EVIDENCE FOR TP-AGB STARS IN HIGH-REDSHIFT GALAXIES, AND THEIR EFFECT ON DERIVING STELLAR POPULATION PARAMETERS

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ABSTRACT

We explore the effects of using different stellar population models on estimates of star formation histories, ages, and masses of high-redshift galaxies by fitting the SEDs with models by Maraston (hereafter M05) and by Bruzual & Charlot (hereafter BC03). We focus on the thermally pulsing asymptotic giant branch (TP-AGB) phase of stellar evolution, whose treatment is a source of major discrepancy. In this respect, BC03 models are representative of other models whose treatment of the TP-AGB phase is similar. Moreover, M05 and BC03 models adopt stellar tracks with different assumptions on convective overshooting. For our experiment we use a sample of high-z (1.4 ≤ z ≤ 2.7) galaxies, for which rest-frame UV spectroscopy and spectroscopic redshifts are available, along with Spitzer IRAC and MIPS photometry from GOODS. The mid-UV spectra of these galaxies exhibit features typical of A- or F-type stars, indicative of ages in the range ~0.2–2 Gyr, when the contribution of TP-AGB stars is expected to be maximum. We find that the TP-AGB phase plays a key role in the interpretation of the Spitzer data, where the rest-frame near-IR is sampled. Generally, M05 models give better fits than BC03 models and indicate systematically lower ages and lower masses (by ~60%, on average). Photometric redshifts derived using M05 models are also in better agreement with the spectroscopic ones, especially when the rest-frame near-IR fluxes from Spitzer IRAC are included in the fit. We argue that the different results are primarily a consequence of the different treatment of the TP-AGB phase, although other differences in the input stellar evolution also contribute. This work provides a first direct evidence for a strong contribution by TP-AGB stars to the SED of galaxies in the high-redshift universe (z ~ 2).

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift — stars: AGB and post-AGB

Online material: color figure

1. INTRODUCTION

Age dating the stellar populations of galaxies provides us with a cosmic timescale that is independent of cosmological models, and with a means of reconstructing their star formation history (SFH). Moreover, the same population synthesis tools used for age dating provide also an estimate of the stellar mass of galaxies. Thus, deriving SFHs and masses for large numbers of galaxies at various redshifts allows us to attempt an empirical reconstruction of the formation epochs and mass-assembly history of galaxies. Theoretical models for galaxy formation and evolution can then be adjusted in order to comply with the galaxy evolution scenario emerging from the observations. Clearly, the evolutionary population synthesis tools play a critical role in this process, and we must pay as much attention as possible to ensure that they provide ages and masses as accurate as possible. In this paper we focus on the problem of age and mass determinations for galaxies that are dominated by stars in the age range 0.2 Gyr ≤ t/ ≤ 2 Gyr, because this is a range where different population synthesis tools give quite discrepant results. Moreover, at redshifts beyond 2 (or 3) the universe itself is younger than ~3 (or ~2) Gyr, and galaxies at such high redshift are bound to contain stars younger than ~2 Gyr. Hence, the use of an accurate stellar population tool is essential for the correct interpretation of the properties of high-redshift galaxies, right at a cosmic time when different renditions of the hierarchical galaxy formation paradigm diverge dramatically (see, e.g., Fig. 9 in Fontana et al. 2004).

For a long time it has been known from both theoretical arguments (Renzini 1992; Renzini & Buzzoni 1986) and direct observations of Magellanic Cloud clusters (Persson et al. 1983) that stars in the advanced evolutionary stage known as the thermally pulsing asymptotic giant branch (TP-AGB) can contribute a major fraction of the total bolometric light of a stellar population. In the models of Maraston (1998, hereafter M98), TP-AGB stars contribute up to ~40% of the bolometric light (and up to ~80% in the near-IR) of stellar populations in the age range 0.2 Gyr ≤ t/ ≤ 2 Gyr. The contributions are calibrated with observations. In other models in the literature instead the TP-AGB contribution is lower. For example, in the models by Mouchine & Lancón (2002), the maximum bolometric contribution is only 20%, and in other sets of models, although not given explicitly, it appears to be even lower (see Maraston [2005, hereafter M05] for a wider discussion).

The first appearance of TP-AGB stars in the life of a stellar population has been called the “AGB-phase transition” (Renzini & Buzzoni 1986), and its direct effect is a strong increase of the near-IR flux, as TP-AGB stars emit most of their radiation at λ > 1 μm. With the advent of the Spitzer Space Telescope, the rest-frame near-IR is now accessible to very high-redshifts, which

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allows one an improved analysis of the spectral energy distribution (SED) of high-redshift galaxies, and makes it even more important than before to dispose of reliable stellar population tools.

The following concrete example illustrates the case. For a sample of high-z galaxies with photometric redshifts \( z \sim 2.4 \) and with data extending from the rest-frame UV to near-IR (from Spitzer), Yan et al. (2004) estimated an age of 1.5–3.5 Gyr for the dominant stellar population (~99% by mass), with the residual trace of young stars as due to a recent star formation episode. The Yan et al. result was obtained using the synthetic population tool by Bruzual & Charlot (2003, hereafter BC03). Two of those galaxies were reanalyzed by M05 using her own synthetic stellar populations, obtaining ages \( \sim 0.6–0.8 \) Gyr, right in the middle of the epoch when TP-AGB stars dominate. Moreover, the derived stellar masses are smaller when using Maraston models \((\sim 10^{10} M_\odot \text{vs. the typical value of } \sim 10^{11} M_\odot \text{ quoted by Yan et al. 2004})\). Whereas both results may be astrophysically plausible, it is worth emphasizing that their implications concerning the formation redshift for the bulk of the stars and the galaxy mass assembly are vastly different. The difference is likely the result of the different weight given to the TP-AGB in the two sets of models, with the TP-AGB contribution being systematically lower in the BC03 models than in the models of Maraston (2005). When using BC03 models a massive contribution of old stars is required in order to match the observed near-IR fluxes, and in the meantime a sprinkle of young stars is necessary to account for the rest-frame near-UV. On the contrary, a two-component stellar population is not required by the M05 models, as a single age (younger) population accounts at once for the SED from the near-UV to the near-IR. It is interesting to recall in this context the early result of Lilly (1987), who found for a sample of \( z \sim 0.45 \) cluster galaxies that synthetic near-IR colors not including the AGB phase were not red enough to match the data at given optical color. The problem was cured by adding AGB effects on top of these early models using the fuel consumption theorem.

Besides the treatment of the TP-AGB, the BC03 and M05 models also differ for the set of stellar isochrones used to construct the synthetic populations, which may account for part of the difference in the results.

In this paper we investigate further the effect of stellar population recipes on the modeling of galaxy SEDs, and we do so by applying the two sets of models to infer the mass and age (or best-fit SFHs) to a specific sample of high-redshift galaxies. Note that the results obtained with the BC03 models are representative of what would be obtained with other widely used models, such as P\( \acute{e} \)gase (Fioc & Rocca-Volmerange 1997) and Starburst99 (V\( \acute{a} \)zquez & Leitherer 2005), due to similar recipes for the TP-AGB phase and identical input stellar evolutionary tracks (M05).

In § 2 we recall the main differences between the BC03 and the M05 models. The main observational characteristics of the galaxies selected for this study are given in § 3, along with a comprehensive description of the fitting procedure. The results are presented in § 4. Finally, § 5 is dedicated to a general discussion of the main results of this investigation. We adopt the current “concordance cosmology,” with \( \Omega_\Lambda, \Omega_M, \text{and } h = (H_0[km\,s^{-1}\,Mpc^{-1}] / 100)] \) equal to 0.7, 0.3, and 0.7, respectively. The age of the best-fit model is required to be lower than the age of the universe at the given spectroscopic redshift.

2. MAIN DIFFERENCES BETWEEN THE TESTED STELLAR POPULATION MODELS

The BC03 and the M05 stellar population models differ in the following aspects: (1) the stellar evolutionary models used to construct the isochrones; (2) the treatment of the TP-AGB phase; and (3) the procedure used for computing the integrated spectra. This latter point will not be discussed separately here (see M05). For full details on what follows below, we refer the reader to M05.

Input stellar models.—The BC03 models are based on the Padova stellar tracks (e.g., Fagotto et al. 1994), whereas the M05 models are mostly based on the Frascati stellar tracks (e.g., Cassisi et al. 1997). The two set differ mostly for (1) the Padova tracks include a certain amount of convective overshooting on the main sequence (MS), whereas the Frascati tracks were constructed assuming no overshooting; and (2) the temperature distribution of the red giant branch (RGB) phase, which is shifted to cooler temperatures in the Padova tracks for solar metallicity and above, a result of the different calibration of the mixing-length theory used for the modeling of envelope convection.

Convective-core overshooting has two effects on stellar models. First, it prolongs the MS lifetime for given stellar mass, while leaving the effective temperature almost unchanged. This results from the extended convective core ensuring more hydrogen fuel to the central regions where nuclear burning takes place. Thus, isochrones constructed from models with overshooting are hotter, and therefore bluer, than those constructed from models without overshooting. Second, overshooting delays the appearance of stars with a degenerate helium core and the accompanying development of the RGB. For example, the RGB develops at an age of \( t \sim 0.5 \) Gyr in the Frascati models, and at an age of \( t \gtrsim 1 \) Gyr in the Padova models (Ferraro et al. 2004; M05). The development of the RGB makes the SED redder, so in the age range \( \sim 0.5–1 \) Gyr models with overshooting are bluer, as they lack a well-developed RGB. The net effect is that theoretical SEDs based on overshooting models are bluer and therefore give systematically older ages than those based on models without it. Furthermore, by having a reduced contribution by the RGB, population models using stellar tracks with overshooting have lower luminosity for given age and mass in stars, i.e., have higher \( M/L \) ratios; hence higher galaxy masses are derived for given luminosity. In summary, the net effect of overshooting is that for a given SED the BC03 models indicate older ages and higher masses than the M05 models. Of course, this applies to population ages such that MS stars do have a convective core, i.e., for ages younger than a few Gyr.

While it is likely that overshooting makes convective cores somewhat more extended in mass, the size of this extension remains somewhat conjectural. On the one hand, there exists no firm prediction from first principles, as in most situations involving turbulence. For stellar populations between \( \sim 1 \) and \( \sim 10 \) Gyr, the corresponding stellar masses at the MS turnover range from \( \sim 2 \) to \( \sim M_\odot \), with the mass of the convective core decreasing with decreasing mass, and eventually vanishing for \( M \sim 1.2 M_\odot \), the precise value depending on composition. Thus, what one would need to know is the amount of convective overshooting (e.g., expressed as a fraction of the mass of the convective core) as a function of the stellar mass. This unknown function can only be empirically constrained by observations. In a recent attempt, based on fitting the shape of the color-magnitude of some open clusters, Vandenberg et al. 2006 concluded that overshooting would amount to \( \sim 10\% \) of a pressure scale height, of course vanishing as the convective core itself vanishes. An overshooting about this size is also indicated by the asteroseismology of a \( \beta \) Cep star (Dupret et al. 2004), and by and large is consistent with the amount assumed in the Padova models. On the other hand, observations...
of LMC star clusters rule out the late RGB development implied by
the Padova tracks (Ferraro et al. 2004). To decide what is the
size of overshooting as a function of stellar mass goes well be-
yond the aims of this paper, and we shall limit ourself to explor-
ing the differences in the results when using different sets of
models.

The temperature of the RGB.—Whereas for ages less than
\( \sim 1 \) Gyr the M05 code gives redder SEDs than the BC03 code,
after the completion of the RGB phase transition this tendency is
reversed and the M05 SEDs are bluer (Fig. 27 in M05). This is
due to the warmer RGBs in the Frascati stellar tracks compared
to the Padova ones (Fig. 9 in M05), which in turn results from
different calibrations of the mixing-length parameter used in
modeling envelope convection. The ages derived with the M05 models are older than those obtained from the BC03 models.

The TP-AGB phase.—The treatment of the TP-AGB phase is
perhaps the main difference between the M05 and the BC03 mod-
els. The contribution of the TP-AGB stars to the integrated light of
a synthetic stellar population critically depends on what is adopted
for the stellar mass loss taking place during this phase. The higher
the assumed mass loss, the sooner the star loses its envelope, and
the sooner the TP-AGB phase is terminated. Once more, there is
no theory relating the mass-loss rate to the basic stellar parameters,
and once more one has to rely on empirical calibrations. The life-
time of the TP-AGB adopted by BC03, from Vassiliadis & Wood
(1993) was tuned to reproduce the maximum TP-AGB luminosity
of a sample of Magellanic Cloud clusters from Frogel et al. 1990.
In M05, instead what is calibrated is the fractional contribution of
the TP-AGB to the total bolometric light, and this calibration is
made essentially on the same MC clusters using the Frogel et al.
data. Sharing basically the same observational calibrating data, the
two codes should give consistent results. As shown in M05 they
do not, and the effective contribution of the TP-AGB is much
larger in M05 compared to BC03. Full illustration of the differ-
ences is given in M05, where it is also shown that other popu-
lation synthesis models, namely, Pégase and Starburst99 behave
very much like the BC03 ones. Again, rather than tracing the ori-
gen of the discrepancy, we focus here on the effects on the study of
high-redshift galaxies.

Summing up the effects of both overshooting and TP-AGB,
the M05 models are brighter and redder than the BC03 models for
ages between \(-0.2\) and \(-2\) Gyr. Here the use of the M05 models
implies the derivation of lower ages and stellar masses. At older ages
the M05 models are instead bluer.

3. GALAXY DATA AND SED FITTING

For the present test we use the sample of seven galaxies in the
Hubble Ultra Deep Field (HUDF), which were singled out by
the BzK criterion for \( z > 1.4 \) passively evolving galaxies (Daddi
et al. 2004). These galaxies show early-type morphologies on
HUDF images and have spectroscopic redshifts between 1.4 and
2.7 (Daddi et al. 2005b, hereafter D05). Redshifts were deter-
mined from the Mg\textsuperscript{+}Fe absorptions at rest frame \( \lambda \sim 2600–
2800 \) Å, producing a characteristic shape, dubbed the “Mg\textsubscript{UV}
feature” by D05, on the HST ACS (Advanced Camera for Sur-
vveys) grism spectra acquired in the framework of the Grism ACS
Program for Extragalactic Science project (GRAPES; Pirzkal
et al. 2004). The presence of the Mg\textsubscript{UV} feature implies that the
UV/optical spectra of these galaxies are consistent with being
dominated by A- or F-type stars (D05). Therefore these objects
are not dominated by OB type stars like typical star-forming gal-
axies and are predominantly passive. We choose these particular
sample for this study because we might expect that the typical
ages of stars in these galaxies are close to the critical 0.2–2 Gyr
range, where the different evolutionary synthesis models differ
by the largest amount. This is therefore an ideal sample of high-
redshift galaxies to search for direct evidence of the effects from
TP-AGB stars.

Three of the seven galaxies were assigned a lower quality (“B” class) redshift by D05, partly for the nonperfect agreement
with the photometric redshifts. This is now improved in most cases
with the addition of the IRAC (Infrared Array Camera) photom-
etry to the SEDs and the M05 models (see Table 3 and Fig. 9).

However, for one of the objects with B-class redshift, ID 1446
with \( z = 2.47 \) in D05, we use here a new redshift of \( z = 2.67 \)
based on C [\textit{iii}] \( \lambda 1909 \) emission and a few interstellar absorption
lines. This new redshift was recently derived from the ultradepth
(30 hr integration) VLT+FORS2 spectroscopy taken within the Gal-
axy Mass Assembly Ultra-Deep Spectroscopic Survey (GMASS)
project\textsuperscript{10} (J. Kurk et al. 2006, in preparation). The new redshift is
in much better agreement with the photometric redshifts, espe-
cially with the one obtained with the M05 models (see Table 3 and
Fig. 9).

Stellar population properties for these galaxies were derived
in D05 by fitting their SEDs (10 bands from \( B \) to \( K \)) to BC03
templates spanning a wide range of parameters. Reddening was
restricted to be \( E(B-V) < 0.2 \), and the Calzetti law (Calzetti
et al. 2000) was adopted. In summary, the galaxies were found to
be \( \sim 1 \) Gyr old, to be in passive evolution since at least \( \sim 0.4 \) Gyr,
and to have de Vaucouleurs light profiles and large stellar masses

\textsuperscript{10} See http://www.arcetri.astro.it/cimatti/gmass/gmass.html.
($\geq 10^{11} M_\odot$). They were therefore interpreted as progenitors of massive ellipticals. The physical sizes of some of the objects ($\sim 0.7$ kpc) were found to be significantly smaller than objects with similar masses in the local universe, which remained as an open issue in D05. In the following we take advantage of the Spitzer IRAC (and MIPS [Multiband Imaging Photometer for Spitzer]) imaging obtained over the HUDF as a part of the Great Observatories Origins Deep Survey (GOODS; M. Dickinson et al. 2006, in preparation, and R. Chary et al. 2006, in preparation, respectively). All the seven galaxies were detected with high signal-to-noise in the four IRAC bands (see Fig. 1). IRAC photometry was obtained using $4''$ aperture magnitudes, corrected to total using aperture corrections for unresolved sources. The optical to near-IR SEDs of D05 were based on Sextractor MAG_AUTO apertures. We measured large $6''$ diameter magnitudes in the $K$-band to account for the flux lost by MAG_AUTO, to perform the match with the IRAC magnitudes. In order to account for the uncertainties in this matching process, and in the IRAC aperture corrections, we added a term of $0.1$ mags in quadrature to the errors of the IRAC magnitudes.

Figure 2 shows the observed $I-K$ versus $K-4.5 \mu m$ color-color diagram for our sample. Overplotted are some stellar population models from the M05, BC03, and Pégase libraries, with ages between 0.1 and 3.5 Gyr, in the observed frame at redshift 1.9. Simple stellar populations (SSPs) with solar metallicity are indicated by solid lines, while dashed lines display exponentially declining models with $e$-folding time of 0.3 Gyr (for the Pégase models, only the SSP is shown). As in analogous plots by Labbé 2005 and Papovich et al. 2006, the very red $K-4.5 \mu m$ colors displayed by the galaxies are not reached by the BC03 (or Pégase) templates, unless one adds strong dust reddening to the models. The M05 models match instead the observed galaxy colors at the ages corresponding to the AGB phase-transition. The present database (see the Table 1 for the photometric data) allows the sampling of the galaxy spectral energy distributions up to the rest-frame $K$ band. The whole wavelength range from the rest-frame $UV$ to $K$ will be analyzed in the next section.

### 3.1. SED Fitting

We use an adapted version of the code HyperZ (Bolzonella et al. 2000), kindly made available to us by M. Bolzonella, which performs SED fitting at fixed spectroscopic redshift. The fitting procedure is based on maximum-likelihood algorithms and the goodness of the fit is quantified via $\chi^2$ statistics (see the HyperZ manual for details). The code computes the $\chi^2$ for a certain number of solutions.

#### Table 1

Photometric Data of HUDF Galaxies

| ID    | F435  | $V$     | F606 | $R$   | F775 | F895 | F110 | $J$  |
|-------|-------|---------|------|-------|------|------|------|------|
| 8238  | 29.15 ± 0.62 | 28.59 ± 1.10 | 27.42 ± 0.09 | 26.86 ± 0.2 | 25.60 ± 0.02 | 24.66 ± 0.01 | 23.67 ± 0.01 | 23.16 ± 0.04 |
| 4650  | 25.30 ± 0.04 | 24.83 ± 0.04 | 24.78 ± 0.02 | 24.47 ± 0.03 | 23.89 ± 0.01 | 23.18 ± 0.01 | 23.16 ± 0.04 |
| 1025  | 26.35 ± 0.05 | 25.66 ± 0.20 | 25.84 ± 0.02 | 25.56 ± 0.09 | 25.17 ± 0.01 | 24.52 ± 0.01 | 24.51 ± 0.01 | 23.74 ± 0.07 |
| 3523  | 28.40 ± 0.39 | 28.33 ± 0.88 | 28.77 ± 0.06 | 26.52 ± 0.14 | 25.73 ± 0.03 | 25.00 ± 0.02 | 25.00 ± 0.01 | 23.66 ± 0.02 |
| 3650  | 28.51 ± 0.31 | 27.00 ± 0.27 | 26.42 ± 0.03 | 26.10 ± 0.10 | 25.48 ± 0.01 | 24.57 ± 0.01 | 24.53 ± 0.01 | 23.63 ± 0.05 |
| 3574  | 28.81 ± 0.34 | 28.49 ± 1.04 | 27.10 ± 0.05 | 27.31 ± 0.29 | 26.38 ± 0.03 | 25.57 ± 0.02 | 24.41 ± 0.01 | 23.63 ± 0.05 |
| 1446  | 29.92 ± 1.10 | 28.20 ± 0.78 | 27.52 ± 0.08 | 26.63 ± 0.12 | 26.44 ± 0.03 | 26.12 ± 0.04 | 25.43 ± 0.03 | 25.25 ± 0.22 |

**Note:** The magnitudes are in AB system, which are related to flux density $f_r$ (in erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$) by $m = -2.5 \times \log(f_r) - 48.60$. 

#### Table 2

| ID    | F160W | $K$     | $m$(3.6 $\mu$m) | $m$(4.5 $\mu$m) | $m$(5.8 $\mu$m) | $m$(8.0 $\mu$m) | MIPS(24 $\mu$m) (µJy) |
|-------|-------|---------|----------------|----------------|----------------|----------------|----------------------|
| 8238  | 22.76 ± 0.01 | 22.08 ± 0.02 | 21.29 ± 0.13 | 21.38 ± 0.13 | 21.71 ± 0.13 | 21.38 ± 0.13 | 21.71 ± 0.13 |
| 4650  | 22.76 ± 0.01 | 22.08 ± 0.02 | 21.29 ± 0.13 | 21.38 ± 0.13 | 21.71 ± 0.13 | 21.38 ± 0.13 | 21.71 ± 0.13 |
| 1025  | ...   | 21.80 ± 0.05 | 21.28 ± 0.12 | 21.20 ± 0.12 | 21.27 ± 0.12 | 21.20 ± 0.12 | 21.27 ± 0.12 |
| 3523  | 22.68 ± 0.01 | 22.33 ± 0.03 | 21.60 ± 0.14 | 21.56 ± 0.14 | 21.69 ± 0.15 | 21.56 ± 0.14 | 21.69 ± 0.15 |
| 3650  | 22.28 ± 0.01 | 21.75 ± 0.02 | 21.05 ± 0.12 | 21.01 ± 0.12 | 21.10 ± 0.12 | 21.01 ± 0.12 | 21.10 ± 0.12 |
| 3574  | 23.22 ± 0.01 | 22.67 ± 0.03 | 22.24 ± 0.15 | 22.19 ± 0.15 | 22.12 ± 0.15 | 22.19 ± 0.15 | 22.12 ± 0.15 |
| 1446  | 23.38 ± 0.01 | 22.86 ± 0.04 | 22.18 ± 0.19 | 22.08 ± 0.19 | 22.01 ± 0.19 | 22.08 ± 0.19 | 22.01 ± 0.19 |
stellar populations with different SFHs.

We have constructed templates that cover a wide range of stellar population parameters, namely, (1) metallicities from the most plausible one among our set of templates. This implies that the template set must be densely populated.

Of course, the best-fitting template cannot be regarded as the unique solution for the SFH of each galaxy, but should be seen as the most plausible one among our set of templates.

We have constructed templates that cover a wide range of stellar population parameters, namely, (1) metallicities from $Z_0/5$ to $2Z_0$; (2) ages from $10^5$ yr to 5 Gyr (the maximum possible age for the lowest redshift galaxy)\textsuperscript{12}; and (3) SFH as (a) instantaneous and chemically homogeneous bursts (i.e., SSPs); (b) exponentially declining modes ($SFR \propto e^{-t/\tau}$, or $\tau$-models, with $\tau = 0.1, 0.3, 1$ Gyr); (c) truncated models, where SF is constant for a finite time interval $t_{\text{trunc}}$ and zero thereafter ($t_{\text{trunc}} = 0.1, 0.3, 1$ Gyr); and (d) constant SF.\textsuperscript{13} The templates with prolonged SFHs were constructed using the BC03 software package, for consistency with D05 and in order to be able to run the HyperZ code.

To allow a direct comparison with other works, D05 in particular, the templates refer to a straight Salpeter initial mass function (IMF) down to $0.1M_\odot$. However, several pieces of evidence, from the redshift evolution of the fundamental plane to the $M/L$ of local Es to the metal content of the intergalactic medium strongly favor a Salpeter-like IMF down to $1M_\odot$ but flatter below as required to agree with the dynamically estimated $M/L$ ratios of early-type galaxies (Renzini 2005). The actual shape of the IMF does not affect appreciably the SED since at any age most of the light is produced by stars in a narrow mass interval around the turnover mass. However, it impacts on the amount of light emitted per unit mass turned into stars, thereby affecting the stellar $M/L$ ratio. For example, when using the IMF of Kroupa 2001 the $M/L$ ratio is a factor $\sim1.5$ smaller than in the straight-Salpeter case (M05).

The reddening was allowed to vary among the options offered in the HyperZ package, namely, Milky Way, SMC, LMC, and the so-called Calzetti law for local starbursts (references in Table 3). All these prescriptions refer to a dust-screen configuration. We additionally explore the case of no reddening.

For the objects classified as “class A redshift” by D05 the fitting procedure included also the strength of the Mg$_{\text{UV}}$ absorption feature, as defined in D05\textsuperscript{14} and measured on the GRAPES spectra. The difference between observed and model Mg$_{\text{UV}}$ strength was

\textsuperscript{12} The spacing in age during the runs is fixed by the HyperZ code, see the manual for details.

\textsuperscript{13} The models are available at http://www-astro.physics.ox.ac.uk/~maraston.

\textsuperscript{14} $M_{\text{MgUV}} = 2 \int_5^2 \frac{f_L}{f_{\odot}} d\lambda \int_2^{2.0} f_L d\lambda + \int_2^{2.0} f_L d\lambda$, where the integration limits are in angstrom units.

\begin{table}[h]
\centering
\caption{Galaxy SED Fitting Results: No reddening
}\begin{tabular}{llllllll}
\hline
ID\textsuperscript{a} & $z_{\text{spec}}$ & Model & $t$ (Gyr) & $z_{\text{form}}$ & [Z/H] & SFH & $\chi^2$ & $M^b$ \\
\hline
8238 & 1.39 & M05 & 1.0 & 1.8 & 2 & $e^{-0.10}$ Gyr & 1.5 & $0.46^{+0.48}_{-0.46}$ \\
 & & BC03 & 2.3 & 2.9 & 2.5 & $e^{-0.30}$ Gyr & 2.6 & $1.13^{+0.15}_{-0.13}$ \\
4950 & 1.55 & M05 & 1.7 & 2.7 & 2.5 & $e^{-0.30}$ Gyr & 1.5 & $2.20^{+0.4}_{-0.4}$ \\
 & & BC03 & 1.7 & 2.7 & 2.5 & $e^{-0.30}$ Gyr & 4.9 & $3.50^{+0.8}_{-0.8}$ \\
1025 & 1.73 & M05 & 1.7 & 3.2 & 2 & $e^{-0.30}$ Gyr & 2.2 & $1.00^{+0.1}_{-0.1}$ \\
 & & BC03 & 1.7 & 3.2 & 2.5 & $e^{-0.30}$ Gyr & 3.8 & $1.25^{+0.3}_{-0.15}$ \\
3523 & 1.76 & M05 & 1.4 & 2.9 & 1 & $t_{\text{trunc}} = 1.0$ Gyr & 2.2 & $0.6^{+0.5}_{-0.5}$ \\
 & & BC03 & 2.3 & 4.6 & 2.5 & $t_{\text{trunc}} = 1.0$ Gyr & 3.1 & $1.00^{+0.1}_{-0.0}$ \\
3650 & 1.91 & M05 & 0.5 & 2.2 & 2 & $t_{\text{trunc}} = 1.0$ Gyr & 2.5 & $0.65^{+0.5}_{-0.05}$ \\
 & & BC03 & 2.3 & 5.5 & 2.5 & $t_{\text{trunc}} = 1.0$ Gyr & 3.5 & $1.6^{+0.3}_{-0.2}$ \\
3574 & 1.98 & M05 & 2.3 & 6 & 1/5 & $t_{\text{trunc}} = 1.0$ Gyr & 2.6 & $0.56^{+0.1}_{-0.1}$ \\
 & & BC03 & 2.6 & 8.2 & 0.4 & $t_{\text{trunc}} = 1.0$ Gyr & 4.0 & $0.53^{+0.1}_{-0.1}$ \\
1446 & 2.67 & M05 & 0.7 & 3.7 & 1/2 & $t_{\text{trunc}} = 1.0$ Gyr & 3.0 & $0.42^{+0.11}_{-0.10}$ \\
 & & BC03 & 2.3 & 40 & 1 & $t_{\text{trunc}} = 2.0$ Gyr & 4.9 & $0.80^{+0.30}_{-0.3}$ \\
\hline
\end{tabular}
\end{table}

\textbf{Notes.—} The variable $t$ is the time since the beginning of star formation. The formation redshift $z_{\text{form}}$ refers to $t$, thereby indicating, in case of extended SFHs, the epoch at which the galaxy started to form. The last IRAC filter was excluded for objects up to $z = 1.76$, for which this filter samples rest-frame wavelengths $>2.5$ microns, that is the limit where the empirical TP-AGB star spectra are defined in the M05 models. The same filter configuration was used when the BC03 models were employed. We use the following conversion between AB and Vega magnitudes in the $B$ and $K$ bands: $M_{B\text{Vega}} = M_{B\text{AB}} - (1-0.089)$, $M_{K\text{Vega}} = M_{K\text{AB}} - (1.871)$.

\textsuperscript{a} Galaxy ID as in D05. For galaxy 1446 we use a different redshift from D05, see §3.

\textsuperscript{b} The mass is obtained from normalization of the SED. Ranges refer to the 95% confidence level. Note that the total magnitudes are defined from the values obtained from Sérsic profile fitting given in D05, Table 1.
For given mass turned into stars, such reduction is smaller in stellar after formation, most of which happens within the first few Gyrs. Including law; the reddening since the start of SF; the metallicity \[ Z / H \] giving the stellar mass of a SSP is reduced by smaller than the initial one. Adopting the prescriptions by Renzini and the synthetic SED, which provides the mass that went into stars by the age of the galaxy. This approach was retain in order to allow a comparison with D05. However, such mass overestimates those used for the M05 models. The output of the procedure includes the age, i.e., the time since the start of SF; the metallicity \[ Z / H \]; the SFH; the reddening law; the reddening \( E(B - V) \); and the stellar mass \( M^* \). The stellar mass \( M^* \) is evaluated by comparing the observed and the synthetic SED, which provides the mass that went into stars by the age of the galaxy. This approach was retain in order to allow a comparison with D05. However, such mass overestimates the true stellar mass, as stars die leaving remnants whose mass is smaller than the initial one. Adopting the prescriptions by Renzini & Ciotti (1993) for the initial mass-relevant mass relation, M98 conclude that the stellar mass of a SSP is reduced by \( \sim 30\% \) 15 Gyr after formation, most of which happens within the first few Gyrs. For given mass turned into stars, such reduction is smaller in stellar populations with extended SFHs, due to a relatively higher fraction of living stars. The actual \( M^* (t) \) for some illustrative cases of SFHs is given in Figure 3. Tables 2 and 3 give the stellar mass prior of such reduction, thus enabling a direct comparison with other results. Table 3 also reports the mass decrement (in percent) that corresponds to the given SFH and age. This mass decrement should be applied to the masses listed in column (13).

### 4. RESULTS

#### 4.1. Assuming No Reddening, \( E(B - V) = 0 \)

We first discuss the solutions that are obtained in the assumption of zero reddening. This allows us to single out the effect of stellar population modeling, thus highlighting some interesting differences between the two sets of models.

The corresponding best-fit solutions (lowest \( \chi^2 \)) for using the BC03 (blue lines) and the M05 (red line) models are shown in Figure 4. The observed SEDs are shown as solid symbols with error bars, and information on the individual galaxies and best-fit SFHs is given in Table 2. In Tables 2 and 3 we present the 95% confidence ranges for ages and masses (following Avni 1976), marginalizing over the reddening law, \( E(B - V) \), Z, and the SFH. This means that the uncertainty ranges for the latter are formally less constrained.

Overall, the M05 models allow for better fits (lower \( \chi^2 \)) for all galaxies, in the rest-frame near-IR, as well as in the blue (e.g., the objects at \( z = 1.39, 1.55, \) and 2.67). Given the ages required to fit the observed SEDs, it is likely that the different recipes for the TP-AGB phase are primarily responsible for such effect. For the objects at \( z = 1.91 \) and \( z = 2.67 \) none of the BC03-based templates was able to match the near-IR fluxes. In the case of the \( z = 2.67 \) galaxy not even an age as old as 2.3 Gyr is sufficient to obtain enough near-IR flux. Note also that a short SF phase (SF = constant until \( t_{\text{trunc}} = 0.1 \) Gyr) gives a fairly good fit with the M05 models (which are highly contributed by the TP-AGB dominated at this age), whereas an extended SF (constant until \( t_{\text{trunc}} = 2 \) Gyr) was required when using the BC03 models. In this case the shortburst obtained with the M05 templates supplies both the high optical and the high near-IR fluxes, which come from the warm turnoff and cool TP-AGB stars, respectively. The stellar masses \( M^* \) are typically smaller for the M05 models, being on average \( \sim 60\% \) of those derived with the BC03 models. In part this is a consequence of the lower ages, with the average age of M05 models being also \( \sim 60\% \) of that derived for the BC03 models. The differences are not as high as they would be in case of single bursts, as the more extended SFHs required by the BC03 models have lower \( M^*/L \) ratios.

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**TABLE 3**  
**Galaxy SED Fitting Results**

| ID\(^a\) | \( z_{\text{spec}} \) | \( z_{\text{phot}} \) | Model | \( t \) (Gyr) | \( t_{\text{trunc}} \) (Z, Gyr) | SFH | \( \chi^2 \) | \( M_{\text{b}} \) /10\(^{11}\) | \( M_{\text{b}} \) /10\(^{11}\) | Percentage of \( M^* \) |
|------|------------------|------------------|-------|--------------|------------------|------|----------|-----------------|-----------------|-----------------|
| 8238.. | 1.39             | 1.39             | M05   | 0.7          | 1.7              | 2    | 0.3 Gyr  | 0.15\(^f\)       | 1.1             | 2.4             |
|       | 1.30             | 2.3              | BC03  | 2.9          | 2.5              | e\(-31\) Gyr | 0.15\(^f\)       | 0.94             | 2.9             |
| 4950.. | 1.55             | 1.55             | M05   | 3.5          | 7.5              | 1/2  | e\(-31\) Gyr | 0.25\(^f\)       | 0.6             | 2.8             |
|       | 1.67             | 3.5              | BC03  | 3.5          | 7.5              | 1/5  | e\(-31\) Gyr | 0.07\(^f\)       | 1.1             | 0.3             |
| 1025.. | 1.73             | 1.72             | M05   | 1.4          | 3.1              | 1    | e\(-31\) Gyr | 0.15\(^f\)       | 0.64            | 1.5             |
|       | 1.77             | 3.1              | BC03  | 3.1          | 1/2.5            | e\(-31\) Gyr | 0.07\(^f\)       | 1.1             | 1.5             |
| 3523.. | 1.76             | 1.68             | M05   | 0.3          | 1.9              | 1/5  | e\(-31\) Gyr | 0.4\(^f\)        | 1.2             | 0.4             |
|       | 1.63             | 0.5              | BC03  | 2.1          | 1                | e\(-31\) Gyr | 0.4\(^f\)        | 1.2             | 0.4             |
| 3650.. | 1.91             | 1.88             | M05   | 0.3          | 2.1              | 2    | SSP      | 0.2\(^f\)        | 1.3             | 0.33            |
|       | 1.81             | 1.0              | BC03  | 2.7          | 1.5              | SSP   | 0.2\(^f\)       | 1.9             | 2.0             |
| 3574.. | 1.98             | 1.94             | M05   | 0.2          | 2.1              | 2    | SSP      | 0.3\(^b\)        | 2.5             | 0.2             |
|       | 1.94             | 1.0              | BC03  | 2.9          | 1/5              | SSP   | 0.2\(^f\)       | 2.               | 0.7             |
| 1446.. | 2.67             | 2.74             | M05   | 0.25         | 2.96             | 2    | SSP      | 0.25\(^f\)       | 1.87            | 0.7             |

**Notes:** The best-fit parameters and \( \chi^2 \) refer to the model obtained using the spectroscopic redshift \( z_{\text{spec}} \). The values \( z_{\text{phot}} \) are given for comparison. See Table 2 for other notes.

\( a \) Galaxy ID as in D05. Note that for the galaxy 1446 we use a different redshift from D05, see § 3.

\( b \) Through \( M^* / L_{\text{bkg}} \) and \( M^* / L_{\text{bkg}} \).

\( c \) See Table 2, footnote b.

\( d \) From D05.

\( e \) This column gives the percentage of mass decrement due to stellar mass loss. It should be applied to values in col. (12).

\( f \) SMC reddening law as in Prevot et al. (1984) and Bouchez et al. (1985).

\( g \) Reddening law as in Calzetti et al. (2000).

\( h \) LMC reddening law as in Fitzpatrick (1986).
The most relevant difference in the results from the two sets of models is about the implied formation redshifts (see Table 2). Using BC03 models the stellar populations form at higher redshifts (sometime at much higher redshifts, see e.g., the object at \(z = 2.67\)) and, since the galaxies are also more massive compared to the case when using M05 models, an appreciably faster mass growth of galaxies is implied.

4.2. \(E(B - V)\) as a Free Parameter

The best-fit solutions when also reddening is treated as a free parameter are displayed in Figure 5, and the parameters of the best fits are given in Table 3. For this “reddening” case, in order to exploit all the available information and to control the degeneracies introduced by the larger number of free parameters, we have additionally included the strength of the MgUV feature in the computation of the \(\chi^2\). This was done only for galaxies with Class A redshift, namely, for objects 4950, 1025, 3650, 3574, because for the Class B objects the MgUV is a less robust measurement (D05). Hereafter, unless explicitly stated, text and figures refer to the solutions obtained with variable reddening.

By allowing the best-fit procedure to treat \(E(B - V)\) as an additional free parameter, and allowing it to choose among four different reddening laws, it is no surprise that solutions with appreciably better \(\chi^2\) are found. However, this does not ensure that such solutions are more likely than those assuming \(E(B - V) = 0\). It is also no surprise that some best fits require the Calzetti law, whereas others prefer the SMC law. In just one case the LMC law was preferred, while in no cases the Milky Way law was chosen.

In general, the inclusion of reddening reduces the ages of the best fits obtained with the BC03 models, making them closer to those obtained with the M05 models. However, reddening does not always help to improve substantially the fits to the IRAC bands, like in the case of objects 3650. TP-AGB effects cannot be traded with dust or metallicity effects, which helps reducing the degeneracies in the age determination. Detailed comments on the best fits for the individual galaxies are given in the Appendix.

Figure 6 compares the GRAPES HST ACS spectrum of object 3650 at \(z = 1.91\), with the best-fit solutions corresponding to the BC03 and M05 models (see Table 3). We use this plot for illustrating the effect of the age/metallicity degeneracy that affects the optical, but is alleviated in the near-IR due to the distinctive spectral features of TP-AGB stars. The best-fit solutions recover similarly well the strength of the MgUV line and the spectral shape around it, in spite of having different population parameters, namely, young and metal-rich for the M05 models and older and metal-poor for the BC03 models. However, the BC03-based
solution gives an appreciably poorer fit to the near-IR SED (see Fig. 5), showing how the inclusion of the near-IR fluxes can help breaking the age/metallicity degeneracy.

However, in most cases spectral absorptions and photometric data on a wide spectral range are not available simultaneously. How realistic are then the best fits obtained from the sole photometry? To get insight on this issue, we have repeated the fitting procedure without including the MgUV line when searching the best-fit model. We have then checked how well these “photometric” best-fit models recover the observed MgUV.

This is shown in Figure 7, in which the MgUV strengths predicted by the best-fit “photometric” models are compared to the observed ones. The $\chi^2$ are 1.5 and 6.3, respectively, the former implying that data and predictions are completely consistent, the latter implying a rejection at the 99.9% level. Although based on a very small number of objects, the predicted values from the M05 models are more accurate than those from the BC03 models.

As a final exercise, we have checked the effect on photometric redshifts derived using one or the other set of population models, and of the inclusion of the IRAC fluxes. Photometric redshifts have been computed with the HyperZ code and the same sets of templates and reddening laws that we use for the SED fitting at fixed spectroscopic redshift (z = 3.1). The results are given in Table 3 and shown in Figure 8. The photometric redshifts obtained with the M05 templates are in better agreement with spectroscopic redshifts than those obtained with the BC03 models. The dispersion of the residuals is 0.046 for the M05 models and 0.122 for the BC03 models. The accuracy on the photometric redshifts determined with the M05 templates, in the case of this sample, is 2.6 times better. The photometric redshifts obtained with the BC03 models and the IRAC data appear to be more discrepant than those in which only magnitudes up to $K$ were used (cf. D05). Also these effects likely originate from the different TP-AGB recipes.

Interestingly, we have found that the photometric redshift with the minimum $\chi^2$ was found using the same reddening law as the best-fit SED fitting. If we had used only one reddening law the photometric redshifts would have been worse. This result further supports our treatment of the reddening as a free parameter.

### 4.3. Stellar Masses

The different SFHs derived from the different models have an impact on the derived stellar masses, which is summarized in Figure 9. The top panels display the effects of the models (i.e., M05 vs. BC03) on the derived stellar mass of galaxies, when using only the optical and near-IR bands (left panels) and when also the IRAC 3.5–8 $\mu$m data are used (right panels). The masses predicted by the M05 templates are lower, which is a consequence

Fig. 5.—Same as Fig. 4, but for $E(B-V) \neq 0$. The parameters of the best fits are provided in Table 3.
of the lower ages. The effect is appreciably more pronounced when the IRAC bands are included, as the TP-AGB phase (the most discrepant ingredient between the two models) has its largest contribution in the rest-frame near-IR. However, lower masses can also be derived when the observed-frame $K$ is the reddest band used in the best fit. In fact, for the objects at $z = 1.39$, 1.55, and 1.73, the $K$ band samples the rest-frame $I$, which is already affected by the TP-AGB (M05, Fig. 18). In addition, the later onset of the RGB phase in the overshooting tracks adopted by BC03 helps to make the BC03 templates fainter at ages around 0.5 Gyr. The corresponding $M/L$ ratio is higher and a higher $M/C_3$ is derived (see §2).

The bottom panels in Figure 9 show the effects (for given stellar population models) of the wavelength range included in the fitting procedure: only up to the $K$ band (on the $x$-axis) and with the IRAC bands (on the $y$-axis). The results based on BC03 are not appreciably affected by the inclusion of the IRAC bands (as recently pointed out by Shapley et al. 2005). Instead, for the M05-based solutions, three galaxies are found to have appreciably lower masses when the IRAC fluxes are considered, again the likely effect of the inclusion of the TP-AGB contribution.

Finally, Figure 10 compares the masses obtained in this paper (including the IRAC data) with the calibration for $z \sim 2$ BzK-selected galaxies proposed by Daddi et al. (2004). This calibration was obtained using the observed $K$-band magnitude and $z-K$ color only, along with the BC03 templates. The figure shows that the calibration is well consistent with the BC03-based masses derived in this paper, which is no surprise. The M05 models suggest instead a calibration lower by 0.2 dex, on average.
4.5. The Role of AGNs

In obtaining the best-fitting models we have assumed that the observed SEDs are the results of just stellar emission (in case partly reprocessed by dust). The possible presence of an AGN would obviously affect the SED beyond the contribution of stellar populations. However, differences between the physical properties of galaxies inferred with the M05 or BC03 models remain, as these models have a different ratio of optical to near-IR flux. Therefore, even if at play, AGNs would not alter the sense of this comparison.

More specifically, AGNs probably play a minor role on our analysis. First, no clear AGN features, such as the Mg $\text{II}$ $\lambda$2800 in emission, are observed in the ACS spectra of these galaxies (D05). Also, the shape of the SED over IRAC is clearly stellar with a secure identification of the peak emission at 1.6 $\mu$m. Two of the galaxies (1025 and 1446) have X-ray detections, but as discussed in D05 these are very hard and therefore the AGN in these galaxies must be heavily obscured. Coupled to the evidence of the faintness of the galaxies at 24 $\mu$m, we conclude that the AGN should not influence appreciably the photometry from the UV to the near-IR rest-frame. For example, if we adopt the SED shapes of NGC 1068 or Mrk 231 and normalize them to the 24 $\mu$m photometry of the sources, the contribution of the AGN to the optical to near-IR light of the galaxies would be negligible. Similarly, from the narrow K-band to X-ray flux correlation of AGN shown by Brusa et al. 2005 we conclude that possible AGN in our sources are expected to provide a negligible contribution to the K-band light of our galaxies.

Finally, the overall good agreement between predicted and observed Mg$_{\text{UV}}$ line-strengths (Fig. 7) and the good match between spectroscopic and photometric redshifts (Fig. 8) suggest that a significant AGN contribution is highly unlikely.

5. DISCUSSION

The aim of this paper is to explore how much the SFHs, ages, and masses of high-$z$ galaxies, that are derived by fitting observed to synthetic spectral energy distributions depend on the adopted stellar population models. In particular, we focused on the TP-AGB evolutionary phase, because TP-AGB stars are the dominant bolometric and near-IR contributors in stellar populations with ages $\sim$1 Gyr (M98; M05). Therefore, such phase must be of primary importance at high redshift, when the universe itself was just a few Gyrs old (Maraston 2004, 2005; Renzini 1992), and especially in the interpretation of Spitzer data for high-$z$ objects. The recipes for the TP-AGB phase are found to differ significantly among various models (see M05), which has motivated us to check the robustness of the results obtained for high-$z$ galaxies.

To this aim we have analyzed a sample of mostly passively evolving high-$z$ ($1.4 \leq z \leq 2.7$) galaxies with optical and Spitzer IRAC photometry, modeling the whole spectral energy distribution from the rest-frame $B$ to $K$. The analysis was performed with two libraries of stellar models: the M05 models in which the TP-AGB phase is calibrated on Magellanic Cloud globular clusters, and the BC03 models in which, as in most other models in the literature (e.g., Pégase, Starburst99), the energy contribution from the TP-AGB phase is significantly lower than in the Maraston models. Furthermore, the two models adopt stellar evolutionary tracks, in which the onset of the red giant branch is predicted at different ages, which also impact on the time evolution of the synthetic spectral energy distribution. The differences between stellar population models are widely discussed in M05 and recalled in §2.

Besides the 14 photometric bands spanning from rest-frame $B$ to $K$, the procedure introduced in this paper also includes the strength of a near-UV absorption feature (the Mg$_{\text{UV}}$ at 2800 Å; see D05) for searching the best-fit galaxy models. In this way the effect of the age/metallicity degeneracy is substantially reduced. We have also checked that even without using the spectroscopic information, but only with the photometric SED, the best fits obtained with the M05 models recover well the strength of the Mg$_{\text{UV}}$ feature, hence provide consistent models for distant galaxies.

We then show to which extent the derived ages and masses of the sample galaxies are model dependent. The M05 models typically match the rest-frame near-IR and optical very well, without invoking strong reddening and without violating the constraint set by the age of the universe. The BC03-based solutions exhibit in some cases near-IR fluxes that are significantly lower than the data, which requires the addition of old stellar populations or dust reddening or a combination of the two. This is reminiscent of recent results on high-$z$ galaxies in which Spitzer IRAC data are interpreted with the BC03 models (e.g., Yan et al. 2004) or the
galaxies, where the stellar populations are young therefore TP-AGB therefore on the impied galaxy formation scenarios. The Pe´ gase models (e.g., Villar-Martı´n et al. 2006). The young solutions required to match the blue side of the SED could not match the rest-frame near-IR, which led the authors to assume an underlying old population to be responsible for the near-IR fluxes. The age of the — dominant by mass — old component, comparable to the age of the universe, makes the SFH contrived.

The lower masses derived from the M05 models may help understanding the origin of an apparent discrepancy noted by D05 and concerning the relationship between the physical sizes and the masses of the galaxies in the present sample. The galaxies were found to be too small for the given masses in comparison to local early-type galaxies. The lower masses derived here already help in alleviating the discrepancy, but do not solve it entirely.

According to the best-fit BC03 models, three galaxies have rather low metallicities $(Z/z)/5$ and at the same time high masses $(>10^{11} M_\odot)$. Such objects do not match the high metallicity that seems to feature local early-type galaxies. For example, Maraston et al. 2003, by comparing the absorption indices of early-type galaxies with those of bulge globular clusters, empirically show that the metallicity of early-type galaxies must exceed the solar value, since the galaxy indices are higher than those of the solar-metallicity globular clusters (their Fig. 1). Metallicity gradients are going to decrease the light-average-determined metallicity slightly, but not to such low values (Mehlert et al. 2003). Only one such object is found with the M05 models.

Finally, we find that the stellar population models impact on photometric redshift determination. The use of IRAC bands and M05 models give photometric redshifts that are in excellent agreement with the spectroscopic ones. Again, we ascribe this effect to the prescriptions for the TP-AGB phase.

It is embarrassing to realize to which extent the recipes for the TP-AGB phase and the convective overshooting impact on the stellar ages and masses that are derived for high-$z$ galaxies, and therefore on the impied galaxy formation scenarios.

In this work we have focused on predominantly passive high-$z$ galaxies, where the stellar populations are young therefore TP-AGB stars must exist. Our spectral fitting represents the first direct evidence for such stars in the early universe. Going to even higher redshifts might reveal further interesting aspects of galaxy evolution, a scope we are pursuing in the future. However, TP-AGB stars may matter at any redshift depending on the specific SFH. For example, van der Wel et al. (2006) measured the evolution of the rest-frame $K$-band fundamental plane from $z \sim 1$ to the present, by using IRAC imaging of a sample of early-type galaxies. They find that the $K$-band luminosities of the low-mass objects are too large (at given $B$ luminosity), or the $B - K$ colors too red, with respect to the prediction of the BC03 or Vazdekis et al. (1996) models. The M05 models were found to provide a better match to the data, which was attributed to the treatment of the TP-AGB phase.

In conclusion, the specific recipes used to construct the stellar population models play a central role in the derivation of the SFHs of high-$z$ galaxies. This should be kept in mind when the derived parameters such as ages and masses are used to constrain galaxy formation. In a future paper we will repeat the same analysis on a much larger sample of high-$z$, selected as actively star-forming galaxies, in order to establish also for that case the uncertainties in deriving their ages and masses due to stellar population models.

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APPENDIX

Here we comment in more details on the best fits obtained for individual objects for the reddening case (see Table 3).

$8238$, $z = 1.39$.—The $M_{\text{GUV}}$ line was not included in the $\chi^2$. The object is $\sim 0.7$ Gyr old, metal-rich, and in passive evolution since 0.4 Gyr. The reddening follows an SMC-like law. The stellar mass is $0.45 \times 10^{11} M_\odot$ with small dispersion. For the BC03 models, the best solution has a worse $\chi^2$, a significantly older age and a significantly longer formation timescale. The stellar mass is a factor of 2.2 larger and consistent with what obtained in D05 from fitting the sole optical bands. It is interesting to note that the same, stellar mass would have been derived by fitting the M05 models up the solar observed-frame $K$ (see Fig. 9). This is due to two effects. First, at redshift $\sim 1.4$ the observed $K$ samples into the rest-frame $J$, which is already affected by the TP-AGB prescriptions (M05). Second, as pointed out in § 2, another important difference between the two sets of models exist, namely, the energetics of the different input stellar evolutionary tracks. The M05 models are based on tracks in which the RGB phase starts developing at younger ages with respect to the Padova tracks used in BC03. The delay in the latter is due to the overshooting (see discussion in M05). The result is that the M05 SSP models are brighter around 1 Gyr (cf. M05, Fig. 7), which implies a lower stellar mass, an effect anticipated in M05. It should be noted that the earlier onset of the RGB phase compares very well with the observed RGB contribution in Magellanic Cloud globular clusters (Ferraro et al. 2004), while the predictions based on the Padova tracks display a severe discrepancy with the data.

$4950$, $z = 1.55$.—The $M_{\text{GUV}}$ line was included in the $\chi^2$. The best-fit solution is 3.5 Gyr old, is forming stars according to a tau model with $e$-folding time of 1 Gyr, the metallicity is half-solar, and $E(B-V) = 0.15$ (SMC law). The extended SFH is consistent with the irregularities and blobs in the $B$-band image and with its spiral-like morphology (D05). This galaxy has a huge de Vaucouleurs bulge and turned out to be the most massive object of the sample. The observed $M_{\text{GUV}}$ is remarkably well reproduced by this model. $M_\star$ is large and very well constrained. It is consistent with both the value of D05 and that derived here with the BC03 models. The best solution obtained with the BC03 models has similar overall parameters, but the reddening is larger and the $\chi^2$ is worse.

$1025$, $z = 1.73$.—The $M_{\text{GUV}}$ line was included in the $\chi^2$. The best fit is $\sim 1.4$ Gyr old, still forming stars at a very modest rate ($\tau$ model, with $\tau = 0.3$ Gyr). The stellar mass is $0.6 \times 10^{11} M_\odot$. The solution obtained with the BC03 model has a lower metallicity and a larger mass.

$3523$, $z = 1.76$.—The $M_{\text{GUV}}$ line was not included in the $\chi^2$. The $M_{\text{GUV}}$ for this galaxy is very small $(0.094 \pm 0.09 \, \text{Å})$, which implies either very young ages or very low metallicities. The solution allowing for the best comparison to the observed line turned out...
to be young and rather metal-poor. Its MgUV is 1.07. The galaxy is passively evolving since 0.2 Gyr. The solution obtained with the BC03 models allows a worse match to the MgUV line (1.14) because of the higher metallicity. A higher metallicity is found because it provides more flux to the near-IR.

3650, z = 1.91.—The Mg UV line was included in the $\chi^2$. The galaxy is young and metal-rich, and in passive evolution for the M05 models. It has formed stars at a remarkable rate as $M^*$ is $8.3 \times 10^{11} M_\odot$. The spectrum displays a nice near-IR excess that is very well fitted. The match to MgUV is remarkable good (1.25 vs. the observed 1.25). The solution obtained with the BC03 models is older and significantly more metal-poor, although the stellar mass of the galaxy if higher ($2 \times 10^{11} M_\odot$). This mass is too large for a metallicity $Z$ in comparison with what found in the local universe. This solution matches worse to the observed SED.

3574, z = 1.98.—The Mg UV line was included in the $\chi^2$. The best fit is young, metal-rich, and rather highly reddened. The model is passively evolving. The best solution obtained with the BC03 models is older and metal-poor.

1446, z = 2.67.—The Mg UV line was not included in the $\chi^2$. In this paper we use a recent re-determination of the spectroscopic redshift (see §3) that is now in much better agreement with the photometric one obtained with the M05 templates. The fit using the M05 templates is good in both the cases of zero and not zero reddening (Figs. 4 and 5). In case of the BC03 templates the non-reddening option provides a worse fit, the template clearly lacking near-IR flux.

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ERRATUM: “EVIDENCE FOR TP-AGB STARS IN HIGH-REDSHIFT GALAXIES, AND THEIR EFFECT ON DERIVING STELLAR POPULATION PARAMETERS” (ApJ, 652, 85 [2006])

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Due to an error at the Press, in Table 1 data are incorrect for HUDF 4650 for the J, F160W, K, and m bands, and for all galaxies in the last two columns, m(8.0 μm) and MIPS (24 μm) (which incorrectly repeat previous columns). The correct full table is given here.

The Press sincerely regrets this error.

| ID    | F435 | F606 | F817 | F895 | F110 | J     |
|-------|------|------|------|------|------|-------|
| 8238  |      |      |      |      |      |       |
| 4650  |      |      |      |      |      |       |
| 1025  |      |      |      |      |      |       |
| 3523  |      |      |      |      |      |       |
| 3650  |      |      |      |      |      |       |
| 1446  |      |      |      |      |      |       |
| 3574  |      |      |      |      |      |       |
| 1446  |      |      |      |      |      |       |

| ID    | F160W | K    | m(3.6 μm) | m(4.5 μm) | m(5.8 μm) | m(8.0 μm) | (μJy) |
|-------|-------|------|-----------|-----------|-----------|-----------|-------|
| 8238  |       |      |           |           |           |           |       |
| 4650  |       |      |           |           |           |           |       |
| 1025  |       |      |           |           |           |           |       |
| 3523  |       |      |           |           |           |           |       |
| 3650  |       |      |           |           |           |           |       |
| 1446  |       |      |           |           |           |           |       |
| 3574  |       |      |           |           |           |           |       |

Note.—The magnitudes are in AB system, which are related to flux density \( f_\nu \) (in ergs s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\)) by \( m = -2.5 \times \log (f_\nu) - 48.60 \).