EARLY-TYPE GALAXIES IN THE PEARS SURVEY: PROBING THE STELLAR POPULATIONS AT MODERATE REDSHIFT

IGNACIO FERRERAS1, ANNA PASQUALI2, SANGEETA MALHOTRA3, JAMES RHoads3, SETH COHEN3, ROGER WINDHORST3, NOR PIRZKAL4, NORMAN GROGIN4, ANTON M. KOEKEMOER4, THORSTEN LISKER5, NINO PANAGIA6, EMANUELE DADDI6, AND NIMISH P. HATHI7

1 Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK; ferrer@star.ucl.ac.uk
2 Max-Planck-Institut für Astronomie, Koenigstuhl 17, D-69117 Heidelberg, Germany
3 Department of Physics and Astronomy, Arizona State University, P.O. Box 871504, Tempe, AZ 85287-1504, USA
4 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
5 Astronomisches Rechen-Institut, Zentrum für Astronomie, Universität Heidelberg, Mönchhofstr. 12-14, D-69120 Heidelberg, Germany
6 CEA Saclay, Orme des Merisiers, 91191 Gif-sur-Yvette Cedex, France
7 Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA

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ABSTRACT

Using Hubble Space Telescope (HST)/Advanced Camera for Surveys (ACS) slitless grism spectra from the PEARS program, we study the stellar populations of morphologically selected early-type galaxies in the GOODS North and South fields. The sample—extracted from a visual classification of the (v2.0) HST/ACS images and restricted to redshifts z > 0.4—comprises 228 galaxies (F775W < 24 mag, AB) out to z ≤ 1.3 over 320 arcmin², with a median redshift z_M = 0.75. This work significantly increases our previous sample from the GRAPES survey in the HUDF (18 galaxies over ∼11 arcmin²). The grism data allow us to separate the sample into “red” and “blue” spectra, with the latter comprising 15% of the total. Three different grids of models parameterizing the star formation history are used to fit the low-resolution spectra. Over the redshift range of the sample—corresponding to a cosmic age between 5 and 10 Gyr—we find a strong correlation between stellar mass and average age, whereas the spread of ages (defined by the root mean square of the distribution) is roughly ∼1 Gyr and independent of stellar mass. The best-fit parameters suggest that it is the formation epoch and not the formation timescale that best correlates with mass in early-type galaxies. This result—along with the recently observed lack of evolution of the number density of massive galaxies—motivates the need for a channel of galaxy formation bypassing any phase in the blue cloud, as suggested by the simulations of Dekel et al.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: stellar content

Online-only material: machine-readable tables

1. INTRODUCTION

For nearly a century, we have known that the local galaxy population follows a bimodal color distribution, with a majority of star-forming galaxies and a minority of early-type systems (Hubble 1926; Strateva et al. 2001; Blanton et al. 2003). This distribution (which has been observed up to z ∼ 1; Bell et al. 2004) is commonly interpreted as the outcome of different star formation histories (SFHs), with blue galaxies undergoing a more much prolonged star formation activity than the early types. This does not rule out that early-type galaxies may also experience occasional episodes of star formation at z ∼ 0. However, if they do, they produce an amount (in mass) of young stars definitively lower than the blue-peak galaxies (Trager et al. 2000; Ferreras et al. 2006; Rogers et al. 2007). Early-type galaxies are known to exhibit a tight color–magnitude relation (up to z ≤ 1; Stanford et al. 1998) which is the direct result of a metallicity sequence where more massive galaxies are also metal richer (Bower et al. 1992; Kodama & Arimoto 1997; Vazdekis et al. 2001; Bernardi et al. 2003). The small scatter in their colors and mass-to-light ratios (M/L’s; see, e.g., Kelson et al. 2000), and their relatively high α/Fe (Nelan et al. 2005; Thomas et al. 2005) suggest that early-type galaxies formed the bulk of their stars at high redshift (z ≥ 3); van Dokkum et al. 1998; Thomas et al. 2005) and on a relatively short timescale (i.e., ∼1 Gyr for the more massive galaxies; Thomas et al. 1999). While these properties can be well reproduced by the “monolithic collapse hypothesis” (Eggen et al. 1962; Larson 1974; Lintott et al. 2006), this scenario does not fit well within the currently accepted ΛCDM galaxy formation paradigm, in which galaxies form through hierarchical buildup. In semianalytical models, the hierarchical growth of dark matter structures is complemented by the addition of simple prescriptions of the baryonic physics which describe star formation, chemical enrichment, stellar and active galactic nucleus (AGN) feedback (e.g., Scannapieco et al. 2005; Croton et al. 2006; Hopkins et al. 2006, 2008; Monaco et al. 2007; Somerville et al. 2008). The model predictions are in reasonable agreement with the observed properties of early-type galaxies (see, e.g., Kaviraj et al. 2005; De Lucia et al. 2006; Khochfar & Silk 2006a, 2006b), but they still cannot reproduce the observed high [α/Fe] ratios. On the other hand, support to the merging scenario is given by the detection, at rest-frame UV wavelengths, of recent episodes of star formation in early-type galaxies (Ferreras & Silk 2000; Kaviraj et al. 2007, 2008; Rogers et al. 2007; Schawinski et al. 2007) and by the evidence that less massive early-type galaxies increased their mass by 20%–40% since z = 1 (Bell et al. 2004; Ferreras et al. 2005; Treu et al. 2005a).

We note that all the knowledge collected on early types is primarily based on the nearby galaxy population. Extending the study to a large number of early-type galaxies at intermediate and high redshifts allows us to trace their mass assembly and SFHs in great detail and, consequently, to fine-tune the theory of galaxy formation and evolution. Ferreras et al. (2009a, 2009b)
derived the evolution of number density and size (i.e., half-light radius) for a sample of early-type galaxies between $z = 1$ and $z = 0$, extracted from the GOODS North and South fields (see also Ferreras et al. 2005) and compared it with recent surveys such as GOODS/MUSIC (Fontana et al. 2006), DEEP2 (Conselice et al. 2007; Trujillo et al. 2007), COMBO17 Borch et al. (2006), 2dFGRS (Croton et al. 2005), and SDSS (Shen et al. 2003). They found that massive early types do not exhibit any significant change in comoving number density over the past 8 billion years. In contrast, there exists a noticeable evolution in size, implying an increase of about a factor of 2 for early-type galaxies more massive than $10^{11} M_{\odot}$ and a factor of $\sim 50\%$ for the less massive ones. This result is in agreement with Daddi et al. (2005), Conselice et al. (2007), Trujillo et al. (2006, 2007), Scarlata et al. (2007), van Dokkum et al. (2008), and van der Wel et al. (2008). The latter also found that the $\sigma-R_e$ relation is different for nearby and distant early-type galaxies, suggesting a significant change in the dynamics of these galaxies. Given the exposure times needed for accurate velocity dispersions in these galaxies, it does not come as a surprise that the amount of evolution of the velocity dispersion is still controversial (see, e.g., Cenarro & Trujillo 2009; van Dokkum et al. 2009; Cappellari et al. 2009). Comparison with the semianalytical models of Khochfar & Silk (2006a, 2006b)—where galaxy growth occurs via dissipative major mergers—suggests that the constant comoving number density at high $M_*$ is due to a balance between the “sink” (i.e., loss due to mergers of massive galaxies producing more massive galaxies) and the “source” terms (i.e., gain from mergers at lower mass) in the $0 < z < 1$ range. Ferreras et al. (2009a) also showed that the slope of the Kormendy relation in the $0.4 < z < 1.4$ range is consistent with $z = 0$ values (see also Ziegler et al. 1999; Waddington et al. 2002). Only the average surface brightness is seen to change, according to pure passive evolution of old stellar populations.

The fact that stellar populations in early-type galaxies undergo passive evolution is confirmed by their colors and photometric spectral energy distributions (SEDs). Morphologically selected early-type galaxies have been so far identified in clusters up to $z \approx 1.4$ and their colors have been proven to be consistent with those of $z = 0$ early types through pure passive evolution of their stars (see, e.g., Dressler & Gunn 1990; Aragón-Salamanca et al. 2003; Rakos & Schombert 1995; van der Marel & van Dokkum 2007; Cool et al. 2008; Whiteley et al. 2008). Ellis et al. (1997), Stanford et al. (1998), and Blakeslee et al. (2003) showed that early-type galaxies in clusters at $z \sim 0.5$–1.2 complete their star formation by $z \gtrsim 3$ (see also Ferreras et al. 1999; Gladders et al. 1998; Kodama et al. 1998; Nelson et al. 2001; van Dokkum et al. 2000). The same can be said for the most massive early-type galaxies ($M_* > 10^{11} M_{\odot}$) in the field at the same redshift, while the less massive ones appear to sustain a more prolonged star formation (see, e.g., Bell et al. 2004; van der Wel et al. 2004, 2005; van Dokkum & Ellis 2003; McIntosh et al. 2005; Treu et al. 2005a, 2005b).

Although photometric colors and SEDs are clearly the most affordable observables to obtain in terms of telescope time, they do not disentangle between age and metallicity effects as accurately as spectra and line indices. The measurement of the Mg$b$ index and of the H$_\delta$ and H$_\gamma$ strength in early-type galaxies up to $z = 0.83$ has independently provided $z > 2$–3 as the redshift at which their stars formed (Ziegler & Bender 1997; Kelson et al. 2001). Spectroscopy from the ground has made also possible to use a set of Fe$\text{II}$, Mg $\text{II}$, and Mg $\text{I}$ lines in the rest-frame UV and identifies massive early-type galaxies ($M_* > 10^{11} M_{\odot}$) up to $z \sim 2.15$ (Cimatti et al. 2004; Glazebrook et al. 2004; McCarthy et al. 2004; Saracco et al. 2005). In particular, Cimatti et al. (2004) stacked together the rest-frame UV spectra of four early-type galaxies with $1.6 < z < 1.9$ and compared the average with synthetic spectra of simple stellar populations (SSPs) to find a mean stellar age of about 1 Gyr for solar metallicity (or better 0.5 Gyr $< z < 1.5$ Gyr for $2.5 > Z/Z_{\odot} > 0.4$). Similarly, Cimatti et al. (2008) combined the spectra of 13 early-type galaxies at $z = 1.6$ and determined a mean stellar age in the range 0.7–2.8 Gyr for $Z = 1.5$–0.2 $Z_{\odot}$, corresponding to a formation redshift $z_F > 2$. Along this line, Kriek et al. (2008) averaged the rest-frame optical spectra of 16 early-type galaxies at $2 < z < 3$ to find the typical SED of a poststarburst galaxy with an age of about 1 Gyr for solar metallicity. They concluded that early-type galaxies are likely to form between $z = 2$ and 3 and are not yet in place at $z = 3$ (see also Dunlop et al. 1996; Spinrad et al. 1997; Driver et al. 1998; Brummer & van Dokkum 2007; Kodama et al. 2007).

At redshifts $z \gtrsim 1$, though, the performances of ground-based spectrographs is severely limited by the atmosphere and its OH lines, and also by the optical faintness of the targets ($I \gtrsim 23$ mag). The high-redshift population of early-type galaxies is, thus, best investigated from space with low-resolution spectroscopy. This is the case of the Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS), which is equipped with a slitless grism covering the spectral range 5500–10500 Å with a dispersion of 40 Å pixel$^{-1}$ in the first spectral order (Pasquali et al. 2006a). The HST/ACS grism has been used for spectroscopic surveys like GRAPES (Piz Kazlak et al. 2004) and PEARs (S. Malhotra et al. 2009, in preparation), where early-type galaxies brighter than $I \lesssim 26$ mag have been identified up to $z = 2.5$ and their individual spectra (typically with signal-to-noise ratio (S/N) $> 10$ pixel$^{-1}$) have been analyzed to constrain their stellar populations. The low resolution of these spectra clearly prevents us from measuring line indices, but allows us to detect the broad feature Mg UV in the rest-frame 2640–2850 Å (Daddi et al. 2005; Maraston et al. 2006) at $z > 1.3$ and measure the Mg$b$ break at 0.4 $< z < 1.2$ and use it along with the continuum to estimate stellar ages and metallicities down to $M_* \approx 10^9$–$10^{10}$ $M_{\odot}$ (Pasquali et al. 2006b). This limiting stellar mass is a factor of about 10 lower than what can be achieved with ground-based spectroscopy, and makes it possible, for the first time, to study the stellar populations at the faint end of the red sequence at $z \sim 1$. For example, Pasquali et al. (2006b) identified 18 early types in the Hubble Ultra Deep Field (Beckwith et al. 2006) with $0.49 \lesssim z \lesssim 1.15$. They fitted the individual HST/ACS grism spectra with synthetic SFHs, based on the models of Bruzual & Charlot (2003) and including chemical enrichment (Ferreras & Silk 2003). They found stellar ages varying from 3–4 Gyr at $z > 0.65$ to 5–6 Gyr at lower redshifts, stellar metallicities between 1 and 0.03 $Z_{\odot}$ and stellar masses between $3 \times 10^9$ and $3 \times 10^{11} M_{\odot}$. The estimated ages are consistent with a formation redshift $z \gtrsim 2$–5.

In this paper, we extend the analysis of Pasquali et al. (2006b) to a sample of early-type galaxies that is a factor of 11 larger than in the HUDF. The objects—228 in total—are extracted from the sample of morphologically selected early-type galaxies of Ferreras et al. (2009a) in the GOODS North and South fields and have been observed as part of PEARs.\footnote{http://archive.stsci.edu/prepds/pears/} This is the largest...
database of individual, high-S/N grism spectra obtained so far for early-type galaxies at $z \sim 1$, that allows a study of their stellar populations as a function of stellar mass and redshift, and can place more stringent constrains on the formation and evolution of (not only massive) early-type galaxies since $z \sim 1$. Throughout this paper, a standard $\Lambda$CDM cosmology from the VVDS five-year data is used to determine ages and rest-frame properties (Komatsu et al. 2009).

2. COLLECTING THE SAMPLE OF EARLY-TYPE GALAXIES

The data consist of ACS images taken with the WFC G800L grism. The PEARs survey comprises eight pointings toward the GOODS North and South fields—four pointings each—with three HST roll angles for each pointing (20 HST orbits per field), plus the HUDF with four roll angles (40 HST orbits). A forthcoming paper (S. Malhotra et al. 2009, in preparation) will describe the PEARs project and data in detail. The HUDF data come from an earlier similar project, GRAPES (Pirzkal et al. 2004; Pasquali et al. 2006b). We use the PEARs IDs from the master catalog of source extractions. The G800L grism produces slitless, low-resolution spectra in the wavelength range 6000–1000 Å. The optimal spectral resolution ($R \sim 100$) is achieved for unresolved sources, whereas for our sample of early-type galaxies, the effective resolution is lower, around $R \sim 50$.

The master catalog of PEARs detections was cross-correlated with the sample of 910 visually classified early-type galaxies in the GOODS North and South fields of Ferreras et al. (2009a). This sample completes the one presented previously in the CDFS field (Ferreras et al. 2005). The selection consists of visual inspection (in all four ACS bands) of all source detections brighter than $i_{775} \leq 24$ mag (AB) by four people, with two rounds of visual inspection for those galaxies that were harder to classify. No color cuts or CAS-based selections were made, although the sample is consistent with the high concentration and low asymmetry expected in spheroidal galaxies with respect to later morphological types (T. Lisker et al. 2009, in preparation). Furthermore, the visually classified sample comprises 80% of red, quiescent stellar populations. We believe visual inspection alone is much more efficient at selecting spheroidal galaxies, eliminating contamination from late-type galaxies or unresolved sources, and removing the bias inherent in color-based selection methods. From this catalog, we extract the available PEARs spectra of each identified object from our database. The spectra are background corrected and scaled to match the direct image magnitudes of each object. Each file contains the spectra extracted for the different position angles (P.A.’s; typically around three P.A.’s per galaxy). We compute a simple average of the spectra available for each object, possibly excluding those P.A.’s whose spectra are clearly deviant. The errors in the final combined spectra are computed by propagating the flux errors in each individual SED. The spectra were visually inspected, and some of them had to be discarded because of a very low S/N, contamination from nearby sources, or because they were located close to the edge of the field. Out of the original sample of 910 galaxies (533 in HDFN and 377 in CDFS), we extracted 136 spectra in the North and 131 in the South. The number of rejected galaxies is 19 and 18 in the North and South fields, respectively.

Regarding redshift, we start with estimates from the PEARs-based general catalog of photometric redshifts (S. Cohen et al. 2009, in preparation; see also Cohen et al. 2009), and the photometric redshift catalog of Mobasher et al. (2004) and Ferreras et al. (2009a). Spectroscopic redshifts are available from FORS2 (Vanzella et al. 2008) and the VIRMOS-VLT Deep Survey (VVDS; Poppesso et al. 2009) in the South, and from the Team Keck Redshift Survey (TKRS; Wirth et al. 2004) in the North. However, our slitless grism data have enough S/N to allow for an estimate of the redshifts directly from the low-resolution spectra. Two of us (I.F. and A.P.) inspected visually each SED and compared it with a number of template spectra to determine a rough estimate of the redshift. Then, we ran a simple code that uses the guess and templates to accurately determine the redshift via a standard maximum likelihood method. The accuracy of our redshifts is as good as spectroscopic estimates for most of the galaxies, especially those with a prominent 4000 Å break (i.e., the majority of the sample) or those with emission lines. Incidentally, some of our (grism-based) redshift estimates improved on the spectroscopic values from pipeline-processed databases such as GOODS/FORS2. This improvement is to be expected for the faintest galaxies with a quiescent spectra. In those cases, the continuum from the ground-based spectroscopic data is very noisy and, simply put, our low-resolution spectra yield more photons per pixel over the CCD, significantly improving the signal. Hence, we consider our quoted redshifts as spectroscopically accurate.

Finally, we apply a cut in redshift, removing from the analysis all galaxies with redshift $z < 0.4$. At those redshifts the 4000 Å break—on which the modeling strongly relies—falls outside of the sensitivity region of the G800L grism. This cut reduces the sample to 124 and 104 galaxies in the North and South fields, bringing the total to 228 early-type galaxies with $z \geq 0.4$ and $i_{775} \leq 24$ mag (AB). The median redshift of the sample is $z_m = 0.75$. If we measure the S/N as the average S/N per pixel over the spectral window 8000–8500 Å our sample has a median value of S/N $\sim 15$ pixel$^{-1}$.

2.1. Sample Properties

The main observational data are presented in Table 1. Figure 1 shows the distribution of total apparent magnitude (top) and size (half-light radius; bottom). The original sample of visually classified galaxies from Ferreras et al. (2009a) is shown as small dots. The PEARs sample of early-type galaxies is shown as circles. We subdivide the sample into “red” (gray dots) and “blue” types (open circles). This classification is taken from the original data and is determined by the spectral template that gives the best fit in the analysis of photometric redshifts. For the PEARs sample presented here, the division is much more accurate because this information is complemented by the visual appearance of the low-resolution SED. “Red” galaxies feature prominent 4000 Å breaks, whereas “blue” galaxies have a clear blue continuum with the occasional presence of emission lines. The sample comprises 195 “red” and 33 “blue” spheroidal galaxies. The accuracy of the total magnitudes and half-light radii is estimated from simulations of synthetic galaxies with Sersic profiles with similar values of size and magnitude as the original sample. We recover the original values with an uncertainty $\Delta i_{775} = 0.05$ mag and $\Delta R_e / R_e = 0.09$ (Ferreras et al. 2009a). We overlay “x” symbols over those galaxies with an X-ray detection from the Chandra Deep Fields North and South (Alexander et al. 2003; Luo et al. 2008). Twenty-two sources have an X-ray detection which extends over the full range in apparent magnitude. It is worth emphasizing that all X-ray-detected sources in our sample are photometrically classified as “red” galaxies.
The distribution of rest-frame properties of our sample is shown in Figure 2, where the absolute magnitude in the $V$ band (top), stellar mass (middle), and physical half-light radius (bottom) is shown with respect to redshift. The $K$-correction and the $M/L$ estimate needed for the top two panels is taken from the best-fit models of the runs explained in Section 3. The “red” (“blue”) galaxies are shown as filled gray (open black) circles. “Blue” early types are mostly faint, low-mass galaxies. We should emphasize that our selection process (visual classification) does not introduce any bias regarding the color distribution. The lines in the top panel correspond to the $i_{F775W} < 24$ mag limit imposed on the original sample. Since the translation from apparent to absolute magnitude depends on the template SED for the $K$-correction, we show the apparent magnitude limit corresponding to two types of populations: quiescent (solid line) and young (dashed line). These two cases are the extrema of the photometric types used in Ferreras et al. (2009b), namely, $t = 0$ and $t = 7$. These types correspond to an exponential SFH at fixed solar metallicity, beginning at a formation redshift $z_{F} = 3$ with timescale $\tau = 0.05$ Gyr ($t = 0$) or $\tau = 8$ Gyr ($t = 7$). Similarly to Figure 1, the “$\times$” symbols are overlaid on those galaxies with an X-ray detection from the Chandra Deep Fields (Alexander et al. 2003; Luo et al. 2008). Almost all X-ray detections correspond to “red” galaxies. The dashed line in the bottom panel illustrates the resolution limit at $2R_{e} \sim$ FWHM$_{HST}/$ACS. The solid line is the surface brightness limit, considering the cosmological dimming, at $i_{AB} = 24$ mag (AB), assuming a surface brightness at $z = 0.7$ of $\mu_{F775W} = 22$ mag arcsec$^{-2}$.

Local galaxies appear significantly larger and with higher $M/L$. The latter can be explained by pure passive evolution of the stellar populations, but the change in size requires a mechanism beyond stellar evolution. This result is shown for the full sample of GOODS spheroidal galaxies in Ferreras et al. (2009b) and confirms previous results at similar or higher redshifts $z < 0.4$, we end up with the sample presented in this figure (circles): 91+13 (CDFS) and 104+20 (HDFN) galaxies. The first number represents those with a “red” SED (gray filled circles): prominent 4000-break and no emission lines. The second number corresponds to “blue” SEDs (open circles, see the text for details). We overlay an “$\times$” symbol on those galaxies with an X-ray detection from the Chandra Deep Fields (Alexander et al. 2003; Luo et al. 2008). Note that all X-ray detections correspond to “red” galaxies. The dashed line in the bottom panel illustrates the resolution limit at $2R_{e} \sim$ FWHM$_{HST}/$ACS. The solid line is the surface brightness limit, considering the cosmological dimming, at $i_{AB} = 24$ mag (AB), assuming a surface brightness at $z = 0.7$ of $\mu_{F775W} = 22$ mag arcsec$^{-2}$.

The rest-frame $U−V$ color–magnitude and color–stellar mass relations are presented in Figure 4, with the same coding for photometric type as in the previous figures. Note color is correlated more strongly with stellar mass than with absolute magnitude. The dashed line gives the Coma color–magnitude relation from Bower et al. (1992) for E+S0s. The extent of the line covers the magnitude range probed in Coma. The relation at high redshift is in good agreement with Coma if we consider that passive evolution of a stellar population with

### Table 1

| PID | R.A. | Decl. | $i_{F775W}$ | $R_{e}$ | $z$ | R/B |
|-----|------|-------|-------------|--------|-----|------|
|     |      |       | (AB)        | (pixel) |     |      |
| 6560 | 53.1649933 | $-27.819334$ | 21.37 | 17.33 | 0.97 | R     |
| 56798 | 189.1671143 | $+62.218311$ | 20.70 | 11.04 | 0.48 | R     |
| 83499 | 189.1973572 | $+62.274567$ | 21.57 | 13.30 | 0.85 | R     |

Notes:
- PEARs ID number.
- “Red” versus “blue” early type (see the text for details).
- 1 pixel = 0.03 arcsec.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 2. Rest-frame properties of PEARS early-type galaxies. The sample is shown with respect to absolute V-band magnitude (top), stellar mass (middle), and projected half-light radius (bottom). The masses and magnitudes are computed using the best-fit SFH. “Red” and “blue” galaxies are represented by filled and open circles, respectively. The solid lines at the top panel track the $i_{AB} = 24$ mag cut in apparent magnitude for two extreme cases: an old, passively evolving population (solid) or an extended star formation history (dashed). The small dots correspond to the original sample of visually classified spheroidal galaxies from Ferreras et al. (2009a). We overlay an “×” symbol on those galaxies with an X-ray detection from the Chandra Deep Fields North and South (Alexander et al. 2003; Luo et al. 2008).

Figure 3. Comparison of half-light radius ($R_e$; top) and V-band $M/L$ ($\Upsilon_V$ with respect to the solar value; bottom) with a $z \sim 0$ sample of galaxies with Sersic index $n_S > 2.5$, extracted from the SDSS NYU Value Added Galaxy Catalog (gray dots; Blanton et al. 2005). The half-light radius (top) and $M/L$ in the V band is shown as a function of stellar mass (left) or absolute magnitude. “Red” (“blue”) PEARS galaxies are represented as black solid (open) circles.

Figure 4. Rest-frame $U−V$ color–magnitude relation (right) and color–stellar mass relation (left). Filled (open) circles correspond to photometric “red” (“blue”) galaxies. The dashed line gives the $z \sim 0$ color–magnitude relation of Coma early-type galaxies from Bower et al. (1992).

Figure 5. Quantitative morphology of the PEARS early-type galaxy sample. The plot shows the concentration, $M_{20}$ (a normalized second order moment of the 20% brightest pixels) and asymmetry. Filled (gray black open) circles correspond to “red” (“blue”) spheroidal galaxies. See the text for details.

Figure 6. Rest-frame $U−V$ color–magnitude relation (right) and color–stellar mass relation (left). Filled (open) circles correspond to photometric “red” (“blue”) galaxies. The dashed line gives the $z \sim 0$ color–magnitude relation of Coma early-type galaxies from Bower et al. (1992).

3. MODELING THE STAR FORMATION HISTORIES OF GALAXIES

Our slitless spectra have good enough S/N down to the $i_{775W} = 24$ mag (AB) limit of the original sample. The S/N ranges from 30 down to 4–5 pixel$^{-1}$ at the limiting magnitude. One of the main advantages of G800L grism data for the analysis...
presented here is the superb flux calibration of the spectra enabled by the optimal flat fielding of the images. We estimate flux calibration systematic errors below 5% within the spectral range of interest (Pirzkal et al. 2004).

The wavelength coverage of the ACS/G800L grism (6000–9500 Å) is ideally suited for the analysis of old stellar populations at $z = 0.4–1.5$, because the prominent 4000 Å break falls within its sensitivity range. Furthermore, the compact nature of early-type galaxies and their homogeneous stellar populations minimizes the contamination and loss of spectral resolution compared to slitless grism data of late-type or irregular galaxies.

### 3.1. Methodology

We follow a standard likelihood method fitting the low-resolution spectra to grids of models. A proper extraction of the age and metallicity distribution requires the use of composite models of stellar populations. SSPs (i.e., models with a single age and metallicity) will give luminosity-weighted age estimates that can differ significantly from a more physical mass-weighted age according to a composite stellar population (Ferreras & Yi 2004; Pasquali et al. 2005; Serra & Trager 2007; Rogers et al. 2009). In order to assess systematic differences related to the parameterization of the SFHs, we consider the following four models (whose parameters are summarized in Table 2).

1. **Simple stellar populations (SSPs).** SSPs are the building blocks of any population synthesis model. They correspond to a stellar population with a single age and metallicity. Although SSPs are often a fair approximation of a globular cluster, the longer timescales and more complex chemical enrichment history of a galaxy make an SSP a very rough approximation in this case. Furthermore, the fact that a single age and metallicity are used to fit the data can introduce a significant difference between the SSP determine age and a more physical mass-weighted age. Nevertheless, we include these models in the analysis for comparison, given that they are the simplest models from which the composite models are generated. This case explores a grid of $128 \times 128$ SSPs over a wide range of ages and metallicities, as given in Table 2.

2. **$\tau$-model (EXP).** The SFH is described by an exponentially decaying function, with a timescale ($\tau$) and a formation redshift ($z_F$), corresponding to the epoch at which star formation starts. The metallicity is the third free parameter and it is kept constant throughout each SFH.

3. **Two-burst model (2BST).** Superposition of two SSPs, described by four parameters: the age of the old ($t_0$) and the young components ($t_F$), the mass fraction in young stars ($f_Y$), and the metallicity of the system (assumed to be the same for both populations).

4. **Chemical enrichment model (CSP).** We follow a consistent chemical enrichment code that incorporates the evolution of metallicity with the star formation rate. The model is defined in Ferreras & Silk (2000) and was previously applied to similar data from the GRAPES sample of early types and bulges in the HUDF (Pasquali et al. 2006b; Hathi et al. 2009). The formation history is described by four parameters: a star formation efficiency ($\nu$) controlling the transformation of gas into stars via a Schmidt law, an outflow parameter ($\beta$) which is the mass fraction of gas ejected as a result of the ongoing star formation rate, the exponential timescale of gas infall ($t_F$), and the formation epoch given by the redshift ($z_F$) at which infall starts.

### Table 2

| Model/Param | Min  | Max  | Comments |
|-------------|------|------|----------|
| SSP         |      |      | Age      |
| $t$ (Gyr)   | 0.1  | 2    |          |
| log($Z/Z_\odot$) | -1.5 | +0.3 |          |
| tO          | 2    |      |          |
| $z_F$ (Gyr) | 0.1  | 2    | Young    |
| $f_Y$       | 0.0  | 1    | Mass fraction |
| log($Z/Z_\odot$) | -1.5 | +0.3 |          |
| EXP         |      |      | Metallicity |
| log $\tau$ (Gyr) | -1  | +0.6 | Exp. Timescale |
| $z_F$ (Gyr) | 0.1  | 2    | Young    |
| $f_Y$       | 0.0  | 1    | Mass fraction |
| log($Z/Z_\odot$) | -1.5 | +0.3 |          |
| 2BST        |      |      |          |
| $t_o$       | 2    |      |          |
| $z_F$ (Gyr) | 0.1  | 2    | Young    |
| $f_Y$       | 0.0  | 1    | Mass fraction |
| log($Z/Z_\odot$) | -1.5 | +0.3 |          |
| CSP         |      |      |          |
| $\nu$ (Gyr$^{-1}$) | 20  |      | SF efficiency (fixed) |
| $t_F$ (Gyr) | -1  | +0.6 |          |
| $\beta$ (Gyr$^{-1}$) | 0  | 1   | Outflow fraction |
| $z_F$ (Gyr) | 0.1  | 2    | Formation epoch |

Notes:

1. **SSP, 2BST:** the oldest age possible for the old component corresponds to a formation redshift $z_F = 10$ at the redshift of the galaxy, e.g., 6.7 Gyr for a $z = 0.7$ galaxy.
2. **EXP, CSP:** the latest formation redshift available corresponds to the observed redshift of the galaxy minus 0.1 Gyr, e.g., $z_F > 0.72$ for a $z = 0.7$ galaxy.

For a given choice of parameters, the models determine the distribution of stellar ages and metallicities. These distributions are used to combine SSPs from the latest 2007 models of Charlot & Bruzual (hereafter CB07; Bruzual & Charlot 2003; Bruzual 2007, latest models in preparation), assuming a Chabrier initial mass function (Chabrier 2003). Note that the CB07 models have been recently updated with respect to the high-resolution spectra. However, at the low-resolution grism spectra considered in this paper, the difference between CB07 and the expected CB09 models is negligible (S. Charlot, private communication). The resulting spectra are degraded to the slitless PEARS SED, and compared via a standard maximum likelihood method. Each model is explored on a grid comprising between 32,000 and 65,000 realizations for a range of parameters as described in Table 2. The best-fit model is used to determine the age and metallicity of the underlying populations, and the $M/L$ required to translate flux into stellar mass.

### 3.2. Extracting Star Formation Histories

Figures 6 and 7 show some of the best fits of the CSP models for the “red” and “blue” galaxies, respectively (see Table 3 for a list of the model predictions). The model SED is shown as a solid black line, and the observed SED is shown in gray (including the 1σ uncertainty as dashed lines). Note that “blue” galaxies have emission lines, most notably [O ii], [O iii], and Hβ. These lines are masked out in the likelihood analysis. The blue spectra show a significant range of ages, from large 4000 Å breaks (as in PID 119723) to very young stars (e.g., 47252). In this paper, the analysis only deals with stellar populations, hence the presence of an AGN could significantly alter the estimated ages of the “blue” galaxies. Nevertheless, Figure 2 shows that the subsample of “blue” galaxies is dominated by low-mass systems, for which one would expect a significant contribution to blue light from young stellar populations. One could argue that these low stellar mass estimates are biased because of the
contribution from the AGN. However, the apparent magnitude of all “blue” galaxies in our sample is consistently fainter than “red” galaxies (see Figure 1). The “red” subsample (Figure 6) looks much more homogeneous, with a prominent 4000 Å break and no emission lines. The SEDs also display the characteristic dip around the G band (rest-frame 4300 Å) and for the lower redshift galaxies one can also discern the Mg feature at rest-frame 5170 Å (see, e.g., PID 122743 or 127697 in Figure 6). Needless to say, the low resolution of the G800L grism prevents us from doing any analysis of the absorption lines. However, the “smoothed-out” features of these spectra can contribute to constraining the age and metallicity distribution. Indeed, higher resolution spectra ($R \sim 2000$) of Virgo elliptical galaxies at very high S/N ($S/N > 100$ Å$^{-1}$) has shown that independent fits to the equivalent widths or a direct fit to the SED give age distributions that are in good agreement (Rogers et al. 2009).

4. RESULTS AND CONCLUSIONS

Figure 8 shows the (mass-weighted) average age (top), age scatter (defined as an rms, middle), and metallicity (bottom) as a function of stellar mass for three bins in redshift (top panel). These estimates correspond to the CSPs. The best-fit SFH from the models is used to compute the average and rms of the age distribution. “Red” and “blue” early types are shown as filled gray or open black circles, respectively. Characteristic error bars are included. The figure includes simple fits to the age distribution for the lowest redshift sample (black line in the top left panel) and the highest redshift bin (black line in the top right panel). The lines in gray are just copies of these two lines in the other panels, to guide the eye. The arrow in the top right panel is the expected age difference between the high- and the low-redshift bin (i.e., pure passive evolution).

The figure allows us to understand the blue-cloud-red sequence diagram of the sample. Our blue-cloud spheroidal galaxies are younger systems with roughly similar metallicities to the red-sequence distribution. It is worth mentioning that the CSP models suggest that all our galaxies have a similar spread of stellar ages, and it is only the average age that correlates with stellar mass. This result is consistent with the more detailed analysis of Rogers et al. (2009) on high-S/N spectra of elliptical galaxies in the Virgo cluster. The lines shown in the top panel illustrate that passive evolution over this redshift range can explain the “red” spheroidals—which represent the large majority of the sample. The average ages of the subsample at lower redshift ($0.35 \leq z \leq 0.67$; top left) suggest that the correlation between stellar age and mass is such that instead of a monotonic trend, the scatter in age increases in galaxies with stellar masses below $10^{10} M_\odot$ (see, e.g., Caldwell et al. 2003; Gallazzi et al. 2008; Yamada et al. 2006; Rogers et al. 2009).

In order to check systematic effects arising from the specific way to parameterize the models, we compare in Figure 9 the average age and metallicity distribution of the three models considered. There is overall good agreement between the CSP and the EXP models (top panels), whereas the age and metallicities of SSP and 2BST models differ significantly with respect to CSP models. Quite often, SSP ages are younger than the average ages of the CSP models, however, some of the SSP ages are older than those for a composite model. This is compensated by a lower metallicity, as the best fit wanders along the age–metallicity degeneracy. We should emphasize that CSP models include a range both in the age and the metallicity distribution. Composite models have been found to give more realistic metallicity constraints than SSPs (Ferreras & Yi 2004). However, we cannot look into the reduced $\chi^2$ values to rule out one model against another: all models give equally acceptable values of $\chi^2_{\nu} \sim 1$. Observations at higher spectral resolution dot not fare better at disentangling this degeneracy (Rogers et al. 2009), but see Koleva et al. (2008).

It is also worth mentioning that for the composite models (2BST, EXP, and CSP) there is good agreement between the best-fit metallicities for the red galaxies—with a realistic
Figure 6. Sample of best fits to the grism data of “red” early-type galaxies using models with chemical enrichment (CSP). Fits to the other two models considered in this paper (EXP and 2BST) do not differ much from these. The observed SEDs are shown in gray, including a 1σ error envelopes (dashed lines). The model fits are shown as black solid lines. Each galaxy is labeled (from top to bottom) by their PEARS ID, $i_F$ magnitude and redshift.

Figure 7. Same as Figure 6 for a sample of “blue” early-type galaxies. The fits also correspond to CSP models. In this case, the fitting method excludes spectral windows of size ±100 Å around $[O\text{III})$, $[O\text{II})$, Hβ, and Hα lines whenever the redshift moves them into the spectral range of the grism data (see Straughn et al. 2008 for details of emission line galaxies in the PEARS HUDF spectra).
Figure 8. Best-fit average age (top), age spread (middle, defined as the rms of the distribution), and metallicity (bottom) for CSP models. The lines in the top panel are simple least-square fits to the red galaxies for the lowest and highest redshift bins. These lines are shown in black for the subsamples where the fit was done. The gray lines are copies of these two fits, to guide the eye. The arrow in the top right panel corresponds to the look-back time between the median redshift of the high- and low-redshift bins. On the left panels, characteristic error bars are shown. “Red” (“blue”) early-type galaxies are shown as gray filled (black open) circles.

Figure 9. Comparison between the predicted average ages and metallicities for the models explored in this paper (see the text for details). The solid line gives the 1:1 mapping. Solid (open) circles correspond to “red” (“blue”) early-type galaxies.
Our “blue” early types have formation what mainly correlates with stellar mass to give the age–mass (our present age)—it is the formation epoch (top middle panel) to a cosmic age between 5 and 10 Gyr (with 13.5 Gyr being $z_{\text{F}}$). This is consistent with the observed increase of the recent star formation in spheroidal galaxies with redshift (Kaviraj et al. 2008), and can be related to merging processes (Sánchez-Blázquez et al. 2009).

Although our work improves on the analysis, since we use SEDs instead of photometry to constrain the age distribution, and we consider a large volume of parameter space to describe the SFH.

The old populations found in massive early-type galaxies in combination with the lack of number density evolution (see, e.g., Ferreras et al. 2009b) confirm that red-sequence spheroidal galaxies with masses above $\sim 10^{11} M_{\odot}$ have the bulk of their stellar populations formed at $z_{\text{F}} \gtrsim 3$. This result confirms previous findings (see, e.g., Tantalo et al. 1996; Vazdekis et al. 1997; Pérez-González et al. 2008; Wiklind et al. 2008; Mancini et al. 2009) although our work improves on the analysis, since we use SEDs instead of photometry to constrain the age distribution, and we consider a large volume of parameter space to describe the SFH.

The old populations found in massive early-type galaxies in combination with the lack of number density evolution (see, e.g., Ferreras et al. 2009b) confirm that new channels must be involved to explain the presence of galaxies on the red sequence at the massive end. In analogy to the cartoon version of the galaxy evolution tracks A–C in Figure 10 of Faber et al. (2007), we propose a new one (track D) in the right panel of our Figure 12. Tracks A–C (left panel) follow the standard growth via wet mergers on the blue cloud, followed by quenching of star formation (the near vertical black arrow) after which growth to the top of the red sequence consists of dry mergers (white arrow). This option is still controversial, since different semianalytic models predict a very different redshift evolution of the number density (Ferreras et al. 2009b; Hopkins et al. 2009a). On the other hand, the recent work of Dekel et al. (2009) based on the
Mare Nostrum cosmological simulations suggests a significant amount of massive galaxy growth via cold accretion at the intersection of cosmic filaments. This process would bypass the evolution in the blue cloud, as visualized by our track D on the right panel of Figure 12. In this case, most of the stellar component in a massive galaxy would grow in situ, over a short and early period, explaining the old populations found in massive galaxies (i.e., the “explosion” symbol in our track D). Furthermore, this process would be very efficient, turning gas into stars over short timescales, thereby explaining the small infall timescales found (Figure 11). The fact that formation epoch correlates with stellar mass would indicate the connection by Dekel et al. (2009) would dominate at the most massive end. Additionally, this process would be very efficient, explaining the small infall timescales found (Figure 11). The best-fit values range between $z \sim 0.5$ and $z_F \sim 10$, as expected in hierarchical formation scenarios that produce a broad peak in the cosmic SFH at $z \sim 1–2$. However, we also note that the highest formation redshifts pile up either between $z_F \sim 7–8$ or around $z_F \sim 10$. While the estimates of the SFH at $z \sim 1–2$ are not accurate enough to state the difference between the epochs $z_F \sim 7–8$ and $z_F \sim 10$ with any great confidence, it is tempting to note that these redshifts coincide remarkably well with the epochs in WMAP-year 5 cosmology where the peak of the Pop III star formation should have occurred at $z \sim 10.8 \pm 1.8$ in order to produce the WMAP-year 5 polarization optical depth (Dunkley et al. 2009), and with the epoch of $z_F \sim 7–8$ in which the global component of Pop II stars should have started shining in dwarf galaxies in order to finish reionization by $z \sim 6$. Future data and modeling should concentrate on whether these epochs can be defined any more accurately than possible here. This analysis may be feasible with the upcoming HST/WFC3 grism spectra of the earliest type galaxies at $1 \leq z \leq 3$ in the near future.

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Figure 12. Our proposed additional channel for the formation of galaxies on the red sequence is shown as “D track” (right), in comparison with the standard picture from Faber et al. (2007, A–C tracks, left). The age distribution of our sample of moderate redshift early-type galaxies along with recent findings of a lack of evolution of the comoving number density or the intrinsic color distribution of massive galaxies (see e.g., Fontana et al. 2006; Ferreras et al. 2009b; Conselice et al. 2007) suggest an in situ buildup of the stellar populations bypassing any trajectory in the blue cloud (except for the very short lived formation stage corresponding to an intense, highly efficient process of star formation). This proposed channel can be justified by the cold accretion streams found in recent numerical simulations (Dekel et al. 2009).
