 4, solar metallicity and star-formation e-folding time of 0.3 Gyr, that provides a good match to the observed colours of LRGs) versus redshift. The rest-frame r band is a good match to the observed i band for these objects (in which they were

selected by the 2SLAQ survey). The *FUV* data are less abundant and probe a much bluer wavelength regime than is conventionally used to study the UV upturn and hence not used here.

We isolated a 150×150 arcsec² postage stamp in the *GALEX* image around the optical position of each galaxy. Where more than one observation was available we averaged all images to produce a single image for each galaxy. As expected, given the sensitivity of *GALEX*, only a few objects are individually weakly detected in *NUV*, even in total exposures of several hundred ks. Consequently, we stacked the data using the following scheme. We divided our sample into several cells in absolute magnitude and redshift, each containing typically a few hundred galaxies (except for a few low luminosity bins at low redshift and the two highest luminosity bins at high redshift), and produced a median stack for all *GALEX* postage stamps for each cell. By using the median of typically several hundred galaxies, we can remove the influence of outliers (e.g. objects with star formation) from our photometry. These images are shown in Fig. 2 where the resulting objects are generally well detected.

At the typical redshifts of these galaxies, and given the *GALEX* pixel scale of 1.5 arcsec and point spread function of 4.5 arcsec, our objects are essentially unresolved in the *NUV* data, and we therefore carry out photometry within a 10 arcsec radius aperture, which would include > 97 per cent of the light for a star.

We followed the procedure by Atlee et al. (2009) and calculated the uncertainties on the mean magnitude by bootstrap re-sampling. This includes both counting statistics and the effects of intrinsic scatter. The bootstrapping analysis folds all intrinsic variations in the sample into the uncertainty on the mean magnitude. We drew 100 bootstrapping realizations in each magnitude/redshift bin and used the RMS of the resulting magnitudes as the uncertainty on the mean magnitude.

We determined the mean foreground extinction for our galaxies using the values by Schlafly & Finkbeiner (2011) and the Milky Way extinction law of Cardelli, Clayton & Mathis (1989): these are 0.29 mag for the *NUV* and 0.07 mag for the *i* band. Internal extinction is ignored as LRGs are typically devoid of dust and gas. Observations of local SDSS LRGs by Barber, Meiksin & Murphy (2007) returned a mean extinction of $A_z = 0$, while even for cluster ETGs at $z = 1.3$, Rettura et al. (2006) measured internal extinctions $E(B - V) < 0.05$.

In Fig. 3, we plot the observed $g - i$ and $r - i$ median colours for galaxies in these stacks together with several models from Conroy et al. (2009) and Conroy & Gunn (2010). The solar metallicity model with $z_f = 4$ and $\tau = 0.3$ Gyr provides a very good representation of these data, with any scatter in the colours being explained by a small spread in age/metallicity, confirming that the rest-frame optical colours of our galaxies show no evidence of current star formation. The stacked optical data strongly imply that only a subset of the passively evolving models, namely those with solar metallicity (including Bruzual & Charlot 2003 and Conroy et al. 2009) and reject significantly higher and lower metallicity models at all redshifts probed here.

3 DISCUSSION

3.1 Comparison with models

Fig. 4 compares our colours for LRGs in the 2SLAQ sample with those from Atlee et al. (2009), where we used a model from Conroy et al. (2009) with solar metallicity, formation redshift of 4, and star formation e-folding time of 0.3 Gyr (values that typically reproduce ETG colours at all redshifts below 1.5) to convert from their *NUV* –

V to our *NUV* – *i*.¹ There is reasonably good agreement, given the differences in selection, between our data and those of Atlee et al. (2009) except for their highest redshift point that appears to be too blue (this may be due to the small number of such galaxies in their sample and selection effects noted by these authors). We also plot a model from Conroy et al. (2009) with formation redshift of 4, solar metallicity and star formation e-folding time of 0.3 Gyr (same as we used above) to show how this does not reproduce the observed *NUV* – *i* colours of field LRGs: these are typically 1.5–2 mag bluer, the typical excess flux of the UV upturn (recall that these colours are nearly equivalent to rest-frame *FUV* – *r*). We also took a single stellar population from Han et al. (2007) and converted their colours to our observed *NUV* – *i*, using the *k* – corrections from Atlee et al. (2009). While these colours are bluer than the model by Conroy et al. (2009) and Conroy & Gunn (2010), which explicitly avoid modelling the UV upturn, they do not match the observed colours of 2SLAQ LRGs, being about 1 mag too red. Indeed, it has already been argued that the sdB stars in our Galaxy are redder (in UV colours) than the UV upturn in ETGs (Yi 2008).

However, field LRGs may be less quenched than cluster ETGs and show residual star formation at low levels. Salvador-Rusiñol et al. (2020) use UV spectroscopic indices to claim that their sample of BOSS LRGs at $z = 0.4$ shows residual star formation at about the 1 per cent level, although the data may also be interpreted as being produced by blue HB stars. To test this, we have added a constant rate of star formation to the original model of Conroy et al. (2009) and Conroy & Gunn (2010), with a mass fraction formed during a constant mode of star formation of 1 per cent, 0.5 per cent, and 0.1 per cent of the total mass, added to the initial burst at high redshift. The observed *NUV* – *i* colours may be qualitatively explained by models forming between 0.1 per cent and 0.5 per cent of the total mass in a regime of constant star formation superposed over the original burst at $z = 4$. We also show the effect of this constant rate of star formation in Fig. 3 on the optical colours, showing that they are essentially unchanged from those of models with no extra star-forming component. However, these models become about 1 mag bluer across the redshift range we explore, whereas we see no evidence of such evolution in the observed colours over this redshift range.

The star formation rates of local ellipticals can be estimated from the rate of core collapse supernovae. For $z < 0.2$ ETGs in the SDSS, Sedgwick et al. (2021) estimate star formation rates of approximately $0.1 M_\odot \text{ yr}^{-1}$, although Irani et al. (2021) argues that these are likely to be overestimated by up to an order of magnitude owing to the mis-identification of core collapse supernovae and contamination from supernovae associated with nearby diffuse galaxies. This latter is of course a possible source of contamination in our data as well. These star formation rates are equivalent, if they are constant, to one of the Conroy et al. (2009) and Conroy & Gunn (2010) models forming 0.01 per cent of the total mass since $z = 4$. Star formation rates of this magnitude cannot therefore be excluded, based on our data alone, although they are lower than those inferred by Salvador-Rusiñol et al. (2020). However, resolved images of nearby galaxies do not show any of the expected populations of B stars or earlier type that would be needed (O’Connell et al. 1992), while *FUV* images of nearby ellipticals from *Astro HUT* show none of the clumpiness otherwise associated with star-forming regions elsewhere. Nevertheless, only

¹As in previous work, we adopt the models by Conroy et al. (2009) as these make no attempt to semi-empirically fit the UV upturns as do Bruzual & Charlot (2003).

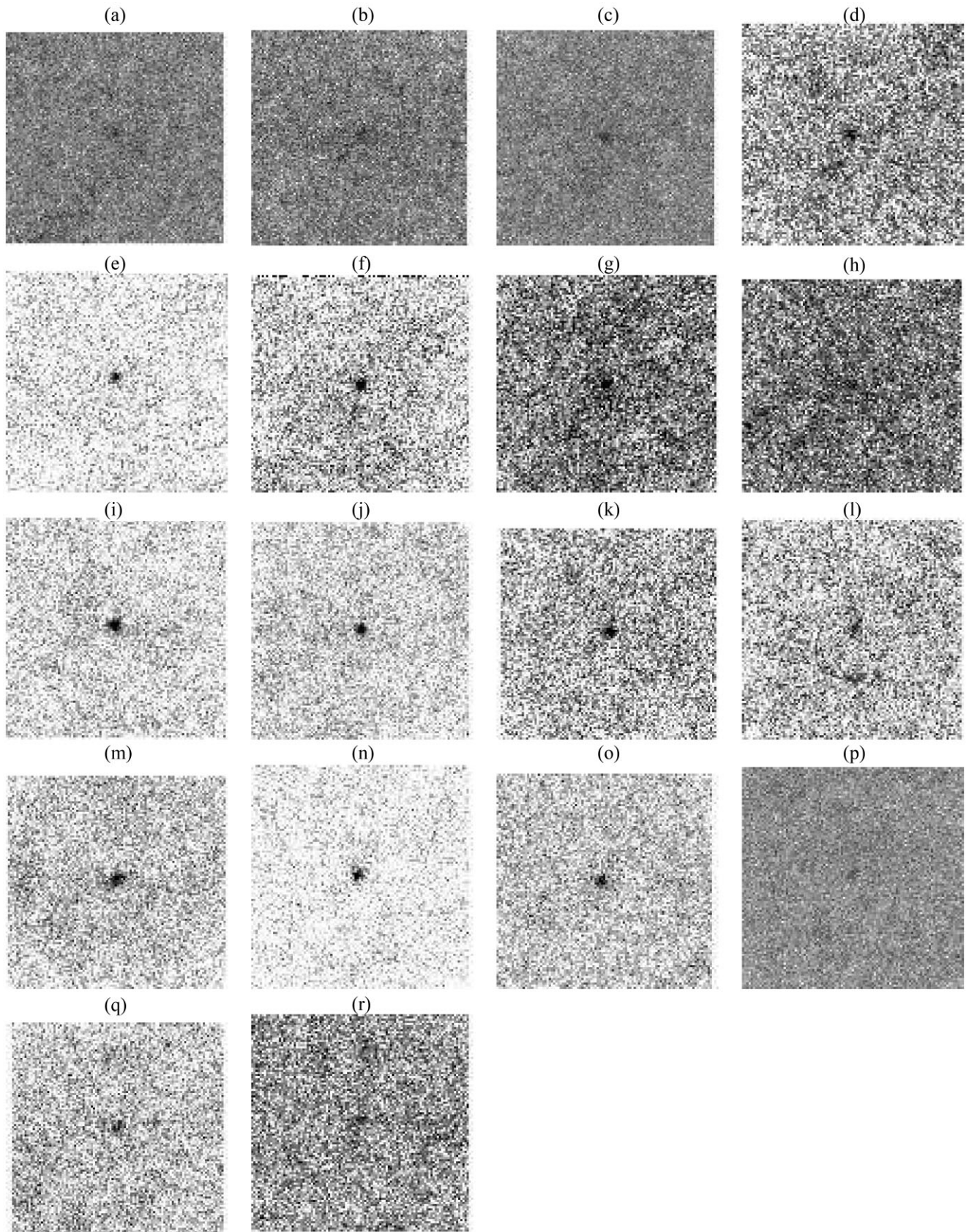


Figure 2. *NUV* images of the median stacks for 2SLAQ LRGs in the magnitude/redshift cells identified in Table 1. The letters above each postage stamp are the identifier in the table.

Table 1. Photometry for galaxies in the sample. The sample is split into cells (labelled A-R) centred on absolute magnitude M_r and redshift z with a given width in redshift δz resulting in N_{gal} galaxies per bin. The photometry for the resulting median stack is given in NUV with its 1σ uncertainty (err) and in i (from SDSS photometry), with uncertainty on the median i magnitude is < 0.01 .

ID	M_r	z	δz	N_{gal}	NUV	err	i	$NUV - i$
A	-21.75	0.35	1.0	55	24.89	0.88	19.36	5.53
B	-21.75	0.425	0.50	228	25.13	0.64	19.69	5.44
C	-21.75	0.475	0.50	378	25.61	0.66	19.91	5.70
D	-22.25	0.425	0.50	228	26.92	0.94	19.17	7.75
E	-22.25	0.4625	0.25	412	25.18	0.40	19.05	6.13
F	-22.25	0.4875	0.25	533	26.06	0.52	19.63	6.43
G	-22.25	0.5125	0.25	431	25.05	0.34	19.70	5.35
H	-22.25	0.5375	0.25	282	26.05	0.81	19.83	6.22
I	-22.75	0.45	1.0	640	25.26	0.33	19.09	6.17
J	-22.75	0.525	0.50	725	25.76	0.43	19.38	6.38
K	-22.75	0.575	0.50	434	25.82	0.79	19.61	6.21
L	-22.75	0.625	0.50	157	25.13	0.75	19.78	5.35
M	-23.25	0.45	1.0	198	24.23	0.24	18.62	5.61
N	-23.25	0.525	0.50	212	24.49	0.34	18.90	5.59
O	-23.25	0.575	0.50	199	24.63	0.32	19.15	5.48
P	-23.25	0.65	1.0	139	24.97	0.85	19.46	5.43
Q	-23.75	0.55	1.0	56	24.37	0.75	18.70	5.67
R	-23.75	0.65	1.0	44	24.36	0.62	19.04	5.32

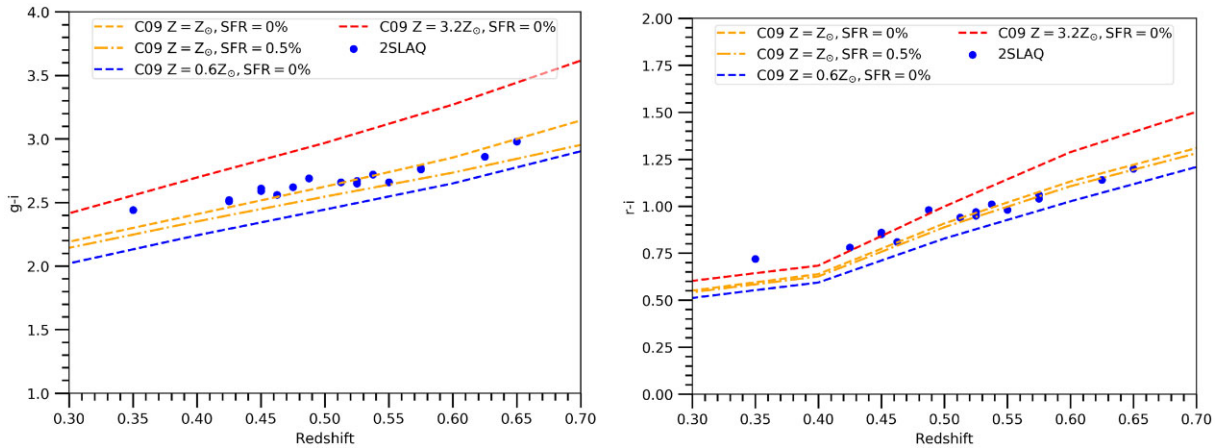


Figure 3. Comparison of observed $g - i$ and $r - i$ median colours for 2SLAQ galaxies in this sample (see Table 1) with models from Conroy et al. (2009) and Conroy & Gunn (2010) with formation redshift of 4, $\tau = 0.3$ Gyr and various metallicities. This also includes a comparison with a model with residual star formation forming 0.5 per cent of the stellar mass at a constant rate after the initial burst.

observations at higher ($z \sim 1$) can truly discriminate a UV upturn component from other models.

In this figure, we also compare our data with models from Chung et al. (2011, 2017). These include a population of stars with extra helium enrichment and have been shown to account for the evolution of the UV upturn colours in cluster ETGs (Ali et al. 2018a,b,c). These models assume $z_f = 4$, metallicity of 0.02 and 0.04, and $Y_{\text{ini}} = 0.23$ (cosmological value), 0.28, 0.33, and 0.38 for a chemical infall model (where $Y = Y_{\text{ini}} + 2Z$). We do not plot the two models with lower He abundance as they lie very close to the standard FSPS model with no upturn, to avoid confusion. The data are not compatible with models of standard (i.e. cosmological He abundance) composition, as shown in Fig. 4 above as well, but are well encompassed by models with $0.33 < Y_{\text{ini}} < 0.38$ (i.e. $Y = 0.37 - 0.42$ assuming solar metallicity – Fig. 3). There are no detectable effects on optical colours. This is similar to what is observed in clusters of galaxies, although the required He abundance is slightly lower than inferred in Ali et al. (2018c). This may be partly

explained by differences in the ages and star formation histories of ETGs in clusters and the field, with field galaxies expected to be somewhat younger and to have had a more extended star formation history.

However, unlike the work in clusters by Ali et al. (2018c, 2021), we do not here reach the redshift where the UV upturn colours start to evolve strongly, which is at $z > 0.7$ in galaxy clusters, where we may more strongly discriminate between models. While we do not see (or expect to see) this strong evolution in colour given the redshift range probed, the strong similarity in the behaviour of this sample and that of ETGs in clusters, indicates that the same process is likely to be responsible for the UV flux in both environments. Given that the best explanation for the behaviour displayed by cluster ETGs is the presence of an He-rich population, ‘switching on’ the blue HB at $z = 0.7$, the simplest explanation of the result shown here is the same. Clearly a test of this will be attempting to explore the strength of the UV upturn in field galaxies at higher redshift, the subject of a future paper.

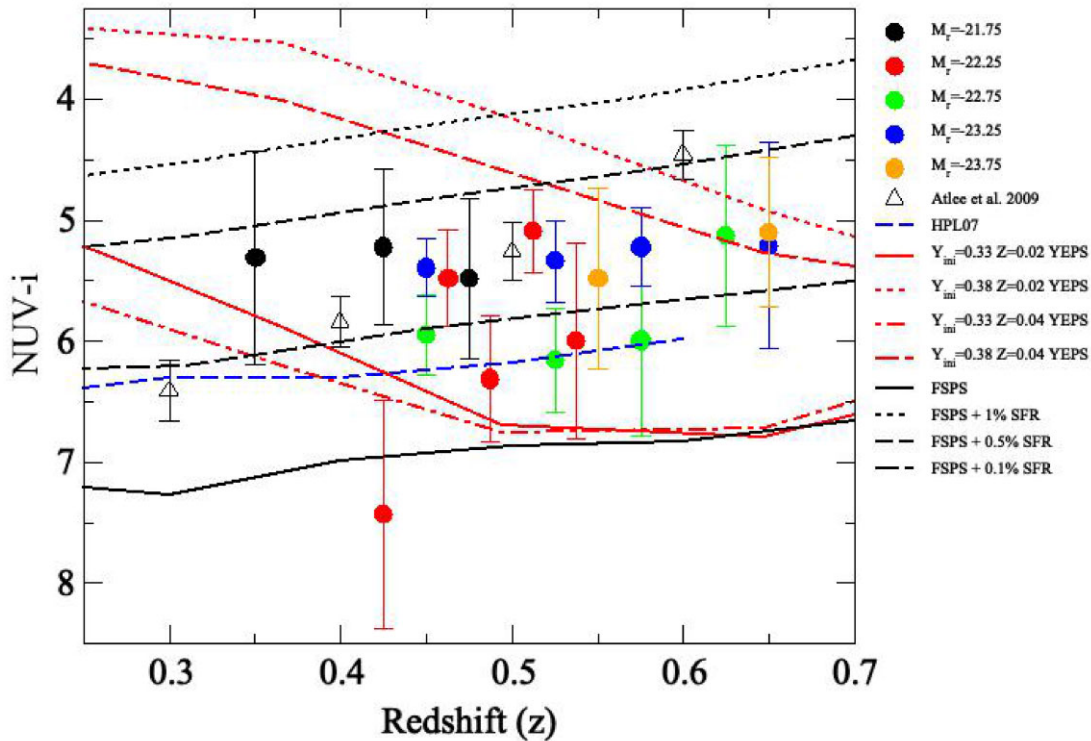


Figure 4. $NUV - i$ colours for 2SLAQ galaxies as a function of redshift and absolute r magnitude ($k + e$ corrected as described in the text): see legend in the figure. We also show data from Atlee et al. (2009) in the same redshift range.

3.2 Variations with metallicity and age

In this paper, we adopt a single fiducial model for age, metallicity, and star formation e-folding time over which an He-rich subpopulation, with various degrees of He enrichment, or a binary population or residual constant star formation, are superposed.

The colour of the UV upturn in the models of Conroy et al. (2009), Conroy & Gunn (2010) and Chung et al. (2011, 2017) does not change strongly with age, as the HB stars do not evolve beyond the RR Lyrae gap except for ages far in excess of the Hubble time. It is only He, or residual star formation, respectively, that can drive these models' UV colours to the blue.

Low metallicity populations for these models can be excluded by the poor match to the optical colours that would result (see Fig. 4) and by the previous observation that a significant contribution by low metallicity stars would strongly weaken the CN and Mg lines observed in the spectra of LRGs. If residual star formation takes place in more metal poor gas, this would of course also result in much bluer optical colours than we observe.

Han et al. (2007) do not consider lower metallicity stellar populations for their binary model. We would expect such stars to be bluer purely by the effects of line blanketing; however, the same consideration applies as to the effect of such a low metallicity population on the otherwise strong metal lines in the UV spectra of LRGs.

3.3 Interpretation

These observations indicate that the UV upturn is a fundamental property of the stellar populations of ETGs across all environments (Ali et al. 2019; Phillipps et al. 2020) from field to cluster, irrespective of environment at least below $z = 0.7$. Since field LRGs are likely

to be less quenched than cluster ETGs, it is appropriate to consider the level of residual star formation within them. Given that we see the same level of UV emission in both field and cluster ellipticals and we know that the UV emission in cluster galaxies does not arise from star formation, these observations argue against a significant role for star formation in the production of the UV flux observed in these galaxies. One caveat is that these field LRGs are likely to dwell within relatively massive haloes, and therefore sample a comparatively denser environment (Tal et al. 2012, 2013).

These data on their own do not suffice to establish the cause of the UV upturn in the field population, as they do not yet reach the putative redshifts at which strong evolution in this colour is expected to occur due to the blue HB being populated several Gyr after the zero-age main sequence (Chung et al. 2011, 2017). Nevertheless, the similarity between field and cluster galaxies, and the similar lack of evolution below $z = 0.6$ in the LRG sample of Le Cras et al. (2016) tends to suggest that a similar phenomenon is being observed across a wide range of environmental densities. It appears likely that the UV upturn represents the occurrence of a novel enrichment channel taking place within 2 Gyrs of the big bang across a wide variety of environments and over several orders of magnitude in stellar mass to produce a sub-population with excess He. However, these current observations do not give an indication as to the nature of this channel. This is likely to require spectroscopic observations at significantly higher redshift. Despite this, we know that such He rich stars exist within globular clusters and other systems. Identifying the enrichment pattern responsible will likely solve both problems.

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DATA AVAILABILITY

Data can be retrieved from the relevant archives (SDSS, 2SLAQ) as mentioned in the text.

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