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% and 42%, although we cannot formally exclude a contribution due to residual star formation at the ~ 0.5% 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: galaxies:formation and evolution – stars:horizontal branch

1 INTRODUCTION

The ultraviolet 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 metalicities 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 $\sim 600$ Å wideband 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 $\sim 3000$ Å(effectively all optical-IR colours) of ETGs to within a few percent, even at young ages (e.g., Bruzual & Charlot 2003; Conroy et al. 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 et al. 1993, 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 (Rosenfeld 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 25000K 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 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-Rusiño 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 a He-enriched chemical composition. An increase in mass loss for metal rich stellar populations as proposed by Yi et al. (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 et al. (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 et al. (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 the galaxies in the UV upturn colour and their dependence on $M_{\text{g}}$ 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 centers of galaxies by around 25%. This would imply that binaries would have...

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to be both more frequent and tighter (to explain the bluer colours) as a function of radius (and Mg2 strength), a process that appears to require considerable fine-tuning.

Tantalo et al. (1996) and Chung et al. (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 et al. 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 (Goudhrooj 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 Philippus 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 – Crosset 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 Adlee et al. (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 $z = 0.9$. This is 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 $2\sigma$ level) with redshift. Only models with a He-rich subpopulation are able to reproduce the whole evolutionary trend in the color 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% 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 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, while section 4 presents our conclusions. We adopt the latest cosmological parameters from Planck Collaboration et al. (2020). All magnitudes quoted are in the AB system.

2 DATA AND PHOTOMETRY

Our dataset 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% 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 redshifts) the ultraviolet 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 (Morrissey et al. 2005; Martin 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) > 1000s and within 39.6′ of the center 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) vs. 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 prove a much bluer wavelength regime than is conventionally used to study the ultraviolet upturn and hence not used here.

We isolated a $150'' \times 150''$ 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′′ and point spread function of 4.5′′ our objects are essentially unresolved in the $NUV$ data and we therefore carry out photometry within a 10′′ radius aperture, that would include > 97% of the light for a star.
UV upturn in LRGs

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

| ID | $M_r$ | $z$ | $\delta z$ | $N_{gal}$ | $NUV$ | $\text{err}$ | $i$ | $NUV-i$ |
|----|------|----|---------|---------|-----|-----|---|-------|
| 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 |

$A_z = 0$, while even for cluster early type galaxies 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); 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 colors at all redshifts below 1.5) to convert from their $NUV-V$ to our $NUV-i$. 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.

1 As 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.
Conroy & Gunn (2010) with formation redshift of 4, of the total mass since Conroy et al. (2009); Conroy & Gunn (2010) models forming 0.01% of the total mass in a regime of constant star formation superposed over the initial burst. These supernovae are associated with nearby diffuse galaxies. The latter is of identification of core collapse supernovae and contamination from 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 models become 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-Rusinol 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% 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%, 0.5% and 0.1% 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 and 0.5% 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, Sedwick 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); Conroy & Gunn (2010) models forming 0.01% 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-Rusinol 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 bumpiness otherwise associated with star-forming regions elsewhere. Nevertheless, only 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 $Y_{int} = 0.23$ (cosmological value), 0.28, 0.33 and 0.38 for a chemical infall model (where $Y = Y_{int} + 2Z$). 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 $0.33 < Y_{int} < 0.38$ (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 helium 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) and Ali et al. (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 explantation for the behaviour displayed by cluster ETGs is the presence of a 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.
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 a 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 horizontal branch 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 ultraviolet 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 that 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 halos, 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 Gyr 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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