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THE AGES, METALLICITIES, AND STAR FORMATION HISTORIES OF EARLY-TYPE GALAXIES IN THE SDSS

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ABSTRACT

We use the spectra of ∼22,000 early-type galaxies, selected from the Sloan Digital Sky Survey, to infer the ages, metallicities, and star formation histories of these galaxies. We find clear evidence of "downsizing," i.e., that galaxies with larger velocity dispersion have older stellar populations. In particular, we find that most early-type galaxies with velocity dispersion exceeding 200 km s^{-1} formed more than 90% of their current stellar mass at redshift $z > 2.5$. Therefore, star formation was suppressed around this redshift. We also show that chemical enrichment was rapid, lasting 1–2 Gyr, and find evidence that [Fe/H] is subsolar. We study the robustness of these results by comparing three different approaches: (1) using Lick absorption line indices, (2) fitting a single-burst stellar population model to the whole spectrum (lines and continuum), and (3) reconstructing the star formation and metallicity histories in multiple age bins, providing a method to measure mass-weighted ages and metallicities. We find good agreement between the luminosity-weighted ages and metallicities computed with these three methods.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: general

1. INTRODUCTION

It is of general interest to theories of galaxy formation to determine observationally how early-type galaxies formed, as this gives clues to how feedback was regulated in these systems (e.g., Benson et al. 2002; Baugh et al. 2003; Hernquist & Springel 2003; Scannapieco & Oh 2004; Somerville et al. 2004; Nagamine et al. 2005; De Lucia et al. 2006; Bower et al. 2006; Croton et al. 2006). The most direct way to do this is to observe the universe at different redshifts. If early types are found up to a certain redshift, then one can determine how far back early-type galaxy formation occurred, and what the stellar mass and appearance of these galaxies was. This indeed would be the best way to break the age-metallicity degeneracy, i.e., the property by which a galaxy can appear either young or old if its metallicity is unclear. However, because star formation becomes more intense in the past, it is difficult to classify a galaxy as an early type at high z, and thus also difficult to find the progenitors of early types by direct observation. Furthermore, obtaining large samples of early-type galaxies at redshifts larger than 1 is very demanding observationally with the current generation of 10 m telescopes. Nevertheless, there has been recent progress at finding the progenitors of nearby early-type galaxies in the redshift range $1 < z < 2$ (e.g., Cimatti et al. 2003; Daddi et al. 2003; Labbé et al. 2005; Papovich et al. 2005, 2006; Caputi et al. 2006; Stern et al. 2006). However, the number of progenitors found is only about 100.

One alternative approach to significantly increase the statistics, and to enable environment studies (Sheth et al. 2006), is to look at the local population of galaxies and try to infer the ages and metallicities of the stars from their stellar populations (e.g., Heavens et al. 2004; Tremonti et al. 2004; Gallazzi et al. 2005, 2006; Panter et al. 2006). This approach suffers from two drawbacks: first, it can only tell us how the stars were formed, and not how the dark matter and stellar material were assembled. Second, information recovered from the integrated light of the stellar populations is subject to degeneracies: for certain features of the spectral energy distribution (SED) of galaxies, it is not possible to distinguish between an old stellar population with a certain metallicity and a younger one with a higher metallicity (Worthey 1994). On the other hand, since galaxies are nearby they are not faint, and therefore large numbers of them can be observed with small telescopes. Furthermore, the use of the full spectral information significantly reduces, or removes altogether, the age-metallicity degeneracy (Fanelli et al. 1987, 1992; Dunlop et al. 1996; Spinrad et al. 1997; Dorman et al. 2003; Jimenez et al. 2004).

An interesting question is whether, given enough spectral coverage and a sufficiently high signal-to-noise ratio (S/N) in the SED, it is possible to recover any evolutionary information from observations of nearby early-type galaxies, i.e., from the fossil record. This question has been addressed before on purely theoretical grounds (e.g., Jimenez et al. 2004). The question that we investigate in this paper is similar, but we make use of observations from the Sloan Digital Sky Survey (SDSS) and stellar population models that specifically include the treatment of non-solar-scaled abundances. In particular, we want to know if the reconstructed star formation history derived from MOPED (Heavens et al. 2000) is consistent with the luminosity-weighted ages and metallicities obtained with other procedures. Early-type galaxies are particularly suitable for this study, since they have simpler star formation histories than disk galaxies.

In a previous study (Heavens et al. 2004), we recovered the star formation histories of a sample of SDSS galaxies, regardless of type and morphology. In this paper, we specifically analyze the subset of early-type galaxies. Our main findings are as follows. First, the star formation of early-type galaxies can be accurately recovered with MOPED, even if the number of parameters is significant. From the sample of early-type SDSS galaxies, we find clear evidence for "downsizing," i.e., that most massive galaxies formed their stars earlier than less massive ones. This effect is more pronounced for early-type galaxies than for the whole galaxy population. Furthermore, we find that more than 60% of massive galaxies formed 90% of their stars at $z > 2.5$. This places a strong constraint on when star formation has to be quenched in

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these systems. Using hydrodynamic models of early-type formation, we show how this can be achieved. Furthermore, we show how chemical enrichment took place in these systems. In total, we use about 40,000 early-type galaxies, a number that is many orders of magnitude larger than any direct observations at $z \sim 2$–3.

This paper is organized as follows. Section 2 describes the sample used in this study. In § 3, we describe the different methods used to determine the ages, star formation histories, and metallicities of early-type galaxies. Sections 4 and 5 describe the comparison between the different methods. We present the star formation history in § 6, and the metallicity history in § 7. We draw our conclusions in § 8.

2. THE SAMPLE

We used the sample of early-type galaxies analyzed by Bernardi et al. (2006). The sample, extracted from the SDSS (York et al. 2000) in its Data Release 2 (Abazajian et al. 2005), contains over 40,000 early-type galaxies selected for having an apparent magnitude $14.5 \leq r \leq 17.75$, with spectroscopic parameter `eclass` < 0, which gives a principal component analysis corresponding to no emission lines, and $\mathtt{fracDev_r} > 0.8$, which is a seeing-corrected indicator of morphology. In addition, only those objects with measured velocity dispersions were selected, i.e., those with S/N > 10 in the region 4200–5800 Å. The sample encompasses a redshift range $0.05 < z < 0.2$, which corresponds to a maximum look-back time of 2 Gyr.

3. THE METHOD

3.1. *Lick Indices*

Bernardi et al. (2006) used Lick indices (Worthey 1994; Trager et al. 1998; Thomas et al. 2003) to derive the luminosity-weighted age and the metallicity of the galaxies in the sample. In order to obtain a S/N in the spectrum high enough to accurately measure the absorption features, they stacked the spectra that had similar properties. This reduced the sample to 925 composite spectra. Bernardi et al. (2006) use the Mg *b*, $\langle \mathrm{Fe} \rangle$, and H$\beta$ and Hγ_F Balmer absorption lines, and α-enhanced stellar population models (Thomas et al. 2003, 2004) to derive ages and metallicities. See Bernardi et al. (2006) for more details.

3.2. *Full Spectral Fit*

Our second technique takes advantage of the large spectral range covered by the SDSS spectra, specifically the measured flux in the region 3500–4000 Å. This region is especially useful when trying to disentangle the age-metallicity degeneracy (Jimenez et al. 2004). Furthermore, a fit to the full spectrum takes advantage of the sensitivity of the continuum to metal blanketing. We used the models by Bruzual & Charlot (2003) at a resolution of 3 Å. We then performed a χ^2 minimization to find the best-fitting model in age and metallicity, the so-called single stellar populations (SSPs). We note that we performed the fit to individual spectra, as we found that the average S/N of the spectra (above 10 per resolution element) was sufficient to yield a meaningful fit.

3.3. *MOPED Fit*

The third and final method uses the MOPED algorithm (Heavens et al. 2000), which goes one step beyond SSP fitting, and recovers the star formation and metallicity histories of a given galaxy (e.g., Heavens et al. 2004) in a minimally parametric way. The recent DR3 release from the SDSS has been analyzed by Panter et al. (2006) using MOPED. From this study we selected those galaxies that overlap with the Bernardi catalog of early types. There were about 22,000 galaxies in common.

In brief, MOPED uses 11 bins, equally spaced logarithmically in look-back time, to describe the star formation history of a galaxy. In each bin there are two unknowns, the strength of the burst and its metallicity, for which matches are sought from a set of synthetic stellar population models to produce the best fit to the observed galaxy. In addition, we used a single foreground dust screen to determine the amount of dust present in the galaxy today. The strength of the extinction is characterized by $E(B-V)$, which is a free parameter in our fit. In all cases, the best value chosen by the fit was $\sim$0. For this study, we used the Bruzual & Charlot (2003) models at 3 Å resolution as the SSP describing the stellar population in each of the bins.

One obvious concern with MOPED is that in a search with such a large number of parameters, degeneracies may be significant. Although this could be the case on an individual basis, Panter et al. (2003) showed that this is not the case for stellar populations with old components (age > 8 Gyr). Furthermore, Panter et al. (2003, 2006) demonstrated that no degeneracies remain for large statistical samples. One clear advantage of MOPED is that it can provide the star formation history of the galaxy, which makes it possible to calculate a mass-weighted age and metallicity, as opposed to the luminosity-weighted quantities derivable by the other two methods. For the early-type galaxies considered here, the situation is better, as their spectra tend to be dominated, as we will show, by one age and metallicity. This lack of secondary significant bursts translates into a more robust MOPED solution. In particular, the metallicity has a typical error of 0.3 dex, while the age is constrained to the bin where most of the star formation takes place, with no covariances of more than 10% on any of the contiguous bins. In the following sections, we show that when one computes the luminosity-weighted age and metallicity from MOPED, the results agree well with those obtained from the Lick or full spectrum methods. There are no significant systematics in the luminosity-weighted ages and Z as computed from the MOPED solutions.

4. THE METALLICITIES OF EARLY-TYPE GALAXIES

Figure 1 shows the comparison between the luminosity-weighted metallicity derived from the Lick indices in Bernardi et al. (2006) and from MOPED. The Lick metallicities are computed with the α-enhanced models of Maraston (2005), while the MOPED metallicities are for the solar-scaled models of Bruzual & Charlot (2003). For the MOPED method, we computed mass-weighted metallicities by adding up the 11 bins, weighting by the luminosity of each component in the SDSS band *r*.

In order to convert the solar-scaled metallicities to the α-enhanced scale, we used the formula by Trager et al. (2000). To do the comparison with the composites from Bernardi et al. (2006), we averaged the metallicities of the MOPED spectra that correspond to a given composite in the Bernardi et al. sample.

We find good agreement between the two methods. There is a slight systematic shift at high metallicities of about 0.1 dex. The MOPED-corrected metallicities tend to be lower than the Lick-derived ones. The 1 σ dispersion around the one-to-one line is of about 0.05 dex. The metallicities for all galaxies are supersolar, with no galaxies below the solar value. The maximum metallicity is about twice the solar value.

5. THE AGES OF EARLY-TYPE GALAXIES

Figure 2 shows a comparison between the luminosity-weighted ages obtained from the single fit to the whole spectrum and the MOPED luminosity-weighted ages (i.e., those obtained by summing up the ages of all 11 bins weighted by their luminosity in the SDSS band *r*).

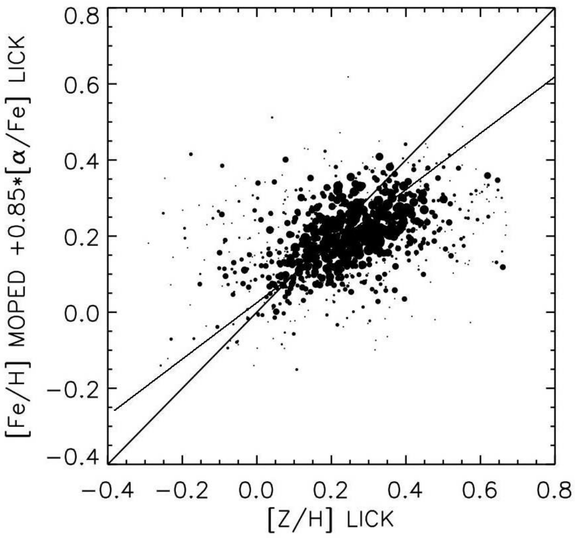

FIG. 1.—Comparison between the luminosity-weighted metallicities obtained from the Lick indices and the luminosity-weighted metallicity (see text) obtained from MOPED. Also shown is the least square fit to the data. The displacement in the data range is about 20% at its maximum.

This is the more direct method to determine the extent to which degeneracies can play a role in the MOPED solution. Because the two methods use the same set of stellar populations models (Bruzual & Charlot 2003), the comparison is free of systematics. It gives a measurement of MOPED degeneracies because it compares a fit with just two parameters, age and metallicity, with the 23 parameters of MOPED.

The agreement is reasonable. There is a tendency for the MOPED ages greater than 10 Gyr to be older than the SSP ages by about 1 Gyr. However, this can be understood from the fact that the last age bin in MOPED is quite wide (10.5–13.7 Gyr), and therefore the uncertainty is of the order of 20%. As Figure 2 shows, and as is also discussed in § 6 below, the weighted age is dominated by this last bin, so the intrinsic uncertainty in the MOPED bin dominates the error in the comparison. In the comparison, we chose 13 Gyr as the age of the bin.

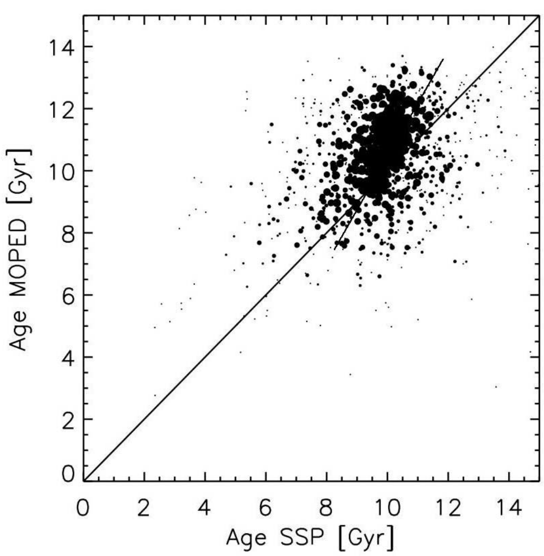

FIG. 2.—Comparison between the luminosity-weighted age obtained with fits to the full spectrum (age SSP) and MOPED. There is a slight trend for MOPED ages to be older by about 5% for the oldest ages; see text for more details.

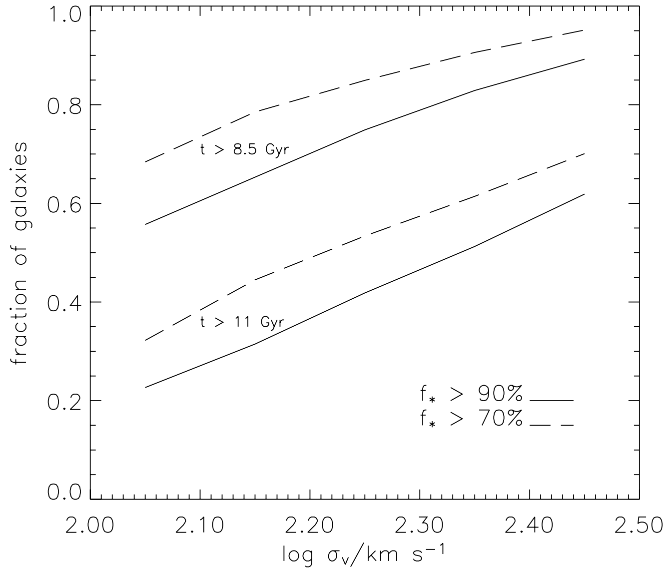

FIG. 3.—Fraction of galaxies in the SDSS sample as a function of velocity dispersion that have formed more than 90% (*solid lines*) and 70% (*dashed lines*) of their stars at a look-back time greater than 11 and 8.5 Gyr. Note the strong correlation between the fraction of galaxies and the velocity dispersion, which is clear evidence of downsizing for the early-type population. Also note that for $\log(\sigma_V/1\ \mathrm{km\ s^{-1}}) > 2.3$, more than 50% of the galaxies formed 90% of their stars at $z > 2.5$. This fraction increases to 90% of galaxies that have formed more than 90% of their stars at $z > 1.2$. This indicates that a significant fraction of massive early types quenched star formation at $z \sim 2.5$.

The comparison with the Lick index ages is not as straightforward, because the Lick index ages were calculated with α-enhanced models. Fully tested α-enhanced models that can be used to fit the full spectrum (lines and continuum) are not yet available.

6. THE STAR FORMATION HISTORIES OF EARLY-TYPE GALAXIES

We can now look in detail at the star formation histories provided by MOPED. In particular, we want to know the typical star formation history of an early type, and how it relates to the mass of the galaxy.

Figure 3 shows what fraction of early-type galaxies in the SDSS formed more than a given fraction of their current stellar mass above a given look-back time. The solid lines show the fraction of galaxies that formed more than 90% of their current stellar mass at look-back times larger than 11 and 8.5 Gyr. First, note the strong correlation with velocity dispersion, which is a clear sign of downsizing for early-type galaxies, i.e., a sign that star formation occurs in more massive galaxies at earlier times (see e.g., Cowie et al. 1999; Bernardi et al. 2003, 2006; Heavens et al. 2004; Kodama et al. 2004; Thomas et al. 2005; Tanaka et al. 2005; Treu et al. 2005; van der Wel et al. 2005; Juneau et al. 2005; Bundy et al. 2006; di Serego Alighieri et al. 2005; Cimatti et al. 2006; Neistein et al. 2006; Mouri & Taniguchi 2006). Also, for galaxies with $\log(\sigma_V/1\ \mathrm{km\ s^{-1}}) > 2.3$, more than 50% of the SDSS early types formed more than 90% of their stars at $z > 2.5$. This fraction increases to 80% at $z > 1.2$. Clearly, large galaxies ($\sigma_V > 200\ \mathrm{km\ s^{-1}}$) are shutting off their star formation at very early epochs. The dashed lines show a similar trend for early types that formed more than 70% of their stars at the same redshifts. For the whole population of massive early types, there is very little stellar mass being added below $z = 1.2$.

Therefore, most of the star formation in massive early types took place at $z > 2$ and in a short burst of duration 1–2 Gyr

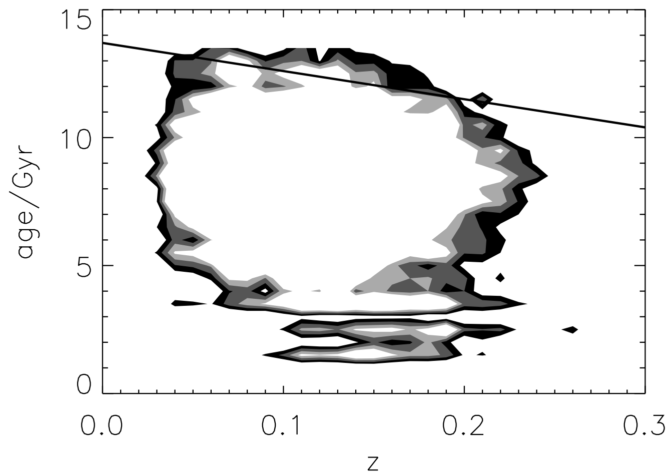

FIG. 4.—Age-redshift distribution for early types in the SDSS. The white region contains 99% of galaxies. There is a clear old edge: higher redshift galaxies are younger than lower redshift ones. The solid line corresponds to the age-redshift relation for the ΛCDM universe.

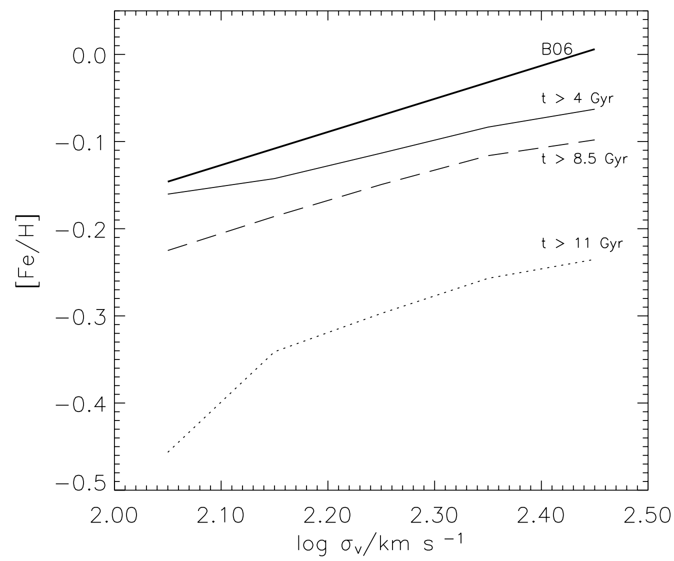

FIG. 5.—Mass-weighted Fe abundance as a function of velocity dispersion for different look-back times. Note the trend of increasing metallicity with increasing velocity dispersion at all epochs. Furthermore, there is an increase in metallicity from $t > 11$ to $t > 8.5$ Gyr, after which the metallicity remains almost constant, which is consistent with a picture in which there is no further inflow of fresh gas. Also, we show the Fe value derived by Bernardi et al. (2006) from their Lick index study at $t = 0$ Gyr.

(Jimenez et al. 1999). The hydrodynamic models in Jimenez et al. (1999) also explain the shutoff in star formation after just 1–2 Gyr as supernova (SN) feedback that heats the gas beyond the escape velocity of the dark matter halo. These models do not include any AGN feedback, yet they seem to reproduce well the trends for early types in the SDSS. The clue to their success is the early assembly of the dark matter halo. Similar trends were also found in Blanton et al. (2000), Granato et al. (2001), and Jimenez et al. (2005).

Because the MOPED star formation history suggests that most of the star formation in early types took place at $t > 11$ Gyr, it is not surprising that luminosity-weighted ages and mass-weighted ages are very similar (Haiman et al. 2006).

The MOPED ages are calculated over bin ages that are somewhat large (about 20% of the age), and they are not accurate enough to see the evolution of the red envelope in detail as a function of redshift. However, it is interesting to look at the full-spectrum fit luminosity-weighted ages as a function of redshift. This assumes that the star formation took place in a single burst, but as we have seen above, this is suggested by the formation history of the MOPED stars. Figure 4 shows the age of the oldest early-type galaxies as a function of observed redshift. The plot shows a contour around a white region that includes 99% of the galaxies. For reference, the solid line is the age-redshift relation for the currently favored ΛCDM universe (Spergel et al. 2006). It is left for future work to provide a robust determination of the Hubble constant from these data (e.g., Simon et al. 2005).

7. THE METALLICITY HISTORIES OF EARLY-TYPE GALAXIES

We now turn our attention to the evolution of metallicity in early types. Figure 5 shows the evolution of the mass-weighted metallicity, computed from the MOPED fit, for the SDSS early-type sample as a function of velocity dispersion and look-back time. As for the mass-weighted age, there is a correlation between metallicity and velocity dispersion. The more massive galaxies are not only the ones that contain the oldest stars, but are also more metal-rich.

This is not too surprising. In fact, a simplistic model (e.g., Jimenez et al. 1999) in which one assigns a deeper dark matter potential to the most massive galaxies will predict just that, i.e., that the more massive objects are able to trap the ISM gas longer due to the higher escape velocity from the dark halo. This in turn means that gas in the more massive halos is more enriched than in the less massive ones.

Furthermore, this model predicts that star formation will stop after 1–2 Gyr due to the gas having been heated up above the escape velocity by SN explosions. From Figure 5, we can see that this is the case; metal enrichment finishes at a look-back time of 8.5 Gyr ($z > 1.2$). Another interesting fact is that the average [Fe/H] of the population is slightly below solar when mass weighted. Note that the overall metallicity is, however, supersolar (Fig. 1). This is also what one expects if star formation is quenched in 1–2 Gyr. In this case, the Type Ia SNe are not yet formed; however, they are the peak producers of Fe.

8. CONCLUSIONS

We have presented further evidence of clear downsizing for the SDSS early-type galaxies. We have also shown that these galaxies, especially the most massive ones, formed a significant number of their stars at $z > 2.5$. Furthermore, we have presented evidence that the buildup of stellar metallicity in early-type galaxies monotonically increases with time, and that star formation is quenched after just 1–2 Gyr. This can be explained by a simple model in which SN heating of the interstellar medium is sufficient to suppress further star formation by expelling it from the dark matter halo of the galaxy. Jimenez et al. (2005) noted that in the ΛCDM cosmology, these massive halos are abundant at $z \sim 3$. They constitute the most natural candidates to host the progenitors of the SDSS early types. The problem that remains to be solved in simulations is to suppress star formation by subsequent gas-rich mergers. This is precisely what AGN feedback provides (e.g., Scannapieco & Oh 2004; Bower et al. 2006; Croton et al. 2006; De Lucia et al. 2006).

Also, we have studied in detail different methods to recover the age(s) and metallicity(ies) for the integrated stellar population of the SDSS early types. We first compared the two most commonly used methods to recover the luminosity-weighted age and metallicity: fitting the whole spectrum with a single-burst model, and using only Lick absorption line indices. We have shown that the two methods provide similar answers. Furthermore, we then compared these two methods to the MOPED algorithm, which does recover a (mostly) nonparametric star formation and metallicity history of the galaxy. Despite the larger freedom in MOPED, we have shown that the MOPED luminosity-weighted age and metallicity agree well with the above methods. Thus, despite the larger number of variables used by MOPED, there do not seem to be significant degeneracies in its solution.

The large number of early types discovered by the SDSS and the fossil record analysis provide a valuable window into the formation of these objects at $z \sim 2$–3, when the universe was only 1/5 of its current age. We were able to use more than 40,000 early-type galaxies for our study. Such a large number of galaxies is not currently available at $z \sim 3$, although we might know of a few handfuls of secure early-type progenitors by direct observation. As an example of the usefulness of such a large sample, in a companion paper (Haiman et al. 2006), we use this fossil sample to constrain the evolution with redshift of the physical parameters that determine the growth of massive black holes at the centers of galaxies. With the tight constraints imposed by the fossil record, it is clear that a significant number of extremely red objects should be detectable at such redshifts with the next generation of telescopes.

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