Spatially resolved colours and stellar population properties in early-type galaxies at $z \sim 1.5$

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ABSTRACT

We present $F_{850LP} - F_{160W}$ colour gradients for 11 early-type galaxies (ETGs) at $1.0 < z_{\text{spec}} < 1.9$ selected from the GOODS-South field. Significant negative $F_{850LP} - F_{160W}$ colour gradients (core redder than the outskirts) have been detected in $\sim 70$ per cent of our sample within the effective radius $R_e$, the remaining 30 per cent having a flat colour profile consistent with a null gradient. Extending the analysis to $R > R_e$, enclosing the whole galaxy, we have found that the fraction of high-$z$ ETGs with negative $F_{850LP} - F_{160W}$ colour gradients rises up to 100 per cent. For each galaxy, we investigate the origin of the radial colour variation with an innovative technique based on the matching of both the spatially resolved colour and the global spectral energy distribution (SED) to predictions of composite stellar population models. In fact, we find that the age of the stellar populations is the only parameter whose radial variation alone can fully account for the observed colour gradients and global SEDs for six ETGs in our sample, without the need of radial variation of any other stellar population property. For four out of these six ETGs, a pure metallicity variation can also reproduce the detected colour gradients. None the less, a minor contribution to the observed colour gradients from the radial variation of star formation time-scale, abundance of low- to high-mass stars and dust cannot be completely ruled out. For the rest of the sample, our analysis suggests a more complex scenario whereby more properties of the stellar populations need to simultaneously vary, likely with comparable weights, to generate the observed colour gradients and global SEDs. Our results show that, despite the young mean age of our galaxies ($< 3$–4 Gyr), they already exhibit significant differences among their stellar content. We have discussed our results within the framework of the widest accepted scenarios of galaxy formation and conclude that none of them can satisfactorily account for the observed distribution of colour gradients and for the spatially resolved content of high-$z$ ETGs. Our results suggest that the distribution of colour gradients may be due to different initial conditions in the formation mechanisms of ETGs.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: stellar content.

1 INTRODUCTION

A viable way to gather insight into the processes that concur to accrete the stellar mass in early-type galaxies (hereafter ETGs, ellipticals plus S0s) is to analyse the spatial distribution and properties of their stellar content which, in principle, can be directly connected to the events experienced by the galaxies. Indeed, the different scenarios proposed to explain the formation of ETGs give different predictions on their stellar population content.

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The revised monolithic model predicts that, in a cold dark matter framework, massive ETGs assemble the bulk of their mass at $z > 2$–3 through the merger of small substructures moving in a common potential well. This initial collapse might be regulated by cold gas streams from the cosmological surroundings, also known as cold accretion (Dekel et al. 2009), the latter becoming less important, for high-mass galaxies, at lower redshift. The subsequent evolution should be mainly characterized by the ageing of their stellar populations, with small new episodes of star formation at $z < 1$, related, for example, to the capture of satellites (Katz 1991; Kawata 2001; Kobayashi 2004; Merlin & Chiosi 2006). During the gravitational dissipative collapse, the metal-enriched gas should naturally flow...
towards the centre of the galaxy, leading to an ETG with stellar populations more metal rich in the centre than in the external regions (i.e. negative metallicity gradient). Moreover, because of the deeper potential well, the star formation is expected to last longer in the central than in the outer regions. This would lead to null or mildly positive age gradients, with stellar populations in the centre $\sim$10 per cent younger than those in the outskirts (Kobayashi 2004). None the less, the effect of metallicity variation on colour profiles should be the dominant one; thus, in this scenario, ETGs are generally expected with negative colour gradients.

The competing formation scheme is the hierarchical scenario. Following the hierarchical assembly of cosmic structures, ETGs are supposed to form through gas-rich (‘wet’) mergers of disc galaxies (e.g. Toomre & Toomre 1972; De Lucia et al. 2006) at high redshift ($z \sim 4$–5). In this phase, a large fraction of the stellar mass of a galaxy is assembled through central intense bursts of star formation (e.g. Renzini 2006). Concurrently, a ‘dry’-merger picture has also been advocated, where bright ETGs would form through the merging of quiescent galaxies (e.g. Bell et al. 2004). Over the past few years, a new scheme of mass accretion of massive ETGs, known as the inside-out growth scenario, has become widely accepted. This scenario is motivated by the observational evidence of ETGs at $1 < z < 2.5$ with effective radii three to five times smaller than the mean radius of local ETGs with the same stellar mass (e.g. Daddi et al. 2005; Longhetti et al. 2007). In this context, supported by a wealth of simulations (e.g. Khochfar & Silk 2006; Bezanson et al. 2009; Hopkins et al. 2009; Naab, Johansson & Ostriker 2009; Wyots et al. 2010), ETGs are supposed to form at high redshift ($z \sim 4$–5) as compact spheroids result from gas-rich mergers. Then, at lower redshift, compact ETGs would undergo subsequent minor ‘dry’ mergers, whose main effect is to add an external low mass density envelope to the compact core ETGs, enlarging the effective radius while leaving the stellar mass nearly constant. Indeed, this scenario shows some limitations, such as the implausible number of minor ‘dry’ mergers necessary to enlarge the ETGs’ size which could produce a scatter in the Fundamental Plane much larger than the observed one, and its failure to explain the presence of normal ETGs observed at high $z$ in number similar to the compact ones (e.g. Nipoti et al. 2009; Saracco, Longhetti & Gargiulo 2010, 2011). From a theoretical point of view, the ‘wet’-merger scenario predicts ETGs with significant radial age variations. Indeed, the galaxy remnant of a wet merger should be characterized by a central stellar population younger, and more metal rich, than the outer one, that is, by a positive (negative) age (metallicity) gradient (Kobayashi 2004). In contrast, ‘dry’ mergers, mixing the pre-existing stellar populations of progenitor galaxies, should dilute any radial variation of age and metallicity, producing flatter distributions (but see also Di Matteo et al. 2009). In the inside-out growth scenario, minor dry mergers are actually believed to only add an outer low-density envelope on the top of a compact core, without mixing the pre-existing stellar populations but redistributing the star content of the satellites in the outer regions of the compact ETG.

The picture described so far shows how important it can be to spatially resolve the properties of the underlying stellar populations of ETGs in order to pinpoint their formation scenario. The most viable way to gather information on the radial variation of the stellar content of a galaxy is to investigate its radial colour variation, being the colour of a stellar population strongly dependent on its age, star formation time-scale, metallicity and (eventual) presence of dust.

ETGs at high redshift (hereafter by ‘high redshift’ we mean $z > 1$) represent the best-suited benchmark to investigate and constrain the mechanisms driving the mass assembly of spheroids due to the short time elapsed since their formation. So far, instrumental limits have allowed only studies of the global (i.e. integrated) properties of high-$z$ spheroids, preventing, indeed, any measure of their spatially resolved information. Recently, the capabilities of the Hubble Space Telescope (HST) have made it possible to overwhelm part of these limitations for the first time. Gargiulo, Saracco & Longhetti (2011, hereafter GSL11) taking advantage of the deep and high-resolution HST Advanced Camera for Surveys (HST/ACS) images of the GOODS-South field derived $F606W - F850LP$ colour gradients $\langle U - F850LP \rangle_\text{restframe} = 1.5$, $\lambda_{\text{eff}}$ of the $F606W$ and $F850LP$ filters is $\sim 5810$ and $9010\,\AA$, respectively for 20 ETGs at $1 < z_{\text{spec}} < 2$. In their work, they ascertained the feasibility of this analysis up to $z \sim 2$ and presented the first spatially resolved information for ETGs at high $z$. Despite the short wavelength baseline covered, $\sim 50$ per cent of the galaxies showed a significant (positive or negative) colour gradient. These results clearly showed that, after 3–4 Gyr (at most) from their birth, ETGs do not exhibit a unique spatial distribution of their stellar populations, implying that they followed different mass assembly paths. Unfortunately, the available HST data, mainly optical, prevented the authors from discriminating the drivers of the observed colour gradients (e.g. radial variations of age, metallicity, etc.) and consequently from constraining the mechanisms responsible for them. Indeed, at ($z \sim 1.5$), the galaxy emission sampled by the $F606W$ and $F850LP$ filters is sensitive to both age and dust variation. Moreover, it is dominated by the youngest ($\sim 1$ Gyr) stellar populations, missing any information on the distribution of the oldest stellar populations.

The recent advent of the first HST Wide Field Camera 3 (HST/WFC3) near-infrared images for part of the GOODS-South area (see Section 2 for details) has opened new possibilities to study colour gradients of high-$z$ ETGs and to constrain their origin. In this paper, we combine the information provided by the WFC3/F160W-band $\langle R\text{-band rest frame at } (z) \sim 1.5, \lambda_{\text{eff}} \rangle$ and $F850LP$-band emission to derive the $F850LP - F160W$ colour gradients $\langle U - R \rangle_\text{restframe} = 1.5$ for a sample of 11 ETGs at $1 < z_{\text{spec}} < 1.5$. The bands we selected sample emissions dominated by different stellar populations. In particular, differently from the $F606W - F850LP$ colour, the $F850LP - F160W$ colour is much more sensitive to age variations than dust content. This allows us to extend and to complement the analysis presented by GSL11.

Actually, Guo et al. (2011) presented $F850LP - F160W$ colour gradients for four massive passively evolving galaxies in the GOODS-South area at $1.3 < z_{\text{spec}} < 2$. They derived the colour profiles by measuring optical—near-infrared (optical—NIR) colours in concentric annuli, and found that high-$z$ ETGs have cores redder than the outskirts. The observed radial trend in colour gradients is not reproduced by the radial variation of a single stellar population parameter (age, metallicity, extinction), although they found that dust should partially contribute to generate the observed colour distribution. In this paper, we examine a sample three times larger than that of Guo et al. (2011), deriving $F850LP - F160W$ colour profiles from the two-dimensional fit of the light profiles in the two bands. Then, we present a new approach to exploit the wealth of available information to constrain the radial variation of the underlying stellar populations. In fact, taking advantage of a unique set of data and an innovative procedure, we are able to constrain the radial variation of stellar population parameters (age, metallicity, dust, star formation time-scale and initial mass function (IMF)) and their contribution to produce the colour gradients we observe in high-$z$ ETGs. Finally, we compare our findings to the predictions of theoretical formation models.

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Throughout this paper, we adopt a standard Λ cold dark matter cosmology with \( H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \), \( \Omega_m = 0.3 \) and \( \Omega_\Lambda = 0.7 \). All the magnitudes are in the AB system.

## 2 The Sample

We have derived \( F850LP - F160W \) colour gradients for 11 ETGs at (\( z \)) \( \sim 1.5 \). The sample has been extracted from the complete sample of 34 ETGs selected on the whole GOODS-South field (GOODS-South v2; Giavalisco et al. 2004) and presented in Saracco et al. (2010). The morphological classification was performed by the authors both on the basis of a visual inspection of the \( F850LP \) images and on the basis of the Sérsic index, \( n_{\text{F850LP}} \) (\( n_{\text{F850LP}} > 2 \)). Starting from this complete sample we have restricted our preliminary analysis to those ETGs with NIR WFC3 data (16 ETGs out of the 34). Indeed, as pointed out in the Introduction, two areas of the GOODS-South field have been imaged in the \( F160W \) band with WFC3 extending the space-based data from the pre-existing optical domain to the NIR one. The Early Release Science (ERS, propID: 11359, PI: R. W. O’Connell) imaged an area of \( \sim 40 \, \text{arcmin}^2 \). Briefly, the observations were acquired with 2-cycle-long exposures for a total exposure time of \( \sim 6 \, \text{ks} \), reaching a 5\( \sigma \) depth in the AB system of \( F160W = 27.25 \) (Windhorst et al. 2011). Additionally, the HUDF09 HST Treasury programme (GO I1563, PI: Illingworth) provides the first ultradeep NIR WFC3 observation of the Hubble Ultra Deep Field (HUDF). The images cover an area of \( \sim 4.7 \, \text{arcmin}^2 \). At the time of our analysis, the first epoch data were available for a total exposure time of \( \sim 80 \, \text{ks} \) and a depth at 5\( \sigma \) of 28.8 in the \( F160W \) filter (AB magnitude, Oesch et al. 2010). Starting from the raw WFC3 images, we have created the mosaic images with the software MULTIDRIZZLE (Koekemoer et al. 2002) reducing the pixel scale of the mosaic from the original value of 0.128 to 0.06 arcsec pixel\(^{-1} \). In the final mosaics, we have stacked only those single exposures not affected by the presence of persistence. Thus, we have obtained the WFC3/\( F160W \)-band mosaics of the ERS and HUDF09 areas. Both mosaics are characterized by a full width at half-maximum (FWHM) of \( \sim 0.2 \, \text{arcsec} \). The exposure times are \( \sim 80 \) and \( \sim 6 \, \text{ks} \) for the HUDF09 and ERS areas, respectively. Signal-to-noise ratio (S/N) \( > 5 \) at 3\( \sigma \) is reached for the faintest galaxies of our sample in the ERS area, the one with shorter exposure time. These S/Ns and the resolution of WFC3 assure us reliable estimates of the surface brightness parameters even in the images with shorter exposure time (see Section 3.1).

Out of the 16 ETGs with NIR WFC3 data available, five objects have been excluded from the present analysis either due to potential problems in the modelling of the NIR galaxy light distribution (four ETGs, Section 3) or due to large uncertainties in the estimate of their structural parameters (one ETG, Section 3.1). These selections result into a final sample of 11 galaxies. Each of these galaxies is provided with spectroscopic redshift (Vanzella et al. 2008, and references therein) and with the wide photometric coverage of the GOODS survey: four deep \( HST/ACS \) images in the \( F435W, F606W, F775W \) and \( F850LP \) bands, extensive observations with ESO telescopes both in the three optical \( U \) bands and with the \( J, H, K_s \) NIR filters, and four \( Spitzer/IRAC \) images in the 3.6, 4.5, 5.8 and 8.0 \( \mu \text{m} \) bands. Morphological parameters (effective radius and Sérsic index) in the \( F850LP \) filter and physical parameters (age and stellar mass) were already estimated for each galaxy of the sample (Saracco et al. 2010). Four out of the 11 ETGs were already studied in GSL11; thus, \( F606W - F850LP \) colour gradients are also available (GSL11).

## 3 Surface Brightness Parameter Estimation

Following GSL11, we have estimated the internal colour gradient of a galaxy as the logarithmic slope of its colour profile, given by the difference between the \( \mu_{F850LP}(r) \) and \( \mu_{F160W}(r) \) surface brightness profiles. As for the \( F850LP \) and \( F606W \) bands, we have modelled the \( F160W \) surface brightness profile of high-\( z \) ETGs with a Sérsic law:

\[
\mu(R) = \mu_e + \frac{2.5b_e}{\ln(10)} \left[ (r/r_e)^{1/n} - 1 \right].
\]  

To estimate the free parameters of the profile, that is, the effective radius \( r_e \) (in units of arcsec), the Sérsic index \( n \), and the normalization term \( \mu_e \), we have used GALFIT (v2, Peng et al. 2002). This software models the galaxy light distribution with a two-dimensional fit. In the fitting procedure, the galaxy model is convolved with the point spread function (PSF), provided by the user, and the software retains as a final solution the parameters of the PSF-convolved model that minimize the residuals to the input galaxy image. For each galaxy, we have constructed different PSF models, each model being obtained by averaging the light profiles of unsaturated stars as near as possible to the position of the given galaxy on the frame. We have run GALFIT for all different PSFs and have retained the case that returns the best residual map (i.e. flattest residuals). For four out of the 16 initially selected galaxies, we found significant substructures in the residual maps, possibly indicating an inaccurate modelling of the galaxy light distribution and/or of the PSF. We have excluded these four galaxies from the analysis (see Section 2).  

### 3.1 Robustness of structural parameter estimates

Given the pixel scale of 0.128 arcsec pixel\(^{-1} \) (0.06 arcsec pixel\(^{-1} \) after drizzling) and the FWHM of the PSF of \( \sim 0.2 \, \text{arcsec} \), the WFC3 images in the \( F160W \) passband are close to the sampling limit. Moreover, even with the excellent spatial resolution of WFC3, most of the high-\( z \) ETGs in our sample have sizes comparable to the FWHM. This makes the accuracy and reliability of the derived PSF used to convolve the galaxy model extremely important. To assess the independence of our results from the method we have adopted to derive the PSF and the consequent robustness of the derived structural parameters, we have derived them also using 2DPhot (La Barbera et al. 2008), a software that works by means of a different approach from GALFIT. 2DPhot is a fully automatic tool, allowing galaxy surface photometry to be performed by fitting galaxy images with two-dimensional, PSF convolved, (Sérsic) models. Differently from GALFIT, 2DPhot constructs a PSF model in a user-independent manner, fitting star images on a given frame with a combination of two-dimensional Moffat functions, taking into account PSF asymmetries and image (under)sampling. In order to reproduce the spikes of the \( HST \) PSF, we have modified the 2DPhot PSF fitting algorithm by smoothing the (average) residual map from the fitted stars (with a 3 \( \times \) 3 pixels median smoothing) and adding the smoothed residuals to the Moffat-based PSF. The 2DPhot initial parameters for Sérsic fitting are also computed through a user-independent approach (in contrast to GALFIT), by comparing the galaxy image with a discrete grid of PSF-convolved Sérsic models, reducing the problem of spurious convergences in

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1 To this effect, at each step of the PSF fitting, the Moffat functions are convolved with a box kernel, that is, the pixel of the given image.
the (non-linear) optimization procedure. In general, we find a very good agreement between $2\text{DPHOT}$ and $\text{GALFIT}$ structural parameters. As an example, in Fig. 1, we compare the effective radii derived with the two software. Errors in $r_e$ have been set equal to 0.02 arcsec, the typical uncertainty of this measure as we have derived through Monte Carlo simulations (e.g. Longhetti et al. 2007). No systematic difference is found between $r_e, \text{GALFIT}$ and $r_e, 2\text{DPHOT}$, despite the different approach and methodology adopted. Only for one galaxy, with $r_e, \text{GALFIT} \sim 0.4$ arcsec, the $r_e$ estimate differs significantly, with $r_e, 2\text{DPHOT}$ being approximately three times larger than $r_e, \text{GALFIT}$. Given this discrepancy, we have excluded this object from our sample; thus, we are left with 11 galaxies in our sample (see Section 2). To be consistent with GSL11, where we estimated structural parameters in the $F850LP$ and $F606W$ passbands with $\text{GALFIT}$, we have decided to adopt $\text{GALFIT}$ estimates of surface brightness parameters also for the WFC3/$F160W$ filter.

To further verify the reliability of surface brightness parameters, in Fig. 2 we compare the best-fitting PSF-convolved Sérsic profiles (black curves) with the observed surface brightness profiles (red points), measured in concentric circular coronae of fixed width on the $F160W$ images. Errors on surface brightness were derived with $\text{SExtractor}$ (Bertin & Arnouts 1996) and take into account the correlated noise introduced by the drizzling technique (Casertano et al. 2000). The vertical black dashed lines mark the radius of the FWHM of the PSF (0.1 arcsec), while the red dot–dashed and solid lines correspond to 2 and 3$r_e$, respectively. The figure shows an excellent agreement between observed and fitted profiles, from the very central region out to a radius of $\sim 3r_e$, and in many cases well

![Figure 1. Comparison of effective radii estimated with $\text{GALFIT}$ and $2\text{DPHOT}$ (see the text). The solid line marks the one-to-one relation.](image)

![Figure 2. Comparison of $F160W$ PSF-convolved Sérsic profiles (black curves) for our sample of 11 ETGs with the observed surface brightness profiles measured directly on the given images (red points). The vertical black dashed lines mark the radius of the FWHM of the PSF, while the red dot–dashed and solid lines correspond to 2 and 3$r_e$, respectively. In the panels related to ETGs 472 and 996, the black curves correspond to PSF-convolved Sérsic profiles derived on a mosaic image of $\sim 80$ ks, while the green curves, not visible, given the almost perfect overlap on the black curves, correspond to the same quantity measured on mosaic images of $\sim 6$ ks.](image)
Table 1. Our sample of galaxies. Column (1): ID number; column (2): spectroscopic redshift; column (3): total magnitude from GALFIT. Errors on magnitude are the formal GALFIT errors; column (4): effective radius in arcsec. A typical error on the estimates of $r_e$ is 0.02 arcsec corresponding to 0.17 kpc at $z = 1.5$; column (5): effective radius in kpc; column (6): Sérsic index; column (7): $F850LP - F160W$ colour gradient. At the median redshift $z = 1.5$, 1 arcsec corresponds to $\sim 8.5$ kpc.

| Object ID | $z$   | $F160W_{\text{abs}}$ (mag) | $r_e,160$ (arcsec) | $R_e,160$ (kpc) | $n_{160}$ | $\nabla_{F850LP-F160W}$ (mag dex$^{-1}$) |
|-----------|-------|---------------------------|-------------------|---------------|-----------|---------------------------------|
| 23        | 1.04  | 20.80 $\pm$ 0.01         | 0.2               | 1.98          | 3.47      | $-0.3 \pm 0.2$                 |
| 11888     | 1.04  | 20.44 $\pm$ 0.01         | 0.18              | 1.50          | 5.39      | $-0.4 \pm 0.1$                 |
| 12294     | 1.21  | 20.93 $\pm$ 0.01         | 0.10              | 0.82          | 2.18      | $-0.72 \pm 0.05$              |
| 996       | 1.39  | 22.57 $\pm$ 0.01         | 0.05              | 0.43          | 5.52      | $-1.0 \pm 0.1$                 |
| 2239      | 1.41  | 21.74 $\pm$ 0.01         | 0.23              | 0.38          | 2.85      | $-0.5 \pm 0.3$                |
| 2286      | 1.60  | 22.20 $\pm$ 0.01         | 0.11              | 0.97          | 2.02      | $-0.1 \pm 0.2$                |
| 2361      | 1.61  | 21.60 $\pm$ 0.01         | 0.09              | 0.77          | 3.35      | $-0.1 \pm 0.1$                |
| 2196      | 1.61  | 21.65 $\pm$ 0.01         | 0.12              | 1.06          | 2.81      | $-0.2 \pm 0.2$                |
| 2543      | 1.61  | 21.93 $\pm$ 0.02         | 0.15              | 1.33          | 5.62      | $-0.8 \pm 0.4$                |
| 2111      | 1.61  | 21.85 $\pm$ 0.01         | 0.04              | 0.38          | 4.73      | $-0.54 \pm 0.07$             |
| 472       | 1.92  | 22.12 $\pm$ 0.01         | 0.04              | 0.38          | 3.23      | $-0.6 \pm 0.1$                |

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Beyond, both for galaxies in the deepest images (IDs 472 and 996) and for those in the shallowest fields. This confirms the accuracy of PSF modelling and Sérsic fitting. For the two galaxies on the HUDF area (IDs 472 and 996), the green curves show the PSF-convolved Sérsic profiles estimated on a mosaic image created to match the exposure time of the shallowest images available ($\sim 6$ ks; see Section 2). The excellent agreement between the black ($\sim 80$ ks) and green ($\sim 6$ ks) solid curves (in fact overlapping) in the figure indicates the homogeneity of our measures and proves the feasibility of deriving reliable structural parameters even with 2-orbit-long images.

In Table 1, we report our effective radii, $r_e$ (in units of arcsec) and $R_e$ (in kpc), as well as the Sérsic index and total magnitude for each of the 11 ETGs in our sample.

4 $F850LP – F160W$ COLOUR GRADIENTS OF HIGH-$z$ ETGs

We recall that colour gradients are generally defined as the logarithmic slope of colour profiles:

$$\nabla_{F850LP-F160W} = \frac{\Delta (\mu_{F850LP} - \mu_{F160W})(R)}{\Delta \log R}. \quad (2)$$

To obtain the measure of this quantity, we have re-estimated the surface brightness parameters in the $F850LP$ band, keeping fixed in the fit of each galaxy the ellipticity and position angle to the values derived for the $F160W$ filter. This ensures that both the $\mu_{F850LP}(R)$ and $\mu_{F160W}(R)$ profiles trace the variation of light density in the same radial direction. Following the prescription commonly adopted for nearby ETGs and for consistency with GL11, we have fitted the slope of the colour profile between 0.1 and $1r_e, F850LP$. The best-fitting line is obtained by an orthogonal least-squares fit, less sensitive to outliers than the direct fit. Fig. 3 reports the results. The black curves indicate the colour profiles, while the red lines indicate the fitted slopes. The dashed lines mark the radius of the FWHM of the PSF, while the coloured area sets $1\sigma$ errors.

The values of the gradients and their relative errors are reported in Table 1. The error on colour gradients is an upper limit to the true error. We estimated it by associating, at each point of the colour profile, the error on colour, $\delta\mu_{\text{col}}$, measured directly from the real images in a thin circular corona of radius $r_e$ (for galaxies with $r_e > \text{FWHM}/2$) or $\text{FWHM}/2$ (for galaxies with $r_e < \text{FWHM}/2$). $\delta\mu_{\text{col}}$ was estimated after reporting the $F160W$ and $F850LP$ images to the same pixel scale and PSF (see Section 5.1). Our results show that the high-$z$ ETGs in our sample have negative or null $F850LP – F160W$ colour gradients. Indeed, three galaxies have colour gradients comparable at $\sim 0$ with zero. In contrast, the remaining galaxies show significant negative values which reveal the presence of stellar populations redder in the centre than those at $1r_e$. The differences observed in the radial variation of the $F850LP – F160W$ colour within the galaxies of our sample show that after $\sim 4$ Gyr at maximum from their birth, the stellar content distribution of high-$z$ ETGs was not homogeneous. This non-homogeneous distribution of the stellar content within the galaxies of our sample corroborates the idea that ETGs have assembled their mass through different mechanisms.

To gain insight into the origin of the observed distribution, first, we have looked for the presence of any correlation of observed colour gradients with global properties of ETGs. Fig. 4 reports the $F606W – F850LP$ (blue points) and $F850LP – F160W$ (red points) colour gradients versus the dust extinction $A_V$ (first panel), total stellar mass (second panel), redshift (third panel), formation redshift (fourth panel; see Saracco et al. 2011 for the definition and estimate of formation redshift) and global age (last panel) of a galaxy. No correlation was detected. Indeed, the absence of a correlation could be due to the fact that we plot colour variation within $1r_e$ versus quantities estimated on the entire galaxy. We have verified that the result does not change when the colour gradients are estimated on the whole galaxy. Thus, the various mechanisms responsible for the different stellar content observed in our high-$z$ ETGs, to the extent of our sample, produce colour gradients which are independent of redshift, formation redshift, stellar mass, global age and dust extinction.

This result confirms that the observed distribution of colour gradients is primarily due to differences in the stellar content of high-$z$ ETGs. Different results were reached by Guo et al. (2011) who found a correlation between dust and colour gradients in the direction of steeper gradients for galaxies with higher dust obscuration. Guo et al. (2011) fixed the dust extinction assuming a Salpeter IMF in the spectral energy distribution (SED) fitting, while we have adopted a Chabrier IMF. Furthermore, they derived their colour gradients fitting the colour profiles between $\sim 1r_e$ and $5–8r_e$. To properly compare our results with those of Guo et al., we have re-estimated the colour gradients in our sample in regions similar to those selected in their paper, and computed $A_V$ assuming a Salpeter IMF (see Table 2). Even in this case we do not find any correlation between dust extinction and colour gradients. Actually, two galaxies of our sample were analysed also in Guo’s paper (IDs 472 and 996 in our paper; IDs 23555 and 22704 in their paper). Our estimates of the effective radius of these two galaxies are $\sim 13$ per cent smaller than theirs, thus consistent within the typical errors on this quantity. Moreover, for both galaxies our estimates of $A_V$ are consistent with those reported by Guo et al. (2011). Since Guo et al. (2011) did not report the gradient values, we try to qualitatively compare our colour profiles to theirs. We would like to stress here that, for these galaxies, the typical error on colour at $1r_e$ is $\sim 0.15$ mag. For galaxy 472 (see our Fig. 7 and the magenta line in the lower panel of their fig. 5), the agreement between our colour profiles and those reported by Guo et al. (2011) seems very good. For galaxy 996, we have found a global negative trend in colour values, but the
amplitude of the colour gradient we detect is less steep than the one measured by Guo et al., due to the external region ($5 < r < 7r_e$) where their profile suddenly falls down, while our profile follows a quite constant variation (see our Fig. 7 and the green line in the lower panel of their fig. 5). The reason for this difference can be due to the presence of another galaxy at a very low projected distance (see our Section 5.1 and their fig. 1). In the F850LP band, this source is not detected due to its faint magnitude; thus, the extreme blue colour observed in the external region by Guo et al. could be due to an underestimate of the flux in the F160W band solely. In contrast, in the fitting procedure of the surface brightness profile, we have simultaneously modelled both galaxies and assured from the residual map that the contribution of the other galaxy is properly taken into account. If this explanation is correct, the consequent flattening of the colour gradient value of this galaxy would strongly weaken the correlation between colour gradients and extinction also in their sample and the eventual residual correlation should be totally due to the small statistics of their sample.
Table 2. Stellar population parameters derived from the fit of the global SED assuming a Chabrier IMF and a Salpeter IMF. Column (1): ID number; column (2): age obtained with a Chabrier IMF; column (3): age obtained with a Salpeter IMF; column (4): $A_V$ obtained with a Chabrier IMF; column (5): $A_V$ obtained with a Salpeter IMF; column (6): log $M_*$ obtained with a Chabrier IMF; column (7): log $M_*$ obtained with a Salpeter IMF. In each fit, we assume solar metallicity.

| Object ID | agecha | agesa | tcha | tsa | $A_V$cha | $A_V$sa | log $M_*$cha | log $M_*$sa |
|-----------|--------|-------|------|------|----------|---------|-------------|-------------|
| 23        | 1.90   | 2.1   | 0.1  | 0.0  | 0.0      | 0.0     | 10.5        | 10.9        |
| 11888     | 2.5    | 2.4   | 0.3  | 0.0  | 0.0      | 0.0     | 10.7        | 11.0        |
| 12294     | 1.0    | 1.0   | 0.1  | 0.25 | 0.25     | 0.25    | 10.6        | 10.9        |
| 996       | 2.5    | 1.7   | 0.3  | 0.2  | 0.10     | 0.30    | 10.3        | 10.5        |
| 2239      | 1.1    | 1.1   | 0.1  | 0.55 | 0.60     | 0.60    | 10.5        | 10.8        |
| 2286      | 1.1    | 1.1   | 0.1  | 0.20 | 0.25     | 0.25    | 10.4        | 10.7        |
| 2361      | 3.25   | 3.25  | 0.3  | 0.0  | 0.0      | 0.0     | 11.0        | 11.3        |
| 2148      | 3.5    | 3.25  | 0.4  | 0.04 | 0.05     | 0.05    | 11.2        | 11.4        |
| 2196      | 1.7    | 1.9   | 0.1  | 0.05 | 0.05     | 0.05    | 10.7        | 11.1        |
| 2543      | 3.0    | 3.25  | 0.4  | 0.05 | 0.6     | 0.6     | 11.0        | 11.3        |
| 2111      | 1.0    | 1.1   | 0.1  | 0.35 | 0.60     | 0.60    | 10.6        | 11.3        |
| 472       | 1.0    | 1.0   | 0.1  | 0.0  | 0.0      | 0.0     | 10.6        | 10.9        |

5 SPATIAL DISTRIBUTION OF STELLAR POPULATIONS IN HIGH-ζ ETGS AND RADIAL VARIATION OF THEIR PROPERTIES

In order to constrain the possible physical mechanisms responsible for the mass accretion within the ETGs, we have designed a new method able to investigate the spatial distribution of the underlying stellar populations in high-ζ ETGs which is directly correlated to the mass assembly processes. Briefly, we have derived the colour maps of our galaxies and, on their basis, we have defined for each ETG of our sample an internal and an external region. Then, we have modelled the global stellar content of each ETG as formed by two main stellar components, one dominating the internal regions, and the other the external ones. With synthetic models of composite stellar populations, we have constrained the stellar properties of the two components in order to simultaneously reproduce the observed colour gradient(s) (in one or two colours) and the whole global SED of the galaxy from 0.3 to 8 μm.

5.1 Colour maps of high-ζ ETGs: a direct look at the spatial distribution of their stellar content

To have a direct look at the two-dimensional distribution of the $F850LP - F160W$ colour in high-ζ ETGs, we have derived their colour maps. To this aim, we have re-reduced the WFC3 images to a pixel scale of 0.03 arcsec pixel$^{-1}$ to match the one of $F850LP$-mosaic images, and used the IRAF task geomap/geotran to align the two mosaics. Then, we have degraded the $F850LP$ images (FWHM $\sim 0.12$ arcsec) to the same PSF of the $F160W$ images (FWHM $\sim 0.2$ arcsec). To this aim, we needed to derive the kernel function $K(r)$ which regulates the transformation between the PSFs in the two bands, that is, which holds

$$PSF_{F850LP}(r) \ast K(r) = PSF_{F160W}(r),$$

where $PSF_{F850LP}(r)$ and $PSF_{F160W}(r)$ are the PSFs in the $F850LP$ and $F160W$ bands, respectively, and the symbol $\ast$ denotes a convolution. For each galaxy, we have modelled its $PSF_{F850LP}(r)$ and $PSF_{F160W}(r)$ and through equation (3) we have recovered its kernel function. The $PSF_{F850LP}(r)$ and $PSF_{F160W}(r)$ of a given galaxy, have been derived by fitting the light profiles of the same unsaturated stars adopted as PSFs in GALFIT; we have already tested those to be good approximations of the true PSF for that galaxy. In Fig. 5, we report a representative example of the fractional encircled energy for the real PSF (black curve) of a star in the $F160W$ (left-hand panel) and $F850LP$ (middle panel) bands, and the corresponding fitted model (red curve). The agreement between the two curves is extremely good in both cases, confirming the quality of our fit. In the right-hand panel of Fig. 5, we report the encircled energy distribution of the $PSF_{F160W}(r)$ model (black line) and the $PSF_{F850LP}(r)$ model convolved with the kernel (red line). The match between the two functions is perfect and differences $< 2$ per cent appear at $R > 4$ arcsec, when present. In particular, it is important to note the optimal agreement in the central region, as said before, is the one mainly affecting the galaxy light profile. This has allowed us to degrade the $F850LP$ images to the PSF of $F160W$ images and to derive the colour maps presented in Fig. 6. The images are colour coded with the reddest colour indicating the region of the galaxies with highest $F850LP - F160W$ values. The red, blue and magenta circles indicate the $r_c$ in the $F160W$, $F850LP$ and $F606W$ bands, respectively. As pointed out before, we have at disposal information on the $F606W$ band only in four galaxies out of the 11. In some
cases, the $r_e$ in the $F_{160}W$ band is represented with a black circle, being the red one not visible on the colour map. The white lines correspond to 1 arcsec. In Fig. 6, we have marked all the pixels $4.5r$ above the mean background in the $F_{160}W$ images as belonging to the galaxy. In spite of this high threshold, the colour maps extend to regions well beyond $4r_{F_{850}LP}$ and at radius greater than $4r_{F_{850}LP}$ for five cases (IDs 12294, 996, 2361, 2111 and 472). The colour map of the whole galaxy shows that differently from the gradients estimated up to $1r_{F_{850}LP}$, all high-$z$ ETGs of our sample have a negative colour gradient. Moreover, they point out that although the general trend is the same, the $F_{850}LP - F_{160}W$ colour varies from the internal to the external regions with different gradients showing that both the spatial distribution and the properties of the stellar content are not homogeneous in high-$z$ ETGs.

5.2 Radial variation of the stellar population properties of high-$z$ ETGs

To identify the stellar population parameters whose variation can account for the observed colour gradients, we have used the following procedure. On the basis of the colour maps which show a quite radial variation of colour within the ETGs of our sample, we have schematized the whole stellar content of each of them with a two-component model assuming that one component dominates the central regions and the other dominates the external regions. By means of the colour maps we have selected two areas (white circles in Fig. 6) in order to maximize both the difference in the mean colour between the two regions and the radial distance between them. At a fixed gradient, maximizing the distance between the two regions means maximizing their colour difference, and this will facilitate in detecting differences between the stellar population parameters of the two components and hence in detecting possible radial variations.

We have assumed as an initial guess for the stellar parameters of the two components the values derived from the fit of the global SED ($\text{age}_{\text{global}}, \text{Z}_{\text{global}}, A_V\text{global}, \tau_{\text{global}}$). Briefly, for each galaxy, the global stellar population parameters were derived through the fit of the SED defined by 14 photometric points and with known spectroscopic redshift. The fit was performed with the software HYPERZMASS (Bolzonella, Miralles & Pelló 2000) using the composite stellar population models of Charlot & Bruzual (unpublished models distributed on demand) with an exponentially declining star formation history ($\propto \exp(-t/\tau)$), and a Chabrier IMF (Chabrier 2003). The best solution was selected on a grid of models with varying age, star formation time-scale $\tau$ ([0.1, 0.3, 0.4, 0.6] Gyr) and solar metallicity. Extinction $A_V$ was left as a free parameter in the 0.0–0.6 range and the extinction curve of Calzetti et al. (2000) was adopted. For more details on SED fitting, see Saracco et al. (2010). For each galaxy of our sample, the set of the four best-fitting parameters are reported in Table 2.

In order to reproduce the colour gradient we observe, it is necessary that one or more parameters of the two components vary from the internal to the external region. Unfortunately, the effect of age, metallicity, dust and $\tau$ variation on the galaxy emission is degenerate in the spectral region we are observing, preventing us, in fact, from identifying the contribution of each parameter to the total emission. For this reason, we have performed our analysis by investigating the effect of each single parameter in turn, without considering the possibility of either a correlated or an anticorrelated
variation of age and metallicity within galaxies. Thus, we have fixed in both components three out of the four parameters in the fitting. For example, to investigate radial age variation as a possible driver of colour variations, we fixed the metallicity, dust extinction and star formation time-scale to the value obtained by the fit of the global SED: $Z_{\text{global}}, A_V_{\text{global}}, \tau_{\text{global}}$. We have looked for the value of age to be associated with the internal and the external populations, $\text{age}_{\text{in}}$ and $\text{age}_{\text{out}}$, respectively, which best reproduce the observed colour gradients. In particular, we have chosen the value of $\text{age}_{\text{in}}$ that minimizes the quantity

$$[(F850LP - F160W)_{\text{mod, in}} - (F850LP - F160W)_{\text{obs, in}}] + [(F606W - F850LP)_{\text{mod, in}} - (F606W - F850LP)_{\text{obs, in}}]$$

(4)

where $(F850LP - F160W)_{\text{mod, in}}$ and $(F606W - F850LP)_{\text{mod, in}}$ are the $F850LP - F160W$ and the $F606W - F850LP$ colours predicted by the model defined by the stellar population parameters ($\text{age}_{\text{in}}, Z_{\text{global}}, A_V_{\text{global}}, \tau_{\text{global}}$), and $(F850LP - F160W)_{\text{obs, in}}$ and $(F606W - F850LP)_{\text{obs, in}}$ are the mean values of the colours observed in the internal region. A similar procedure has been adopted to identify $\text{age}_{\text{out}}$. In the cases for which $F606W - F850LP$ colour gradients are not available, we clearly ignore the second line in equation (4). To fix the contribution to the total stellar mass of the two components so selected, we fit the global SED sampled by 14 photometric points with a linear combination of the SEDs of the two populations.

We have repeated this analysis also for variation of metallicity $Z$, keeping $\text{age}_{\text{global}}, A_V_{\text{global}}$ and $\tau_{\text{global}}$ fixed, and star formation $\tau$ keeping $\text{age}_{\text{global}}, Z_{\text{global}}$ and $A_V_{\text{global}}$ fixed. We have looked for the values of metallicity to be associated with the internal and external populations, $Z_{\text{in}}$ and $Z_{\text{out}}$, respectively, on a grid of subsolar and supersolar values: $0.2 Z_\odot, 0.4 Z_\odot, Z_\odot$ and $2 Z_\odot$, while for the star formation time-scale we have considered the range 0.1–0.6 Gyr.

5.2.1 An example

In Fig. 7, we report an example of the analysis described above for a galaxy of our sample. We select a case that presents some peculiarities to guide the interpretation of the analysis in this more complex case, and it is left for the reader to interpret the analysis in the context of other galaxies not discussed here but presented in electronic form (see Supporting Information). The first column reports the analysis relative to the effect on galaxy colours of pure age variation from the inner to the outer regions. The second and third columns show the same but for metallicity and $\tau$ radial variation, respectively. In each column, we report, from the top to bottom, the $F850LP - F160W$ colour gradient, the $F606W - F850LP$ colour gradient, when available, and the global SED. In the panels related to the colour gradients, the black lines are the colour profiles. The red lines are the fit to the colour profiles up to the external regions derived following the same method as described in Section 4. The red points are the mean colour values of the internal regions measured through colour profiles, that is, $(F850LP - F160W)_{\text{obs, in}}$ and $(F606W - F850LP)_{\text{obs, in}}$ in equation (4). The blue points mean the same for the external regions. The horizontal error bars indicate the extension of the two areas we select (white circles in the colour maps) and over which we computed the mean colours.

In the bottom panel, we report the observed SED (black dots), the best-fitting template (black line) and the relative best-fitting parameters (black text). The red and blue lines are the contributions of the internal and external populations, respectively, to the total emission, and hence to the total stellar mass. The amount of their contribution was fixed such that their linear combination (magenta, cyan and green lines for age, metallicity and $\tau$ variations, respectively) minimizes the residual with the observed SED. In each panel, we report the $\chi^2$ value of this fit. In red, we present the value of the varying parameter which minimizes equation (4) as well as their contribution in mass, and in blue the same for the external region.

The solely linear radial variation of this parameter from the internal value (red text) to the external value (blue text) will produce an $F850LP - F160W$ and an $F606W - F850LP$ colour gradient indicated in the top and middle panels by the dashed lines (magenta, cyan and green lines for age, metallicity and $\tau$ variations, respectively).

Fig. 7 shows that the colour gradient we observe in this galaxy can be due to a variation of the age of the stellar populations from the inner to the outer regions. Indeed, while the global fit returns a mean age of 1.9 Gyr (black text in the bottom left-hand panel), our analysis shows that a population of 2.7 Gyr dominating the central regions (red text in the bottom left-hand panel) and a younger population of 1.0 Gyr dominating the external regions (blue text in the bottom left-hand panel) can perfectly reproduce within the errors (magenta dashed line in the top and middle panels) the internal and external observed $F606W - F850LP$ and $F850LP - F160W$ colours, and hence the colour gradients. Further, the analysis of the SED suggests that in this galaxy the older stellar population contributes to the stellar mass by more than 90 per cent (red line, bottom left-hand panel). In contrast, neither a pure metallicity variation nor a variation of the star formation time-scale alone can reproduce the observed colour gradients. In the case of metallicity (middle column), the internal colours are well reproduced by a population with solar metallicity (red text in the bottom middle panel), the same as that of the global fit, while the external colour cannot be simultaneously reproduced by a single value of $Z$.

For what concerns the analysis of the $\tau$ variation this galaxy requires particular attention. The fit of the global SED suggests a mean $\tau$ for this galaxy of 0.1 Gyr which is the lower value in the grid of the star formation time-scales considered. To cope with this, we assume a population of 2.7 Gyr with $\tau = 0.1$ Gyr as representative of the inner part, as we have already found that this parameter well fits the inner colours. For the external regions, fixing the age to 2.4 Gyr, the value of $\tau$ that best reproduces both external colours is 0.4 Gyr. However, despite it being the best-fitting value, it is not able to reproduce within 1σ the observed $F850LP - F160W$ external colour.

The fact that we have changed the global age value does not influence our analysis. Indeed, we make the starting assumption to associate with the two components the stellar population parameters of the global fit since it can be a good representation of the whole galaxy. However, what we are interested in is the variation of these parameters as a possible driver of the observed colour gradients, and not their absolute values. In Table 3, we report the summary of the results obtained for the other galaxies of the sample, while the plots related to their analysis, similar to Fig. 7, and with the same conventions are available in electronic form (see Supporting Information).

5.2.2 Dust distribution and colour gradient

Actually, as pointed out before, one of the causes of the radial variation of colour we observe in our ETGs can be a non-homogeneous distribution of the dust within the galaxy. Fig. 4 shows that for half of the galaxies in our sample the fit of the global SED returns a
value of $A_V = 0$. Thus, for these galaxies (IDs 23, 11888, 2361, 2196, 472) seems not plausible a scenario whereby the main driver of the colour gradients is a radial distribution of dust. For the remaining galaxies, the observed global SED was best fitted assuming the presence of a non-null quantity of dust. As in the cases of age, metallicity and $\tau$, we test if, starting from a flat colour distribution, a pure radial variation of the dust extinction (more dust in the centre than in the outskirts) can reproduce the observed colour gradients.

In particular, we have made the working hypothesis that the ETGs of the sample have no dust in the outskirts. Thus, the colours we measure in the external regions [i.e. $(F850LP - F160W)_{\text{obs,ext}}$] are the intrinsic colours of the galaxies. In this hypothesis, the reddest colours observed in the centre of the galaxies [i.e. $(F850LP - F160W)_{\text{obs,in}}$] are the direct effect of the extinction of the dust. The necessary amount of dust extinction to redden the intrinsic colours to those observed in the centre is

$$A_V = \frac{[(F850LP - F160W)_{\text{obs,ext}} - (F850LP - F160W)_{\text{obs,in}}] \times R_V}{K(F850LP) - K(F160W)}$$

(5)

where $K(F850LP)A_V/R_V$ and $K(F160W)A_V/R_V$ are the extinction in both bands due to the dust. We have derived $K(F850LP)$ and $K(F160W)$ following Calzetti et al. (2000) and have assumed $R_V = 4.05 \pm 0.80$. For galaxy 2111, equation (5) leads to a dust extinction $A_V$ in the centre $\sim 1$. This value is a lower limit. Indeed, if dust were
Table 3. Colour gradients produced by the variation of a single stellar population parameter from the internal to the external regions. Column (1): top line: galaxy ID number; bottom line: compactness $C$ defined as $R_{\text{ext}}/R_{\text{c}}$, where $R_{\text{ext}}$ is the effective radius of the galaxy and $R_{\text{c}}$ is the radius that a galaxy of equal stellar mass would have at $z = 0$ as derived by the size–mass relation of Shen et al. (2003). EGTGs with effective radius more than 1 $\sigma$ smaller than those predicted by the local size–mass relation, that is, our compact galaxies, turn out to have $C \geq 2$. Column (2): radius up to which we extend the analysis ($R_{\text{ext}}$ in units of $R_{\text{ext}}/R_{\text{c}}$); column (3): $F_{850LP} - F_{160W}$ measured colour gradient; $F_{606W} - F_{850LP}$ measured colour gradient derived up to $R_{\text{ext}}$ from the fit of the colour profile; column (4): top line: $F_{850LP} - F_{160W}$ colour gradient; $F_{606W} - F_{850LP}$ colour gradient produced by a solely radial age variation from age$_{\text{int}}$ in the internal region to age$_{\text{ext}}$ in the external region; bottom line: age$_{\text{ext}}$; age of the internal population – age$_{\text{int}}$; age gradient derived as $d \log$ age$/d \log r$; column (5): the same as column (4) for metallicity radial variation; metallicity gradient is derived as $d \log Z/d \log r$; column (6): the same as column (4) but for star formation time-scale radial variation; column (7): the same as column (4) but for the IMF's slope radial variation. In the case of star formation time-scale and the IMF's slope radial variation, $V_r$ and $V_0$ are omitted. In bold font are reported the variations able to reproduce both the colour gradients and observed global SED.

| Object ID | $R_{\text{ext}}$ | $V_{F850-F160}$ | $V_{F606-F850}$ | $V_{Z_{\alpha in} - Z_{\alpha out}}$ | $\alpha_{\text{in}} - \alpha_{\text{out}}$ |
|-----------|------------------|----------------|------------------|-------------------------------|------------------|
|           |                  | ($\text{mag }^{-1}$) | ($\text{mag }^{-1}$) | ($\text{mag }^{-1}$) | ($\text{mag }^{-1}$) |
|           | ($\text{mag }^{-1}$) | ($\text{mag }^{-1}$) | ($\text{mag }^{-1}$) | ($\text{mag }^{-1}$) | ($\text{mag }^{-1}$) |
|           | ($\text{mag }^{-1}$) | ($\text{mag }^{-1}$) | ($\text{mag }^{-1}$) | ($\text{mag }^{-1}$) | ($\text{mag }^{-1}$) |
| 23        | 2.4              | -0.40$\pm$0.24 | -0.49$\pm$0.29  | 0.02$\pm$0.15               | -0.08$\pm$0.24  |
| 1.1       |                  |                | 2.7 $\pm$ 1.0  | -0.45                      | 0.1 $\pm$ 0.4    |
| 11888     | 2.5              | -0.51$\pm$0.29 | -0.19$\pm$0.31 | 0.16$\pm$0.44               | -0.10$\pm$0.31  |
| 1.6       |                  |                | 3.2 $\pm$ 2.1  | -0.19                      | 0.1 $\pm$ 0.4    |
| 12294     | 4.5              | -1.07$\pm$-     | -1.27           | -0.46                      | -0.10$\pm$0.31  |
| 2.3       |                  | 1.3 $\pm$ 0.3  | -0.73           | 2.0 $\pm$ 0.2               | 0.1 $\pm$ 0.6    |
| 996       | 4.9              | -0.59           | -0.66           | -0.24                      | -0.13$\pm$0.3   |
| 2.6       |                  | 3.0 $\pm$ 1.1  | -0.38           | 2.0 $\pm$ 0.2               | 0.1 $\pm$ 0.6    |
| 2239      | 2.8              | -0.28$\pm$       | -0.22           | -0.24                      | -0.16$\pm$0.3   |
| 1.3       |                  | 1.9 $\pm$ 1.1  | -0.28           | 2.0 $\pm$ 0.2               | 0.1 $\pm$ 0.3    |
| 2286      | 3.2              | -0.42           | -0.55           | -0.72                      | -0.20$\pm$0.3   |
| 1.9       |                  | 1.8 $\pm$ 0.8  | -0.51           | 2.0 $\pm$ 0.2               | 0.1 $\pm$ 0.3    |
| 2361      | 4.3              | -0.54           | -0.83           | -0.30                      | 0.06$\pm$0.3   |
| 4.4       |                  | 3.5 $\pm$ 1.8  | -0.36           | 2.0 $\pm$ 0.2               | 0.1 $\pm$ 0.6    |
| 2196      | 2.0              | -0.70           | -0.86           | -0.52                      | 0.07$\pm$0.3   |
| 2.0       |                  | 3.0 $\pm$ 0.8  | -0.84           | 2.0 $\pm$ 0.2               | 0.1 $\pm$ 0.3    |
| 2543      | 2.0              | -0.73           | -0.68           | -0.67                      | -0.24$\pm$0.3   |
| 2.6       |                  | 3.5 $\pm$ 1.8  | -0.33           | 2.0 $\pm$ 0.2               | 0.1 $\pm$ 0.3    |
| 2111      | 4.9              | -0.76(0.05)     | 0.17(0.3)       | 0.20(0.71)                 | 0.1 $\pm$ 0.3    |
| 3.8       |                  | 1.0 $\pm$ 1.1  | -0.05           | Z$_{\alpha}$ - Z$_{\alpha}$ | 0.1 $\pm$ 0.3    |
| 472       | 8.6              | -0.31(0.83)     | 0.22(0.93)      | 0.20(0.71)                 | 0.1 $\pm$ 0.3    |
| 5.4       |                  | 0.9 $\pm$ 1.4  | 0.18           | Z$_{\alpha}$ - Z$_{\alpha}$ | 0.1 $\pm$ 0.3    |
not localized only in the centre as we have assumed, but also in the periphery, the amount of dust necessary to generate the observed colour gradient would be even higher. The fit of the global SED returns a global value of $A_V = 0.35$, much lower than the one we obtain. Moreover, the amount of dust predicted, which necessarily affects also the emission in the $F_{606W}$ and $F_{850LP}$ bands, produces the $F_{606W} - F_{850LP}$ colour in the central regions of the galaxy redder than the observed one. Thus, for this galaxy, dust does not seem to be the main driver of the observed colour gradients.

For galaxies 2286, 2239 and 2543, the analysis indicates that, in our hypothesis, their colour gradients can be obtained assuming a dust extinction in the central regions of $A_V = 0.55, 0.29$ and $0.83$, respectively. Table 2 shows that for galaxy 2239 the dust extinction we need to reproduce the colour gradient is lower than the one predicted by the fit of the global SED. In contrast, galaxies 2286 and 2543 require a dust extinction $\sim 1.5–2$ times higher than the one obtained from the global SED fitting. These values confirm that for these galaxies, even if not the main driver, a significant contribution of dust in generating the observed colour cannot be excluded.

Finally, for galaxies 996 and 12294 we have obtained $A_V = 1.08$ and $1.53$, respectively, results which disagree with the best-fitting values of 0.10 and 0.25. In these cases, the dust extinction we need to reproduce the observed colour gradients is 6–10 times higher than the one obtained from the global SED fitting, suggesting that, although not possible to exclude at all, the radial variation of dust extinction is certainly not the main driver of the colour variation we observe.

5.2.3 Radial variation of IMF as a possible driver of colour gradients

In the main hypothesis to explain the colour gradients we observe, there is also a change in IMF from the inner to the outer regions of the galaxy.

In spite of the fact that a radial variation of IMF could be a reliable way to produce a colour gradient, it has never been explored due to the lack of suitable stellar population models. For this reason a grid of stellar population models have been kindly produced ad hoc by Stephan Charlot: reproducing the SED of galaxies with different proportions of low- to high-mass stars. In particular we have assumed an IMF analytically described by a power-law form

$$dN/dM \propto M^{-\alpha}$$

with five different values of $\alpha$: 1.5, 2.0, 2.35, 3.0 and 3.5. The value 2.35 corresponds to a pure Salpeter IMF (Salpeter 1955). Fig. 8 shows the relative different amounts of low- to high-mass stars produced by the five IMFs.

The evolution of a star with time is strictly related to its mass. Thus, at fixed age, metallicity, star formation time-scale and dust extinction, the spectral energy emission of a galaxy will change with the IMF due to the different amounts of low- to high-mass stars. Fig. 9 (left-hand panel) shows how the template of the global SED of a possible galaxy of our sample (age = 3.5 Gyr, $\tau = 0.5$ Gyr, $z = 1.6$) would change with different IMFs. To observe the relative differences, we have normalized the observed SEDs in the wavelength range 8250–8750 Å. The colours of the different...
SEDs follow the same code as of Fig. 8. Since we normalized all the curves approximately in correspondence with the F850LP filter, when looking at the emission around 16 000 Å this plot immediately returns how the F850LP − F160W colour changes with the IMF. In particular, for this template, an IMF with a higher abundance of low-mass stars (red line) returns redder colour than the one with a lower number of low-mass stars. Actually, the colour of a star changes through all its life cycle, as it moves on the Hertzsprung–Russell diagram according to its mass. So, the contribution of low- and high-mass stars to the total emission in a fixed band changes at the variation of the ratio age/τ. Fig. 9 (right-hand panel) shows the same plot on the left-hand side but for a galaxy with a different ratio age/τ. This simulated galaxy has age = 1.1 Gyr and τ = 0.1 Gyr. Even in this case, we normalize the curves in the wavelength region 8250–8750 Å. This plot shows how in this case the IMF domain is dominated by the light coming from the high-mass stars in contrast to the previous case. These plots clearly emphasize two main aspects: colours are affected by the IMF, hence the radial colour variation we detect can be effectively due to radial variation of IMF, and the shape of the SED depends on the ratio age/τ and IMF.

To investigate the hypothesis of an IMF radial variation as the main driver of colour gradient, we have adopted the same method as used to study age, metallicity and τ radial variations. For each galaxy, we have fixed the stellar population parameters of the internal and external populations to those derived from the global fit and have looked for the value of the IMF’s slope able to reproduce the observed colour gradients. Since our goal is to investigate the radial variation of low- to high-mass star abundance, we have refitted the observed global SED assuming a Salpeter IMF instead of a Chabrier IMF. In Table 2, the results of the SED fitting with a Salpeter IMF are reported. We have assumed the internal and external populations defined by the new global parameters $A_{\text{global,Sal}}$, $Z_{\text{global,Sal}}$, $A_V$, $Z_{\text{global,Sal}}$, $\tau_{\text{global,Sal}}$ and $\alpha = 2.35$ and we have looked for the value of $\alpha$ to be associated with the internal and external populations, $\alpha_{\text{in}}$ and $\alpha_{\text{out}}$, so that the two populations defined by the set of parameters $A_{\text{global,Sal}}$, $Z_{\text{global,Sal}}$, $A_V$, $Z_{\text{global,Sal}}$, $\tau_{\text{global,Sal}}$, $\alpha_{\text{in}}$, and $A_{\text{global,Sal}}$, $Z_{\text{global,Sal}}$, $A_V$, $Z_{\text{global,Sal}}$, $\tau_{\text{global,Sal}}$, $\alpha_{\text{out}}$, respectively, best reproduce the observed colour gradients and the global SED.

In all but two cases a variation of the abundance of low- to high-mass stars can be excluded as the main driver of the observed colour gradients. In contrast, Fig. 10 shows that for galaxy 2239 an external population accounting for a major part of the mass (>90 per cent) formed with an IMF with $\alpha = 3.0$, that is, with a higher number of low-mass stars than a Salpeter IMF, and a small contribution in mass of an internal population with an IMF defined by $\alpha = 1.5$ can simultaneously reproduce the $F850LP − F160W$ observed colour gradient we have derived, and the observed global SED as well. In the same way, the $F850LP − F160W$ colour gradient and the global SED of galaxy 2543 are well reproduced by a very massive population dominating the internal region characterized by an IMF with $\alpha = 3.5$ and by a small contribution of an external population described by an IMF with $\alpha = 1.5$. As noted before, the different ratio age/τ of these two galaxies reflects in an inverted radial trend of the IMF’s slope to reproduce negative colour gradients. Thus, for these two galaxies, a variation of the slope of the IMF, and hence a variation in the abundance of low- to high-mass stars, can be a possible driver of the radial colour variations we detect. In Table 3, the results of the analysis for all the galaxies of the sample are shown, while in electronic form (see Supporting Information) we present their plots.

6 SUMMARY OF THE RESULTS

We have found that ∼70 per cent (8 out of the 11) of the ETGs in our sample show negative colour gradients at more than ∼2σ (>4σ in five ETGs) in the 0.1–1$R_e$ range, the effective radius range usually adopted to study colour gradients in local ETGs. The remaining 30 per cent show a gradient consistent with a flat colour profile. Extending the analysis to $R > R_e$, enclosing the whole galaxy, we have found that the fraction of high-z ETGs with negative $F850LP − F160W$ colour gradients rises up to 100 per cent. In fact, we have generally found a steepening of colour gradients extending the fit to regions outside $R_e$ ($2R_e < R < 3R_e$).

For six galaxies of our sample (ID 23, 2286, 2239, 2543, 2196, 996), a solely radial variation of the age of the stellar populations can simultaneously reproduce at less than 1σ the observed colour gradients throughout the galaxy and the global SED. For four of these galaxies (ID 2286, 2239, 2196, 2543), radial metallicity variation also can reproduce the colour gradients. In contrast, a radial variation of the star formation time-scale, dust content and abundance of
low- to high-mass stars is able to reproduce both the colour gradients and the global SED in only few of these six galaxies. Moreover, we pointed out that a radial variation of the slope of the IMF is not able to reproduce the observed radial colour variation and spectral emission in any of the four galaxies for which both the $F_{606W} - F_{850LP}$ and the $F_{850LP} - F_{160W}$ colour gradients are available.

These results assign to age and metallicity a central role in generating the observed colour gradients. As pointed out before, a contribution of other parameters to the colour variations we detected cannot be ruled out.

For the remaining five galaxies (IDs 2111, 11888, 12294, 472, 2361), the variation of a single stellar population parameter is not able to reproduce the observed colour gradients and global SED consistently with the findings of Guo et al. (2011) on their sample. This suggests that for these galaxies a simultaneous variation of several parameters has to be invoked to reproduce the observed colour variations and global SED. For these galaxies, an approach that investigates the simultaneous variation of more than one parameter should be considered.

7 DISCUSSION AND CONCLUSIONS

The results of our analysis establish the heterogeneity of the stellar content in high-$z$ ETGs. For $\sim 50$ per cent of the galaxies of our sample (six ETGs), we have found that a pure radial age variation, with the oldest stars located at the centre of the galaxy, is able to reproduce the observed radial colour profile and global SED. The age gradients we have detected for these galaxies span a range of $-0.84$ to $-0.28$ dex per radial decade. For four out of these six ETGs, the colour gradients we have observed can also be accounted for by solely metallicity gradients whose strength varies from $-0.35$ to $-1.45$ dex per radial decade.

Due to the lack of similar measurements on other samples of high-$z$ ETGs, we have compared the age–metallicity gradient values we have found to those observed in the local ETGs.

Studies of ETGs at lower redshift confirm that colour gradients are mainly due to radial metallicity variations. Assuming the age of the stellar populations constant throughout the galaxy, as we did in the case of metallicity gradient analysis, colour gradients in local ETGs turn out to be reproduced by a mean metallicity gradient ranging from $-0.16$ to $-0.3$ (Peletier, Valentijn & Jameson 1990; Idiart, Michard & de Freitas Pacheco 2003; Tamura & Ohta 2003). A further confirmation of the metallicity as a main driver of local gradients comes out from studies at intermediate redshift which show that the colour gradient evolution is better accounted for by the passive evolution of metallicity gradients (Saglia et al. 2000; Hinkle & Im 2001). In fact, our results seem to be inconsistent with these findings. In our sample of high-$z$ ETGs, we have found that only four galaxies out of the 11 have colour gradients well reproduced by pure radial metallicity variation. Moreover, the metallicity gradients we have detected in high-$z$ ETGs ($-0.3$ to $-1.45$) are systematically steeper than those typically observed in local ETGs ($-0.16$ to $-0.3$), even if Ogando et al. (2005) found that this range becomes wider ($0.0$ to $-1.0$) for nearby massive ($M_{\star} > 10^{10} M_{\odot}$) ETGs (see also Spolaor et al. 2009). The steeper metallicity gradients that we have detected derive by a radial metallicity variation from supersolar ($2Z_{\odot}$) values in the inner regions to subsolar values in the external regions ($0.2Z_{\odot}$). Although such extreme values of $Z$ have been observed also in few local ETGs (Mehlert et al. 2003; Rickes, Pastoriza & Bonatto 2008), our results show that metallicity gradients in high-$z$ ETGs of our sample are only marginally comparable with the typical metallicity gradients detected in local ETGs. This result seems to point in favour of a possible evolution of metallicity gradient in the last 9 Gyr.

Concurrently, studies on cluster ETGs at low and intermediate redshift show that pure age variations in their stellar populations are not able to account for their colour gradients (Saglia et al. 2000). In contrast to local results, we have found that for $\sim 50$ per cent of the galaxies of our sample a radial variation of stellar population age alone can reproduce the observed colour gradients and global SED. In fact, recent studies investigating the simultaneous radial variation of both age and metallicity confirm metallicity gradients ($\sim -0.4$ dex per radial decade) as the main driver of observed colour gradients in local ETGs, but also found a small contribution to colour variation of positive age gradients ($\sim -0.1$ dex per radial decade) (Wu et al. 2005; La Barbera & de Carvalho 2009). The age–metallicity degeneracy affecting optical colours does not allow us to consider the simultaneous radial variation of both parameters and hence to detect a possible positive age gradient, whose presence in local ETGs, actually, is still a matter of debate.

To shed light on this issue, high-$z$ ETGs constitute the ideal place to investigate the presence of an age gradient. Indeed, at fixed radial variation of age, $\Delta \tau_{\text{age}}$, its effect on colour profiles is much more enhanced when stellar populations are younger, hence in high-$z$ ETGs. This effect is clearly shown in the left-hand panel of Fig. 11, where we report the differences observed in the $F_{850LP} - F_{160W}$ colour of two stellar populations with age differing by 2 Gyr ($\tau = 0.1$ Gyr, black solid curve), as a function of the age of the youngest stellar population. The same $\Delta \tau_{\text{age}}$ produces a difference in the $F_{850LP} - F_{160W}$ colour of the two populations that is $\sim 10$ times higher if observed in high-$z$ ETGs (age $\leq 4$ Gyr) with respect to those observed in local ETGs (age $\sim 10$ Gyr). A typical radial variation of 2 Gyr, as the one we measure in the ETGs of our sample, will produce in a local ETG a variation in the $F_{850LP} - F_{160W}$ colour of $\sim 0.05$ mag, thus at the very limit of the detection. In contrast, the same age variation will result in a colour variation of $\sim 0.3$–0.5 mag for high-$z$ ETGs. The red and blue lines report the same as the black line, but for pure metallicity variations. In particular, the red line shows the variation in the $F_{850LP} - F_{160W}$ colour observed in two populations with metallicities $2$ and $0.2Z_{\odot}$, while the blue line in two populations with metallicities $Z_{\odot}$ and $0.2Z_{\odot}$.

The right-hand panel of Fig. 11 shows the colour gradient that the above age–metallicity variations would produce when occurring between 0.1 and $3R_{\star}$. Differently from an age variation, the effect of a metallicity variation on colour, and hence on gradient, increases with the age of the galaxy by a factor of $\sim 2$ from high-$z$ ETGs to local ETGs. These plots emphasize how challenging is the detection of an age gradient in local ETGs due to its almost negligible effect on the colour profile. In contrast, in high-$z$ ETGs age and metallicity variations produce comparable effect on the colour profile, thus setting the ideal condition for their detection. This comparison with local samples is only meant to have an indication on how the results obtained at high $z$, both in terms of age–metallicity gradients and in terms of internal and external age–metallicity values, relate with the local values. On the other hand, the unknown evolution experienced by ETGs in $\sim 9$ Gyr from $z \sim 1.5$ to $z = 0$ can affect the stellar properties and distribution (e.g. minor mergers triggering secondary bursts of star formation), making complex any comparison with the local universe. In fact, to properly face on high-$z$ and local values samples of ETGs selected in a homogeneous way, a data set able to trace the evolution of the same rest-frame colour gradient over 9 Gyr, and similar procedures for both the colour gradients estimates and the relative analysis, should be considered. In a forthcoming paper, taking into account all these factors, we will try to address...
the origin of the colour gradients following their evolution from $z \sim 2$ to $z = 0$.

For the remaining five ETGs of our sample, a pure radial variation of a single stellar population parameter is not able to reproduce the observed colour gradients and global SEDs. Differently from the previous cases, where colour gradients could be reproduced by a pure age or metallicity gradient as well as by a simultaneous radial variation of more than one parameter, these galaxies need a more complex scenario whereby more than one property of the stellar populations has to vary from the centre to the periphery to generate the observed colour gradients.

Thus, our analysis clearly indicates that the properties of the stellar population and their distribution within high-$z$ ETGs do not follow a homogeneous and common scheme.

In the following, we try to investigate if the theoretical expectations of the widely accepted scenarios of galaxy formation can explain the observed colour distributions.

In the monolithic revised scenario, colour gradients are supposed to be mainly due to metallicity gradients, being the contribution of age null or mild (and positive). Our findings of no correlation between colour/metallicity gradients and total mass suggest that the monolithic revised scenario is not the favoured mechanism with which ETGs assembled their mass, although the narrow mass range covered and the assumption of the stellar mass as a proxy of the total stellar mass can affect this conclusion.

Theoretical predictions of the inside-out growth scenario point in favour of compact ETGs with cores (Wuyts et al. 2010) redder than the outskirts. This negative colour gradient seems to be due to a combined effect of negative metallicity and positive age gradients, with a non-negligible effect of dust (Wuyts et al. 2010). To compare our results with the theoretical prediction of this model, we define compact galaxies those ETGs with effective radius more than 1σ smaller than those predicted by a local relation for that mass. In contrast, galaxies having the effective radius comparable at 1σ with those expected by Shen et al.’s relations are classified as normal (triangle symbols).

Compact galaxies, as we have defined them, turn out to have $C \geq 2$. In Fig. 12, we report the size–mass relation in the $F850LP$ band for our sample (solid symbols) and for local galaxies (solid line, Shen et al. 2003). The dotted lines represent the scatter at 1σ. We shifted Shen et al.’s relation by a factor of 1.2 towards lower masses to take into account the systematic shift observed in the mass estimations using our models or those adopted by Shen et al. (2003). The circles are compact galaxies, that is, galaxies having the effective radius more than 1σ smaller than those predicted by a local relation for that mass. In contrast, galaxies having the effective radius comparable at 1σ with those expected by Shen et al.’s relations are classified as normal (triangle symbols).
Spatially resolved colours in ETGs at $z \sim 1.5$

1.5 is greater than 4.3 Gyr. Thus, the 2012 The Authors, MNRAS 2698–2714 $F$, measured from numerical simulations. They assumed different initial orbital angular momentum, initial orbital energy and the ratio of initial satellite mass to initial host halo mass and only for two cases they found 3.5 Gyr is enough to complete the merger, while in all the other cases $\tau_{\text{merger}}$ is greater than 4.3 Gyr. Thus, the different stellar content of high-$z$ ETGs does not seem to be due to the effect of subsequent merger events, but primarily due to the formation process. Actually, the continuum distribution of ETGs in the size–mass plane, both at high redshift and in the local Universe, together with the systematic direction of the colour gradient (negative or null) of high-$z$ ETGs, points towards a common formation process responsible for this continuity. The possible different initial conditions, such as the different time-scale of collapsing gas clouds, can be responsible for the observed structural and dynamical differences as we previously suggested (Saracco et al. 2011; Saracco, Gargiulo & Longhetti 2012).

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Figure 13. The $r_{\text{F850LP}}/r_{\text{F160W}}$ ratio as a proxy for the F850LP – F160W colour gradient versus the F850LP – F160W global colour.
SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure 7. Analysis of radial age, metallicity and star formation time-scale variation as a possible driver of observed colour gradients.

Figure 10. Analysis of the radial variation of IMF slope as a possible driver of observed colour gradients.

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