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What drives the star formation in early-type galaxies at late epochs? - the case for minor mergers

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Abstract. Multi-wavelength photometry of early-type galaxies (ETGs) in the COSMOS survey is used to demonstrate that the low-level star formation activity in the ETG population at late epochs ($z < 1$) is likely to be driven by repeated minor mergers. While relaxed ETGs are almost entirely contained within the UV red sequence, their morphologically disturbed counterparts are largely found in the blue cloud, regardless of luminosity. Since empirically determined major-merger rates in the redshift range $z < 1$ are a few factors too low to account for the number fraction of disturbed ETGs, this suggests that minor mergers are the principal mechanism that drives star formation activity in ETGs at low and intermediate redshift.

Keywords. galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation

1. Introduction

The discovery of widespread recent star formation (RSF) in early-type galaxies (ETGs) has brought several changes to our traditional understanding of how this important class of astronomical objects has formed and evolved over time. A substantial literature on ETGs, based mainly on studies that use optical data, has convincingly established that the bulk of the stellar population in luminous early-types (particularly in clusters) have formed at high redshift ($z > 1$). Several pieces of observational evidence point to this fact, including the small intrinsic scatter in the early-type 'Fundamental Plane' (e.g. Jorgensen *et al.* 1996; van Dokkum & Franx 1996), red optical colours (e.g. Bower *et al.* 1992; Ellis & *et al.* 1997; van Dokkum & *et al.* 2000) and chemical evidence for relatively short (< 1 Gyr) star formation timescales in these systems, deduced from the over-abundance of α-elements (e.g. Thomas *et al.* 1999).

The star formation activity that has taken place in these galaxies over the latter half of the Universe (since $z \sim 1$) is therefore appreciably weaker than the primordial bursts that built up the bulk of their stellar populations. A drawback of optical data is its relatively low sensitivity to small amounts of RSF. Young stellar populations, which are dominated by hot, massive, main-sequence stars, output a substantial fraction of their flux in the ultraviolet (UV) spectral ranges (shortward of ~ 2500Å). However, while the impact of low-level RSF on the optical spectrum is reasonably weak, a small mass fraction (a few percent) of young (< 1 Gyr old) stars strongly affects the rest-frame UV (Kaviraj 2008). Furthermore, the UV remains largely unaffected by the age-metallicity degeneracy (Worthey 1994) that typically plagues optical analyses, making it a useful photometric indicator of RSF (Kaviraj *et al.* 2007a).

The properties of the rest-frame 'near UV' (NUV; ∼ 2300Å) have recently been exploited in detail to study the presence of young stellar populations in early-type galaxies at low and intermediate redshifts, an expected consequence of their evolution in the standard LCDM galaxy formation paradigm (Yi *et al.* 2005, Kaviraj *et al.* 2007b, Kaviraj *et al.* 2008, Schawinski *et al.* 2007a,b). These studies have found that, in contrast to their optical colours, luminous early-types show a large spread in their UV colour distribution of almost 5 mags - a direct consequence of the sensitivity of the UV to small amounts of RSF. The basic conclusion that can be drawn from these efforts is that, while the bulk of the stellar mass in the early-type population does indeed form at high redshift ($z > 1$), early-types of all luminosities form stars over the lifetime of the Universe, with luminous systems ($-23 < M_V < -21$) forming up to 10-15% of their stellar mass after $z = 1$, with a tail to higher values. The persistent large scatter in the rest-frame UV colours indicates widespread low-level star formation in the early-type population over the last 8 billion years (Kaviraj 2008).

While unambiguous signatures of RSF have been found in the early-type population, the *source* of that star formation remains uncertain. RSF requires (cold) gas and there are several channels that could provide this gas supply e.g. internal mass loss from stellar winds and supernova (SN) ejecta, condensation from hot gas reservoirs and accretion of gas due to major or minor mergers. The principal aim of this proceeding is to study the role of mergers in driving the low-level recent star formation observed in the early-type population, with a view to exploring the overall contribution of this channel, compared to the other plausible sources of RSF in early-type galaxies.

To achieve these aims, we require (a) photometric data which traces the rest-frame UV spectral ranges (since the mass fractions of young stars are expected to be small) and (b) deep, high-resolution imaging that enables accurate visual morphological classification and identification of features typically generated by mergers (e.g. tidal tails and asymmetries). To this end we exploit publicly available data from the multi-wavelength COSMOS survey (Scoville *et al.* 2007) to explore the early-type population at intermediate redshifts ($0.5 < z < 0.7$).

2. Disturbed morphologies and UV-derived recent star formation in early-type galaxies

In Figure 1, we present the $(u - i)$ colour-magnitude relation (CMR) of our galaxy sample, split by their morphological types. The observed $(u - i)$ colour traces the rest-frame $(NUV - g)$ colour at these redshifts ($0.5 < z < 0.7$). Filled circles indicate ETGs that are relaxed (i.e. show no signs of morphological disturbances indicative of recent interactions), crosses represent ETGs which show disturbed morphologies and small black circles indicate the rest of the galaxy population. ∼ 32% of ETGs appear to be disturbed in the COSMOS images.

Galaxies separate into a broad UV red sequence and blue cloud around $(u-i) \sim 3$. The $(u-i)$ CMR indicates that the relaxed and disturbed ETGs are reasonably well-separated in the rest-frame UV colour. While the relaxed ETGs peak in the UV red sequence with a minor tail in the UV blue cloud ($u - i < 3$), the disturbed ETG population peaks in

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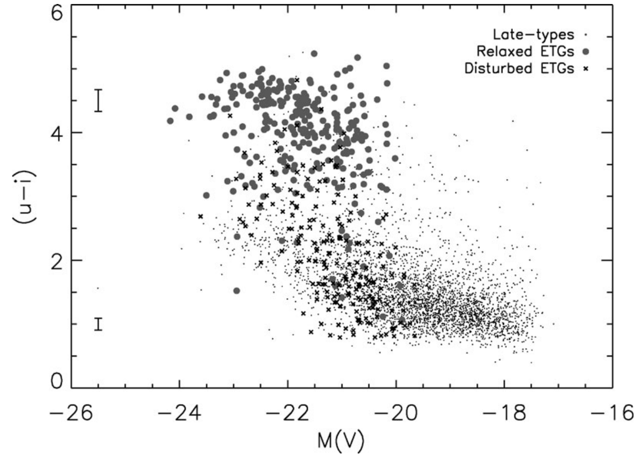

Figure 1. TOP: The $(u-i)$ colour-magnitude relation of the early-type population. Filled circles indicate galaxies classified as relaxed ETGs, crosses indicate disturbed ETGs and small black circles indicate the rest of the galaxy population. The x-axis shows the i-band magnitude.

the UV blue cloud with a significant tail into the UV red sequence. Not unexpectedly, the late-type population is almost completely contained within the UV blue cloud.

The preponderance of disturbed ETGs in the UV blue cloud indicates that merger-induced star formation plays an important role in driving the residual star formation activity observed in the ETG population. Luminous ETGs, such as the ones studied here, could either have undergone equal mass mergers (major mergers) or experienced satellite accretion where the mass ratios are typically below 1:3 (minor mergers). Since our results are restricted to $M_V < -20.5$, galaxies in our sample have masses around 10^{10} $M_\odot$ or greater (Mobasher *et al.* 2007).

Empirically determined major merger rates (Patton *et al.* 2002; Lin *et al.* 2004; Bell *et al.* 2006) indicate that major merger activity in galaxies with masses such as the ones considered in this paper becomes infrequent after $z \sim 1$. It is worth noting that while all of these works have carefully explored the frequency of equal-mass mergers, some discrepancy remains in the reported values for the major merger rate, possibly driven by different selection techniques and cosmic variance. While some studies (e.g. Bell *et al.* 2006; Lotz *et al.* 2006; Conselice 2007) indicate that each massive galaxy undergoes $\sim$0.5 major mergers after $z \sim 1$, i.e. only 50% of the massive galaxy population undergoes a major merger since $z \sim 1$, other efforts (Lin *et al.* 2004) suggest a lower value ($\sim$ 9%). The fraction of ETGs that could be remnants of major mergers in the redshift range probed by this study ($0.5 < z < 0.7$) can be estimated as:

$$\frac{(\Delta T_{0.5-0.7}) + 0.4(\mathrm{Gyrs})}{7.71(\mathrm{Gyrs})} \times f_m, \tag{2.1}$$

where $\Delta T_{0.5-0.7}$ ($\simeq$1.42 Gyrs) is the time elapsed between $z = 0.5$ and $z = 0.7$, 7.71 Gyrs is the look-back time to $z = 1$, '0.4 Gyrs' is the visibility timescale of a major merger (Naab *et al.* 2006; Bell *et al.* 2006) and f_m is the fraction of galaxies that have experienced a major merger since $z = 1$. We find that adopting $f_m \sim 0.5$ (e.g. Bell *et al.* 2006) implies a major merger contribution of $\sim$ 12% to the ETG population studied in this paper, while adopting $f_m \sim 0.09$ from Lin & *et al.* (2004) yields a negligible value of $\sim$2%. It is apparent that even the higher value for the major merger contribution ($\sim$12%) is not sufficient to satisfy the observed disturbed ETG fraction ($\sim$32%) found

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in our galaxy sample. Since morphological disturbances typically accompany UV blue colours and there are too many disturbed ETGs than can be accounted for by major mergers alone, our results point towards minor mergers contributing the bulk of the RSF in the ETG population at late epochs, with at least 60% (and perhaps >90% if the Lin *et al.* value is more representative) of the disturbed ETGs having experienced a minor merger i.e. the accretion of a small gas-rich satellite onto a massive spheroid.

Unlike the large literature that exists on major-merger galaxy 'pairs', observational constraints on minor mergers do not yet exist due to the flux limits of current surveys, since the smaller progenitor is often fainter than the spectroscopic limit of current redshift surveys. However, minor merging is *predicted* to be several factors more frequent than major merging in the standard LCDM paradigm (see e.g. Guo & White 2008). Numerical simulations of minor mergers indicate that, in the local galaxy population, satellites with cold gas fractions between 10 and 40% are able to accurately reproduce the distribution of UV colours observed in the (low-redshift) ETG population (Kaviraj *et al.* 2009). This, combined with the large frequency of minor mergers predicted by the LCDM model, appears consistent with the significant fraction of disturbed ETGs, the preponderance of disturbed systems in the UV blue cloud and the mass fractions formed in the RSF episodes. Furthermore, given the persistently large scatter in the UV colours of ETGs across the redshift range $0 < z < 1$, *it is reasonable to suggest that star formation activity in the ETG population over the latter half of the Universe is dominated by repeated minor merging.*

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