# THE STAR FORMATION HISTORIES OF EARLY-TYPE GALAXIES: INSIGHTS FROM THE REST-FRAME ULTRAVIOLET

SUGATA KAVIRAJ

*Denys Wilkinson Building, Keble Road, University of Oxford, UK*

*skaviraj@astro.ox.ac.uk*

Our current understanding of the star formation histories of early-type galaxies is reviewed, in the context of recent observational studies of their ultra-violet (UV) properties. Combination of UV and optical spectro-photometric data indicates that the bulk of the stellar mass in the early-type population forms at high redshift ($z > 2$), typically over short timescales ($< 1$ Gyr). Nevertheless, early-types of all luminosities form stars over the lifetime of the Universe, with most luminous ($-23 < M(V) < -21$) systems forming 10-15% of their stellar mass after $z = 1$ (with a scatter to higher value), while their less luminous ($M(V) > -21$) counterparts form 30-60% of their mass in the same redshift range. The large scatter in the (rest-frame) UV colours in the redshift range $0 < z < 0.7$ indicates widespread low-level star formation in the early-type population over the last 8 billion years. The mass fraction of young ($< 1$ Gyr old) stars in luminous early-type galaxies varies between 1% and 6% at $z \sim 0$ and is in the range 5-13% at $z \sim 0.7$. The intensity of recent star formation and the bulk of the UV colour distribution is consistent with what might be expected from minor mergers (mass ratios $\lesssim$ 1:6) in a $\Lambda$CDM cosmology.

*Keywords*: Early-type galaxies; galaxy formation; galaxy evolution

## 1. Introduction

The star formation histories (SFHs) of early-type galaxies have been the subject of intense and controversial debate in modern astrophysics. The classical 'monolithic collapse' hypothesis for early-type evolution followed the model of Eggen et al. for the formation of the Galaxy**(author?)**[1]. Refined and implemented by others[2;3], this model postulated that stellar populations in early-type galaxies form in short, highly efficient starbursts at high redshift ($z \gg 1$) and evolve purely passively thereafter. The *optical* properties of the early-type population and, in particular, their strict obedience to simple scaling relations are remarkably consistent with such a simple, largely empirical hypothesis. The small scatter in the early-type 'Fundamental Plane'[4;5] and its apparent lack of evolution with look-back time[6;7;8;9;10], coupled with the homogeneity and lack of redshift evolution in their optical colours[11;12;13;14;15;16] is strong evidence that the bulk of the stellar population in early-type galaxies forms at high redshift. Furthermore, the over-abundance of $\alpha$ elements in these systems[17] indicates that the star formation timescales are shorter than the typical timescales for the onset of Type Ia supernovae (SN). For example, if Type Ia progenitors largely explode within $\sim 1$ Gyr of a starburst[18], then the bulk of the star formation in these galaxies probably takes place on timescales shorter than a Gyr.

While it is consistent with the optical properties of early-type galaxies, a monolithic SFH does not sit comfortably within the currently accepted ΛCDM galaxy formation paradigm in which the stellar mass in local early-type systems is thought to accumulate over the lifetime of the Universe. Following the seminal work of Toomre**(author?)** [19], who showed that most galaxy collisions end in rapid merging and postulated the formation of spheroidal systems as end-products of such merger activity, the mechanics of galaxy interactions [20;21;22] and their link to the formation of early-type systems [23;24] have been studied in considerable detail. Modern 'semi-analytical' models of galaxy formation, within the ΛCDM paradigm, create early-types through 'major mergers', where the mass ratio of the merging progenitors is 3:1 or lower. The constituent stellar mass of early-type galaxies is predicted to form both quiescently in their progenitors and in efficient starbursts when these progenitors merge [25;26;27;28;29].

While theoretical arguments may be compelling, the strongest evidence for the role of interactions in shaping early-type galaxy evolution and inducing coincident star formation comes from observation, both in the local Universe and at high redshift. 40% of local ellipticals contain dust lanes [30], while $\sim$ 75% contain nuclear dust and by implication gas [31;32]. The gas is often kinematically decoupled from the stars, indicating, at least in part, an external origin, e.g. through the accretion of a gas rich satellite [33]. Up to two-thirds of nearby early-types contain shells, ripples and morphological disturbances [34;35] and a significant fraction exhibit kinematically decoupled cores [36], both of which are evidence for interactions in the recent past. While the detection of such spatially resolved fine structure is possible only for galaxies in our local neighbourhood, clear signatures of recent star formation have been found in individual early-type systems out to modest redshifts [37;38;39].

Deep ground and space-based imaging are increasingly providing access to galaxy populations over the last ten billion years of look-back time. A significant fraction ($\sim$30%) of luminous early-type systems at high redshift ($0.4 < z < 0.8$) exhibit blue cores, indicative of merger-driven starbursts triggered by the accretion of low-mass gas-rich companions [40;41]. Furthermore, most blue cores are predominantly contained in early-type galaxies [41] and, not unexpectedly, they are typically accompanied by spectral lines characteristic of recent star formation [42]. A fundamental consequence of early-type evolution in the ΛCDM model is the gradual loss of late-type progenitors [43;44] and a corresponding increase in the fraction of early-type galaxies. Numerous observational studies have detected such an evolution in the morphological mix of the Universe. While $\sim$80 percent of galaxies in the cores of local clusters have early-type morphology [45], a higher fraction of spiral (blue) galaxies have been reported in clusters at high redshift [16;46;47;48;49;50;51;52], combined with increased rates of merger and interaction events [53]. Similar results have been found in large-scale survey data which suggest that the mean mass density on the red sequence (which is dominated by early-type systems at all redshifts) has at least doubled since $z = 1$ (e.g. Bell et al. 2004[54]; Faber et al. 2007[55]). A significant body of observational evidence thus indicates that the SFH of *at least* some early-type galaxies, and perhaps the early-type population as a whole, deviates significantly from the expectations of the classical monolithic collapse hypothesis, both in terms of their structural evolution and the star formation experienced by them over the lifetime of the Universe.

Although the majority of early-type studies in the past have focussed on the optical spectrum, a significant drawback of optical photometry is its lack of sensitivity to moderate amounts of *recent star formation* (RSF). While red optical colours do imply a high-redshift formation epoch for the bulk of the stellar mass in early-type systems, the optical spectrum remains largely unaffected by the *minority* of stellar mass that is expected to form in these objects at low and intermediate redshifts[44]. As a result, it is difficult to resolve early-type SFHs over the last 8 billion years (where the predictions of the two competing models diverge the most) using optical colours alone.

An ideal route to quantifying early-type SFHs at low and intermediate redshift is to exploit a sensitive indicator of RSF. If the early-type population could be studied, over a large range redshift, using such an indicator, then the steady accumulation of stellar mass could be robustly quantified and strong constraints applied to the predictions of galaxy formation models over the last 8 billion years of look-back time. Spectroscopic indicators of RSF already exist, such as the commonly used $H_\beta$ index, higher order Balmer lines such as $H_\gamma$ and $H_\delta$ and the D4000 break. With the advent of large spectroscopic surveys at low redshift, such as the Sloan Digital Sky Survey (SDSS)[56], it is possible to employ spectroscopic line indices to study the local galaxy population. However, equivalent data at intermediate redshift - certainly on the same scale - remains scant, although this is gradually changing with efforts such as the DEEP2 survey[57].

Rest-frame UV photometry provides an attractive alternative. While its impact on the optical spectrum is relatively weak (and virtually undetectable, given typical observational and theoretical uncertainties), a small mass fraction ($< 3\%$) of young ($< 1$ Gyr old) stars strongly affects the rest-frame UV shortward of $3000\mathring{A}$. Furthermore, the UV remains largely unaffected by the age-metallicity degeneracy[58] that typically plagues optical analyses[59], making it an ideal *photometric* indicator of RSF. The sensitivity of the UV to young stars is demonstrated in Figure 1. We assume two instantaneous bursts of star formation, where the first burst is fixed at $z = 3$ and the second burst is allowed to vary in age and mass fraction. The near-UV (NUV; $2300\mathring{A}$) colour of the composite stellar population is plotted as a function of the age (symbol type) and mass fraction (x-axis) of the second burst. It is apparent that even a very small mass fraction ($\sim$1%) of young stars ($\sim 0.1$ Gyrs old) causes a dramatic change in the $NUV - r$ colour compared to what might be expected from a purely old stellar population ($NUV - r \sim 6.8$). Given that typical observational uncertainties in the $NUV - r$ colours from modern instrumentation

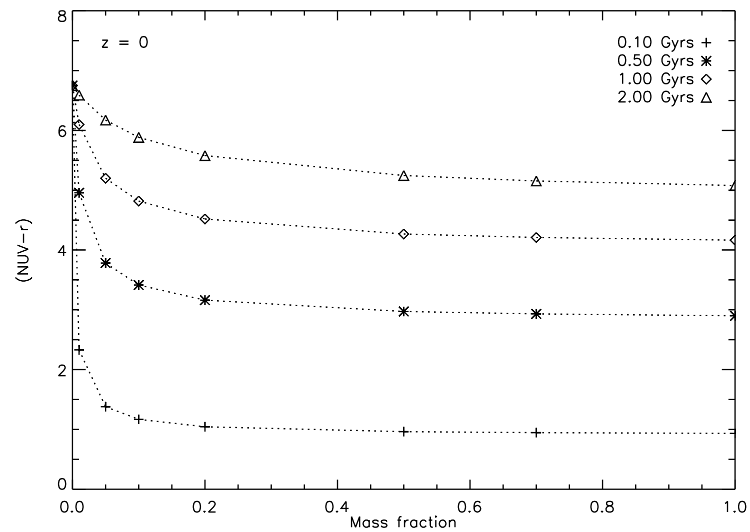


Fig. 1. The sensitivity of the UV to young stars. We assume two instantaneous bursts of star formation, where the first burst is fixed at $z = 3$ and the second burst is allowed to vary in age and mass fraction. The near-UV (NUV) colour of the composite stellar population is plotted as a function of the age (symbol type) and mass fraction (x-axis) of the second burst. It is apparent that even a small mass fraction (∼1%) of young stars (∼ 0.1 Gyrs old) causes a dramatic change in the $NUV - r$ colour compared to what might be expected from a purely old stellar population ($NUV - r \sim 6.8$).

are ∼ 0.2 mag, the usefulness of the UV in detecting residual amounts of RSF becomes quite apparent.

The advent of the GALEX UV space telescope[60] and deep optical surveys (which can be used to trace the rest-frame UV spectrum at high redshift) has provided us, over the last few years, with an unprecedented opportunity to quantify the SFHs of early-type galaxies over the last 8 billion years by exploiting their (rest-frame) UV properties. This review describes the results of recent efforts that incorporate UV photometry to study the evolution of the early-type galaxy population across the redshift range $0 < z < 1$. While the emphasis is on studies that have quantified the buildup of stellar mass in these systems - without necessarily exploring the processes that drive this star formation - possible sources of RSF are explored, both in the context of monolithic collapse and in the standard ΛCDM cosmology.

## 2. The UV colours of nearby early-type galaxies

### 2.1. *Early work and evidence for recent star formation*

Ferreras & Silk[61] were one of the first to study the rest-frame UV colours of early-type galaxies in the nearby Universe. Using Hubble Space Telescope (HST) $F300W$ and optical imaging, they explored the UV colour-magnitude relation (CMR) of the early-type population in the Abell 851 cluster at $z \sim 0.4$. They found that the slope and, in particular, the large scatter in the UV colours was consistent with some early-types having $\sim 10\%$ of their stellar mass in stars younger than $\sim 500$ Myrs. Detailed modelling of this data[62] indicated that minor bursts of RSF - superimposed on an underlying population that forms at high redshift - leads to a natural explanation of the large scatter observed in the UV CMR.

Analysis of the rest-frame UV properties of early-type galaxies at lower redshifts ($z < 0.2$) is complicated by the fact that their UV spectrum may contain contributions from *both* young and old ($> 9$ Gyrs old) stellar populations. Core helium burning stars on the evolved horizontal branch (HB), thought to be the primary cause of the 'UV upturn' phenomenon in massive elliptical galaxies[63;64], emit efficiently in the UV. Thus, the potential contamination of the UV spectrum from such evolved stellar populations has to be taken into account, before the contribution from young stellar populations can be gauged. Clearly, this complicates the robust detection of young stars in local early-type galaxies.

Large-scale UV data from the GALEX space telescope, unprecedented in quality and quantity, provides a unique opportunity to study the RSF-sensitive UV emission from a statistically large sample of nearby early-type galaxies across a range of luminosities and environments. Yi et al.[65] and Rich et al.[66] were the first to study the UV emission of the general early-type population in the local Universe, using GALEX detections of early-type galaxies drawn from the SDSS[67]. To account for contamination from potential UV upturn, Yi et al. compared the UV spectral slope of each early-type object in their sample to the spectral energy distribution (SED) of one of the strongest nearby UV-upturn galaxies (NGC 4552). They found that no more than 4 out of 62 early-types were consistent with significant amounts of UV upturn flux and that *at least* 15% of the early-type population showed strong signatures of low-level RSF, where 1%-2% of the stellar mass fraction was probably comprised of stars less than a Gyr old.

### 2.2. *The GALEX-SDSS view of the local early-type population*

The preliminary result of Yi et al. was refined and the UV properties of early-type galaxies studied more thoroughly in the context of galaxy formation models by Kaviraj et al.[68] (K06 hereafter). A sample of early-type galaxies was drawn from the SDSS by first extracting galaxies that have largely 'de Vaucouleurs' profiles (by setting `fracdev`$> 0.95$ when selecting objects from the SDSS database), followed by visual inspection to remove late-type contaminants. Since scattered light from Active Galactic Nuclei (AGN) may contaminate the UV spectrum (and thus affect the estimation of parameters from the SED), AGN were removed using a 'BPT' type analysis[69;70] using optical emission line ratios computed from their SDSS spectra and radio luminosities measured by the FIRST survey. The sample was restricted to $r < 16.8$ and $z < 0.11$ to ensure the robustness of the morphological classification and the detection completeness of the red sequence, and cross-matched with GALEX

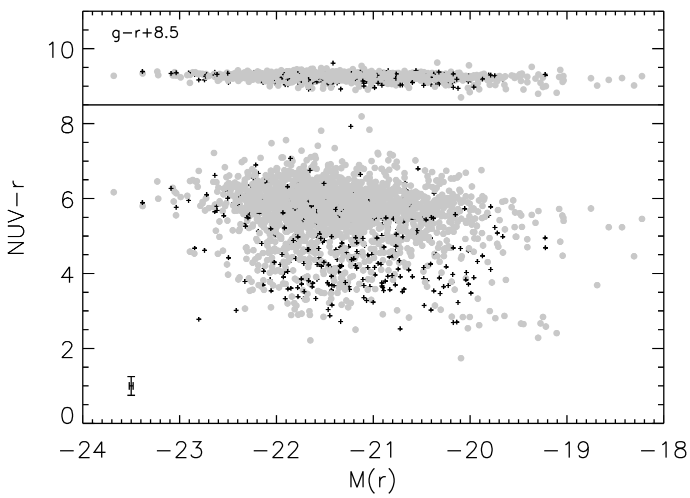


Fig. 2. The optical $g-r$ (top) and the $NUV-r$ (bottom) colour-magnitude relations of the local ($0 < z < 0.11$) early-type population (filled grey circles). The optical CMR is shown on the same scale as its UV counterpart, to highlight the significant difference in their respective scatters. Small black crosses represent galaxies with active (Type 2) AGN, identified using optical or radio analyses and consequently removed from the analysis.

data in the Medium Imaging Survey (MIS) mode with a depth of $m_{AB} \sim 23$. GALEX offers two photometric filters - far-UV (FUV), with an effective wavelength of $\sim 1500\AA$ and the near-UV (NUV), with an effective wavelength of $\sim 2300\AA$. Since UV-upturn flux peaks in the FUV filter, the focus of this study was the NUV filter.

The basic result of this work is shown in Figure 2. The small scatter ($\sim 0.05$ mag) of the optical CMR (top panel) is in stark contrast to the broadness of its UV counterpart, which shows a spread of almost 5 mags in $NUV-r$. An immediate conclusion from Figure 2 is that the UV colours seem inconsistent with the population as whole forming exclusively at high redshift. Indeed, if all early-type galaxies were dustless, simple stellar populations forming at high redshift (as has frequently been assumed from their optical colours), the NUV CMR could be expected to have a spread of less than 1 mag (assuming a spread in metallicities) - several factors less than what is observed. In light of the expected behaviour of the $NUV-r$ colour (shown in Figure 1), it is natural to suspect that at least some of the scatter in the NUV CMR shown in Figure 2 must be due to the presence of young stars, especially in the *bluest* early-type galaxies.

To quantify the presence of young stars, K06 parametrised the SFHs of each early-type object in their sample using a simple model, where two instantaneous bursts of star formation were assumed to describe the evolution of each early-type galaxy. Since the optical colours of the early-type population consistently suggest

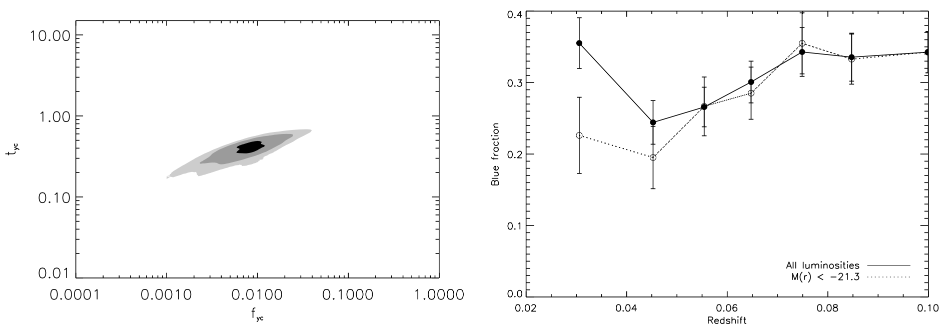


Fig. 3. Stacked likelihood map (left panel) of the blue early-type galaxies in the ($t_{YC}$,$f_{YC}$) parameter space and the fraction of such blue (star-forming) early-type galaxies across the redshift range sampled by K06.

that the bulk of the star formation should have taken place at high redshift, the initial burst was fixed at $z = 3$, with the second burst allowed to vary in age ($t_{YC}$) and mass fraction ($f_{YC}$). A realistic spread in metallicity and dust content were assumed and marginalised values of $t_{YC}$ and $f_{YC}$ and their associated uncertainties were extracted. A negligible fraction of early-types were found to be consistent with an absence of star formation within the last 2 Gyrs. However, 30% of the early-type population, which were also the bluest in the NUV CMR ($NUV - r < 5.5$), showed *unambiguous* signs of RSF i.e. the 95% confidence contours in ($t_{YC}$,$f_{YC}$) space were well-constrained to young ages and mass fractions of a few per cent. The remaining ($\sim$ 70%) galaxies in the sample were consistent with both small levels of RSF and old (> 2 Gyr old) stellar populations, which could not be distinguished, given the uncertainties in the photometry and the stellar models employed in the parametrisation.

Figure 3 shows a stacked likelihood map (left panel) of the blue early-type galaxies in the ($t_{YC}$,$f_{YC}$) parameter space. The typical stellar mass fraction contributed by young stars in these galaxies is around 1%, with a typical (mass-weighted) age of $\sim$ 0.5 Gyrs. The fraction of such blue early-type galaxies (right panel) is around 30% and does not fluctuate appreciably (within the errors) in the redshift range sampled by K06 ($0 < z < 0.11$).

### 2.3. *A comparison to models*

While a simple SFH with two instantaneous bursts can be used to measure the deviation from a monolithic model, it does not reflect the more complex stellar assembly expected in the ΛCDM paradigm. K06 demonstrated (see their Figure 19) that the 'blind' UV predictions of a semi-analytical model, that is calibrated to the optical colours of the (cluster) early-type population, provides quantitative agreement with the observed GALEX-SDSS UV colours of the local early-type population, given reasonable assumptions for the dust properties and lifetimes of birth clouds which host the youngest stars. This suggests that the mix of SFHs that can be predicted in the ΛCDM framework are reasonably consistent with those present in the observed early-type population.

Given the low level of RSF in local early-type galaxies, it is natural to ask whether the level of cold gas required to supply a trickle of young stars could plausibly be supplied in a traditional monolithic scheme. While monolithic models form the bulk of the stellar mass at high redshift (e.g. $z < 2$), the stars created in this primordial burst would recycle a fraction of their mass back into the ISM through stellar winds and supernova ejecta. A fraction or all of this internally recycled gas could potentially fuel further star formation. Using standard chemical enrichment prescriptions, K06 studied *hypothetical* monolithic scenarios, calibrated to reproduce the red optical colours and high alpha-enhancements of massive early-type galaxies in the local Universe. They concluded that monolithic scenarios with reasonable assumptions for the star formation and chemical enrichment history are unable to produce blue early-type galaxies, although they might plausibly reproduce some of the galaxies on the UV red sequence. Note that these scenarios are simply empirical constructs and do not simulate the dynamical evolution of accreted gas in a dark matter (DM) halo. While numerical simulations of baryonic infall in *non-rotating* DM halos can produce galaxies that fit the optical data of luminous early-type systems[3], it is not clear whether the short accretion timescales required can be achieved in a more realistic scenario where the infalling material will have some angular momentum.

## 3. UV colours of the high-redshift early-type population: evidence for stellar mass assembly over the last 8 billion years

The confirmation of widespread RSF in the local early-type population and the identification of a sizeable population whose SFHs cannot be explained through monolithic collapse is an important first step towards understanding their evolution in the local Universe. However, a comprehensive understanding of early-type evolution over a large range in look-back time requires these results to be extended to high redshift by studying the rest-frame UV properties of distant galaxy populations.

Kaviraj et al.[71] (K07 hereafter) selected a suite of three recent optical surveys (MUSYC[72], COMBO-17[73] and GEMS[74]) in the well-studied 'Extended Chandra Deep Field South' (ECDF-S) that provide the ideal tools for studying the rest-frame UV photometry of the high redshift ($0.5 < z < 1$) galaxy population. The MUSYC survey offers deep UBVRIzJK imaging of ECDF-S, to AB depths of $U, B, V, R = 26.5$ and $K = 22.5$. COMBO-17 provides accurate photometric redshifts through 17 filter photometry, while GEMS provides $V/z$-band HST (ACS) imaging of galaxies in ECDF-S out to $z \sim 1$, from which morphologies can be deduced through visual inspection.

Using their GEMS images, K07 extracted a sample of early-type galaxies by morphologically classifying a parent sample of $\sim 4500$ objects. Galaxy SFHs were estimated, and RSF values extracted, by comparing the multi-wavelength photometry of each observed galaxy with synthetic galaxy populations, generated in the framework of the ΛCDM paradigm, using the semi-analytical model of Khochfar & Burkert [27]. Figure 4 shows the main results from this analysis. It is apparent from the top left panel that the large scatter observed in the NUV CMR in the local Universe (Figure 2) persists in the intermediate redshift Universe. Since the solid lines in this plot indicate the positions of simple stellar populations of solar metallicity that form at $z = 2$, the colours of the early-type galaxy population (shown in grey) suggest that a very small fraction of these objects are consistent with *purely* passive ageing since high redshift. K07 estimated that $\sim 1.1$ percent of early-types in their sample are consistent (within errors) with *purely* passive ageing since $z = 2$. This value drops to $\sim 0.24$ percent and $\sim 0.15$ percent for $z = 3$ and $z = 5$ respectively. The results of this study indicates that the luminous ($M(V) < -21$) early-type population shows a typical RSF between 5 and 13% in the redshift range $0.5 < z < 1$, while early-types on the broad red sequence ($NUV - r > 4$) typically show RSF values less than 5% (bottom left panel in Figure 4). The reddest early-types (which are also the most luminous) are virtually quiescent with RSF values of $\sim 1\%$.

In contrast to their low-redshift counterparts, the early-type population in E-CDFS shows a pronounced bimodality in the $NUV - r$ colour distribution, around $NUV - r \sim 3$ (bottom right panel in Figure 4). The peak of the high-redshift $NUV - r$ distribution shows a relative shift from its low-redshift counterpart which is close to what might be expected from the passive ageing of a simple stellar population forming at high redshift (shown by the arrow). This indicates that the bulk of the stellar population in early-type galaxies, at least on the red sequence, is overwhelmingly old. The blue peak in the high-redshift $NUV - r$ distribution contains $\sim 15\%$ of the early-type population, with an average RSF of $\sim 11\%$. In comparison, the bluest 15% of the low-redshift early-type population has an average RSF of $\sim 6\%$, indicating that star formation activity in the most active early- types has halved between $z \sim 0.7$ and present day. Finally, within the errors, K07 found a weak trend of increasing RSF with redshift, from $\sim 7\%$ at $z = 0.5$ to $\sim 13\%$ at $z = 1$, with a typical uncertainty in the RSF of $\sim 2.5\%$.

Since the timescale of this study is $\sim 2.5$ Gyrs, a simple extrapolation (from RSF values in Figure 4) indicates that the *bulk* of the luminous ($-23 < M(V) < -21$) early-type population may typically form up to 10-15 percent of their mass after $z = 1$ (with a tail to higher values), while their less luminous ($M(V) > -21$) counterparts form 30-60 percent of their mass in the same redshift range. These values are probably overestimated since the intensity of star formation is seen to decrease between $z = 0$ and redshifts probed by this study. This tail-end of star formation should exist in *intermediate-age* (3-8 Gyr old) stellar populations in early-type galaxies at present day.

Finally, it is worth noting that the star formation experienced by luminous early-types at late epochs is indirectly consistent with the observed value of alpha-

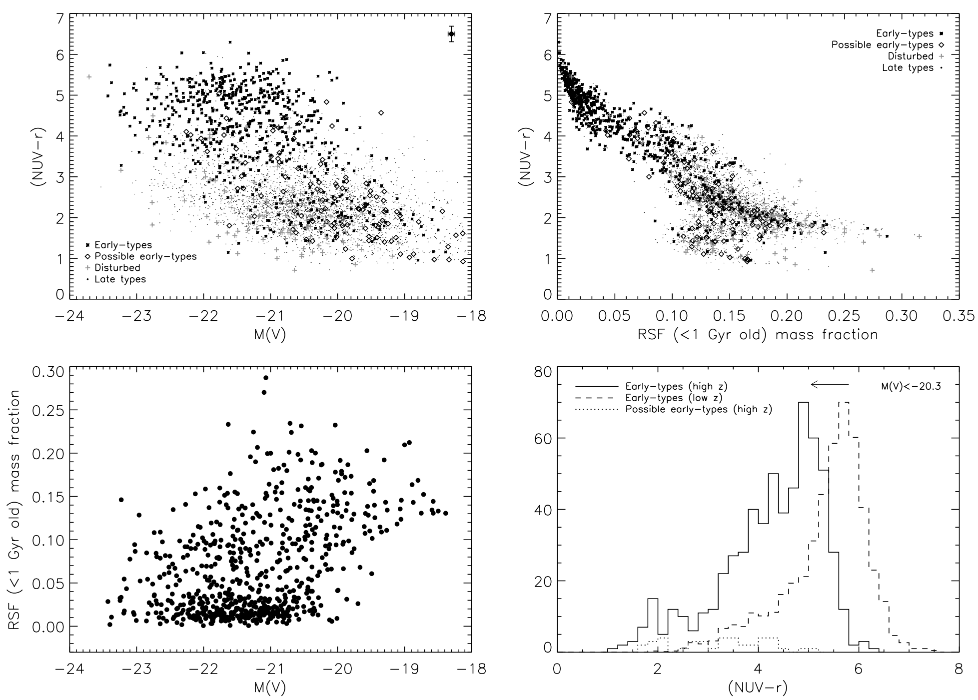


Fig. 4. TOP LEFT: Rest-frame $(NUV - r)$ colour-magnitude relation (top left) of the E-CDFS galaxy population. TOP RIGHT: Rest-frame $(NUV - r)$ colour, plotted against the RSF in the E-CDFS galaxy population. Note that here, RSF is explicitly defined as the mass fraction in stars less than a Gyr old. BOTTOM LEFT: The RSF plotted against absolute V-band magnitude for early-type galaxies only. BOTTOM RIGHT: Comparison of the UV colours of the high redshift early-type sample to their counterparts at low redshift from the GALEX-SDSS work.

enhancements in these objects in the local Universe. For example, if one assumes that the bulk of the stellar mass indeed forms rapidly at high redshift, producing an alpha-enhancement typical of a 'monolithic-type' burst and that the subsequent star formation has an alpha-enhancement that reflects the solar value (due to its longer timescale), then the quantity of RSF ($< 15\%$) in these galaxies is insufficient to perturb the alpha-enhancement from the monolithic value. The RSF values derived from the UV studies are therefore consistent with the observed alpha-enhancements of the luminous early-type population in the local Universe.

## 4. Sources of recent star formation in early-type galaxies

Several plausible sources of low-level star formation exist, which could, either individually or collectively, explain the broadness of the UV CMR and the RSF values calculated in these systems. Condensation from the extensive hot gas reservoirs hosted by massive early-type galaxies may provide a plausible source of (cold) gas that could fuel RSF in these systems. While feedback sources (e.g. AGN and supernovae) might be expected to maintain the temperature of the hot gas reservoir and evaporate infalling cold material in the most massive haloes[75], this process may not be fully efficient, allowing some gas condensation to take place, which could then result in low-level star formation as the cold gas settles in the potential well.

Mergers and accretion events provide an alternative source of young stars. The small levels of RSF in red sequence early-types indicate that the star formation in these galaxies could be driven either by accretion of small gas-rich satellites or through *largely* dry equal mass mergers. Simulations of binary mergers at low redshift (Kaviraj et al., in prep) indicate that the scatter in the early-type UV CMR can be reproduced by 'minor' mergers that have mass ratios between 1:6 and 1:10 and where the accreted satellites have high gas fractions ($\gtrsim$ 20 percent). Figure 5 indicates the colours achieved by the remnants of such minor mergers, where the mass ratios are 1:10 (left panel) and 1:6 (right panel). Note that the larger progenitor is assumed to be a spheroidal galaxy (a pure stellar bulge) while the satellite is modelled as a late-type object (a pure disk). The tracks shown are from an ensemble of simulations, where the free parameters are (a) the efficiency of star formation (varied between 1% and 10%) (b) the gas fraction of the satellite (varied between 20% and 40%) (c) the metallicity of the satellite (varied between 0.004 and 0.04) and (d) the age of the satellite (varied between 1 and 9 Gyrs). The mass, metallicity and age of the parent spheroid are assumed to be $10^{11} M_{\odot}$, 0.02 dex and 9 Gyrs respectively. The remnant is 'observed' at the point where the satellite finally disappears into the parent spheroid so that images (e.g. through an SDSS $r$-band filter) would indicate a single spheroidal object. The colours shown are therefore the bluest possible for each scenario, since star formation declines after this 'final plunge' and the remnant would be expected to redden by about 0.5-1 mag every Gyr.

Figure 5 indicates that minor mergers, with reasonable assumptions for the star formation prescriptions and properties of the merger progenitors, can reproduce the entire extent of the NUV CMR observed at low redshift. However, the *likelihood* of the minor merger channel clearly depends on the expected frequency of such events. Merger statistics in the ΛCDM model indicate that $\sim 5 - 7\%$ of luminous early-types at $z \sim 0$ would experience minor mergers with mass ratios between 1:6 and 1:10 (Sadegh Khochfar, private communication) within the last 0.5 Gyrs. Although further investigation of this issue is necessary, it appears likely that the broad red sequence ($NUV - r > 5.8$) is composed of galaxies which have not had any interaction within the last Gyr and that the ΛCDM merger rates could plausibly account for most but not all of the blue ($NUV - r < 5.5$) galaxies in the early-type population. This, in turn, implies that accretion from the halo might play a role, as might other factors such as low dust contents in star forming regions.

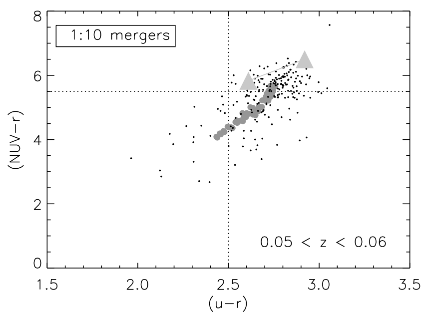


Fig. 5. UV colours achieved by remnants of minor mergers (large grey filled circles), where the mass ratios are 1:10 (left panel) and 1:6 (right panel). The colours of the observed early-type population is show using the small dots. Large triangles indicate the position of a 9 Gyr SSP with half-solar and solar metallicity. See the text in Section 4 for details.

## 5. Summary

The advent of the GALEX space telescope and deep optical surveys have revolutionised our understanding of the properties of the early-type galaxy population in the rest-frame UV. The sensitivity of the UV to recent star formation provides an unprecedented opportunity to quantify the SFHs of early-type galaxies over the last 8 billion years and put strong constraints on models for their formation.

The first generation of studies that have harnessed the UV to directly constrain the RSF in the early-type population indicate that the early-type population, in general, forms stars over the lifetime of the Universe. The SFH of luminous ($M(V) < -21$) early-types is *quasi-monolithic*, with more than 80% of their stellar mass forming at $z > 1$. Fainter early-types experience more prolonged star formation, potentially forming a substantial fraction (30-60%) of their stellar mass at recent epochs ($z < 1$).The derived values of RSF are consistent with the observed values of alpha-enhancements of luminous early-type galaxies in the local Universe.

The rest-frame UV CMR shows a typical scatter of several magnitudes over the entire redshift range $0 < z < 1$, indicating that low-level recent star formation is widespread in the early-type population. The intensity of recent star formation and the *bulk* of the UV colour distribution is consistent with what might be expected from simulations of minor mergers (mass ratios $\lesssim$ 1:6) in a $\Lambda$CDM cosmology.

Forthcoming studies with COSMOS[76] and DEEP2[57] data will significantly consolidate our understanding of the UV properties of the high-redshift early-type population, alleviate the effect of cosmic variance and allow us to the split the observed sample of galaxies not only by luminosity (mass) but also by environment (using spectroscopic redshifts), which is a key driver of galaxy evolution[77].

## 6. Acknowledgements

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