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Ages of elliptical galaxies: single- versus multi-population interpretation

T. P. Idiart, J. Silk and José A. de Freitas Pacheco

ABSTRACT

New calibrations of spectrophotometric indices of elliptical galaxies as functions of spectrophotometric indices are presented, permitting estimates of mean stellar population ages and metallicities. These calibrations are based on evolutionary models including a two-phase interstellar medium, infall and a galactic wind. Free parameters were fixed by requiring that models reproduce the mean trend of data in the colour–magnitude diagram as well as in the plane of indices Hβ–Mg2 and Mg2–(Fe). To improve the location of faint ellipticals (MB > −20) in the Hβ–Mg2 diagram, downsizing was introduced. An application of our calibrations to a sample of ellipticals and a comparison with results derived from single stellar population models are given. Our models indicate that mean population ages span an interval of 7–12 Gyr and are correlated with metallicities, which range from approximately half up to three times solar.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: ISM.

1 INTRODUCTION

The formation of galaxies is certainly one of the most-challenging open problems in cosmology, since theory must account for the evolution and integrated galaxy properties (Silk 2004). Among the different morphological types, elliptical (E) galaxies are the simplest ones, with mass indicators like the central velocity dispersion presenting robust correlations with different spectrophotometric properties (see de Freitas Pacheco, Michard & Mohayaee 2003, for a review). From a theoretical point of view, different formation scenarios have been proposed: one is monolithic collapse, in which the gaseous material is assembled either in the form of a unique cloud (Larson 1974a) or by interaction and merging of a hierarchy of many primeval lumps of matter, not including pre-existing stars, into a protogalaxy (Peebles 2002; Matteucci 2003). The alternative picture, that of hierarchical merging, considers that galaxies form from successive non-dissipative mergers of small-scale haloes over a wide redshift range (White & Rees 1978; Toomre 1977; Kauffmann 1996; Baugh, Cole & Frenk 1996; Baugh et al. 1998). Thus, a fundamental aspect is whether any of the observable properties of E galaxies contains an imprint of their previous formation history which, in essence, is related to the stellar population formation history. Therefore, the key questions are when the bulk of stars were formed and if ellipticals evolved passively or were modified, and to what extent, by interactions with the environment.

In this context, the age distribution of stellar populations in E galaxies is essential to understand their origin and evolution. Absorption line indices combined with colours are powerful tools to derive ages and metallicities of the stellar populations constituting early-type galaxies. However, the interpretation of these integrated spectral characteristics necessarily requires the use of models. In the past, this exercise has been accomplished by different authors using either single stellar population (SSP) models or evolutionary models (EVMs).

SSP models are straightforward applications of the theory of stellar evolution. Given an initial mass function (IMF) and chemical composition, the evolution of such a population and its corresponding spectral characteristics are completely defined. Properties of E galaxies derived from observed spectral indices and SSP models were obtained by Worthey (1994), Trager et al. (2000), Thomas, Maraston & Bender (2003) and, more recently by Howell (2005), among others. Most of these studies have concluded that E galaxies present a small spread in metallicity but span a wide range of ages.

Elliptical galaxies are certainly not single population systems and the reason generally invoked to interpret data by using SSP models, besides simplicity, is that the bulk of stars in E galaxies formed on a short time-scale and, consequently, all stars should have similar ages. Even if the age range of the population mix constituting the galaxy would be quite narrow, the build-up of chemical elements requires successive stellar generations, which are necessarily described by a metallicity distribution. Analyses of mid-ultraviolet (mid-UV) indices by Lotz, Ferguson & Bohlin (2000) clearly demonstrate that single-age and single-metallicity populations are able to explain globular cluster data (true single-population systems) but not E galaxies. Analytical models are, in general, of the
‘one-zone’ type including (or not) mass loss from galactic winds or infall of matter from the intergalactic medium. Star formation begins when a critical gas density is attained and the evolution of the population mix is calculated by summing the properties of SSP models, representative of successive stellar generations. Their formation rate is controlled by the amount of residual gas available for star formation, whereas their chemical composition results from the progressive enrichment in ‘metals’ of the interstellar medium (ISM) by matter ejected from stars, notably supernovae. Examples of evolutionary models can be found in Matteucci & Tornambe (1987), Bressan, Chiosi & Tantalo (1996), Vazdekis et al. (1996), Kodama & Arimoto (1997) and Idiart, Michard & de Freitas Pacheco (2003, hereafter IMP03). In general, these models lead to mean metallicities and [Mg/Fe] ratios comparable to those derived from SSP models, but significant disagreements remain on age determinations of the bulk stellar population.

In this work, new calibrations of spectrophotometric indices permitting estimates of mean ages and metallicities of the stellar population mix constituting early-type galaxies are reported. These calibrations are based on evolutionary models in which the free parameters were adjusted in order to adequately reproduce not only the colour–magnitude diagram (CMD) but also the observed strength of indices like Hβ, Mg2 and (Fe). In spite of adopting the classical ‘one-zone’ approximation, the present model simulates the existence of a two-phase ISM in which stars are formed only in cold gas regions, allowing also a gradual assembly of the galaxy as well as the presence of a galactic wind. The anti-correlation between the indices Hβ and Mg2 can be explained if we make appeal to the downsizing effect (Cowie et al. 1996). Thus, in our model sequence, the less-massive galaxies are assembled later (z ∼ 0.8) than the more-massive ones (z ∼ 3–4). We have also assumed that dust is mixed with the residual gas producing a small internal reddening, which improves the fit of the aforementioned diagrams. This paper is organized as follows: in Section 2 the main features of the model are described; in Section 3 the results for a grid of fiducial models are presented as well as the resulting calibrations for mean ages and metallicities; finally, in Section 4 the main conclusions are given.

2 THE MODEL

2.1 The mass-balance equations

The model is based on the ‘one-zone’ approximation and thus it cannot predict spatial variations. However, when performing the mass balance, we have assumed that the gas is either in a hot or in a cold phase, where the former is a consequence of mass ejection by evolved stars and hot gas ‘cavities’ produced by supernova explosions. The presence of hot gas in bright ellipticals is well established by X-ray observations, which indicate the existence of diffuse thermal emission in these objects, and observations indicate also that cold molecular clouds and not the hot gas phase are the sites of star formation. Two-phase models have been considered in the past and, among others, we mention the work by Ferrini & Poggianti (1993) and that by Fujita, Fukumoto & Okoshi (1996), who have initially adopted a ‘one-zone’ model and, in a subsequent investigation, considered a spherical galaxy with a given mass distribution to study local properties (Fujita, Fukumoto & Okoshi 1997). Here, a more simplified version of these approaches is considered. In order to establish the mass-balance equations, we consider that, as a consequence of the stellar evolution, the gas returns to the medium, contributing to the hot phase. Supernovae are additional sources of hot gas since they inject mechanical energy into the ISM through blast waves produced by the explosion. The onset of a galactic wind removes hot gas from the system and radiative cooling followed by recombination processes transforms part of the hot gas into the cold phase.

We define the gas fraction \( f_g(t) \) as the ratio between the total gas mass present in the galaxy at an instant \( t \) and \( M_0 \), a quantity representing the total mass acquired by the galaxy by ‘infall’ processes (‘infall here means continuous accretion or sudden variations in mass by merging events). If \( x_h(t) \) and \( f_g(t) \) are, respectively, the gas fractions in the hot and in the cold phases, we define \( x_h(t) = f_g(t)/f_g(t) \) and \( f_g(t) = f_g(t)/f_g(t) \) such that \( x_h(t) + x_c(t) = 1 \). Under these conditions, two equations are required to describe the evolution of the total gas fraction \( f_g(t) \) and, for instance, the fraction \( x_h(t) \) in the hot phase, since \( x_h(t) = 1 - x_c(t) \).

The equation governing the total gas fraction \( f_g(t) \) evolution can be written as

\[
\frac{df_g(t)}{dt} = -k(1 - x_h(t))f_g(t) + \frac{df_g(t)}{dr} - \frac{x_h(t)f_g(t)}{\tau_w} + R_{\text{as}}. \tag{1}
\]

The first term on the right-hand side represents the amount of cold gas which is transformed into stars. The star formation rate normalized with respect to \( M_0, R_{\text{as}}(t) = kx_h(t)f_g(t) \), was assumed to be proportional to the available amount of cold gas, with an efficiency \( k \) given in Gyr\(^{-1}\). The second term represents the gas returned to the ISM at a rate

\[
\frac{df_g(t)}{dr} = k \int_{m_1}^{m_0} (m - m_1) \xi(m) R_{\text{as}}(t - \tau_m) \, dm. \tag{2}
\]

The upper limit of the integral was taken equal to 80\( M_0 \) and the lower limit corresponds to the stellar mass whose lifetime is equal to \( t \). In the integrand, \( m_1 \) is the mass of the remnant, which depends on the progenitor mass, \( \xi(m) = A/m^2 \) is the IMF and the star formation rate is to be taken at the retarded time \( (t - \tau_m) \), where \( \tau_m \) is lifetime of a star of mass \( m \). The adoption of a power law at low masses for the IMF is a simplifying assumption that has no bearing on our results, which depend only on the slope at the massive end, which we indeed will vary as a model parameter. The third term represents the mass loss by the galactic wind, whose rate was assumed to be proportional to the amount of hot gas. Finally, the last term gives the rate at which the galaxy accretes mass, here assumed to be of the form \( R_{\text{as}} \propto e^{-t/\tau_c} \).

The second equation, which describes the evolution of the fraction \( x_h(t) \) of hot gas is

\[
\frac{dx_h(t)}{dt} = -x_h(t) \frac{df_g(t)}{dr} + \frac{m_H}{M_0} \frac{1}{f_g(t)} \sum Q_i v_i + \frac{1}{f_g(t)} \frac{df_g(t)}{dr} - \alpha(T) M_0 \frac{x_h(t)}{m_H v_0} f_g(t) - \frac{x_h(t)}{\tau_w}. \tag{3}
\]

In this equation, the first term on the right-hand side, since \( x_h(t) \) is defined with respect to the total gas fraction, takes into account the time-variation of the ‘background’. The second term represents the production of hot gas by supernovae and the sum is performed over both types Ia and II; \( Q \) is the mean number of atoms converted into the hot phase per explosion. This number corresponds to the amount of interstellar gas swept by the blast wave when forming the ‘hot cavity’. Using the Sedov theory, \( Q = 1.35E/m_n V_0^2 \), where \( E \) is the energy of the explosion and \( V_0 \) is the shock velocity. As in Fujita et al. (1997), we assume that the hot gas cavity ends its evolution when the shock velocity is comparable to the stellar velocity dispersion. The frequency \( v_{17} \) of type II supernovae was estimated by

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considering that only stars in the range 9–45 M⊙ explode, whereas the frequency νut of type Ia supernovae was calculated as in Idiart, de Freitas Pacheco & Costa (1996). The third term corresponds to the contribution of the returned gas (see above) and the fourth term gives the rate at which the hot gas, after cooling, recombines into neutral and cold gas. In this term, α(T) is the effective recombination coefficient and Vg is the volume occupied by the gas, identified with the volume of the galaxy. We have assumed a spherical galaxy whose radius is fixed at any time by the radius–mass relation given by Gibson (1997). Finally, the last term gives the rate at which the hot gas is removed by the galactic wind.

Besides the gas evolution, the chemical enrichment of the galaxy is also followed. The chemical evolution is described by the usual equations but includes the contribution of the ‘infall’ term, which dilutes the abundances of heavy elements and the contribution of the wind, which removes enriched gas and modifies the chemical composition of the nearby primordial intergalactic medium. Yields for massive stars were taken from Nomoto et al. (1997a) and those from type Ia supernovae were taken from model W7 by Nomoto et al. (1997b).

### 2.2 Spectrophotometric indices

Integrated luminosities for SSP models for different photometric filters were recalculated by taking into account variations in the exponent of the IMF, in order to obtain self-consistent results. In fact, as in our previous study (IMP03), small variations in the IMF exponent γ were required in order to increase the magnesium yield. The CMD of ellipticals is conventionally interpreted as a mass–metallicity sequence. Larson (1974b) suggested that such a sequence could be explained by a galactic wind able to gradually halt the star formation process as the galaxy mass increases. However, a longer duration of the star formation activity also increases the contribution process of the returned gas (see above) and the fourth term gives the rate at which the hot gas is removed by the galactic wind.

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### 2.3 The computation procedure

In IMP03, models were tailored to reproduce the CMD of E galaxies in Coma and Virgo, since this relation is tight for cluster ellipticals, whereas the scatter increases for E galaxies in the nearby field and in small groups (Schweizer & Seitzer 1992). Here a different approach was adopted. Since we have searched for models able to reproduce simultaneously different spectrophotometric indices, a sample of E galaxies was prepared, including objects with available total magnitudes, which are more representative of colours computed by modellers (see, for instance, a discussion in Scodeggio 2001 and Kaviraj et al. 2005) as well as other spectrophotometric data (Hβ, Mg2 and (Fe) indices), required to fix the parameters of our models.

The system of equations to be solved have three main free parameters: the star formation efficiency k, the ‘infall’ time-scale and the exponent of the IMF. The wind time-scale τw is not a real independent parameter as we will see below. Initially, a grid of models were computed under the assumption that the star formation activity began at the same time for galaxies of all masses. If this hypothesis implies that galaxies have the same age, it does not imply that their stellar populations have the same mean age, because the star formation rate is not necessarily the same for galaxies of different masses. Each model in the grid is characterized by the total mass M0 acquired by infall. Once this parameter is fixed, for a given value of τinf, the initial accretion rate is fixed. In a second step, we adopt a value for the star formation efficiency k. Miranda (1992) derived from hydrodynamic models for the spherical collapse, including a galactic wind, a relation between the fraction of gas lost fW by the galaxy and parameters characterizing the gravitational potential well and the star formation efficiency, as an indicator of the supernova heating. His results can be quite well fitted by the expression

\[
\log f_W = 2.150 - 0.294 \log M_0 + 0.222 \log \langle kT_{age} \rangle.
\] (4)

Adopting this relation, the value of the wind parameter τW is immediately fixed. The numerical solution was performed without using the ‘instantaneous recycling approximation’, leading to the metallicity distribution function required to compute the integrated spectrophotometric properties as in Idiart et al. (1996). For different values of M0, a sequence of models were computed in which the aforementioned free parameters were varied in order to reproduce data on the diagrams (U−V)−Mg, Hβ−Mg and Mg2−(Fe).

If, as in IMP03, the trend of data in the CMD can be well reproduced, this approach leads to faint galaxies with Hβ indices systematically smaller than observations. A possible interpretation of the observed inverse correlation between the indices Hβ and Mg2 was already given in the early 1990s either by Sadler (1992) or by Faber, Worthey & Gonzalez (1992), who concluded that the stellar populations of the brightest E galaxies are older than less-luminous objects. This is consistent with the work by Cowie et al. (1996) who, based on an analysis of the luminosity function in the K band of deep fields, concluded that ‘the mass of star-forming galaxies decreases with redshift’, immortalized as the downsizing in the [α/Fe] ratio. We have also revised our previous index calibrations (Idiart & de Freitas Pacheco 1995; Borges et al. 1995), including additional stellar data to our library in order to have a better representation of solar and non-solar objects.

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1 The required fitting functions for single-population syntheses are available on request from the authors.
effect (see also Juneau et al. 2005). More recent data derived from deep surveys ($z \sim 1–2$) reveal an excess of massive galaxies with respect to predictions of the hierarchical scenario (Cimatti et al. 2004; Glazebrook et al. 2004) or, in other words, that massive ellipticals were already in place at these high redshifts with little subsequent merging, whereas less-massive E galaxies present features characteristic of star formation in the more recent past (Ferreras & Silk 2000). All these observations are contrary to expectations for the hierarchical growth of structure in a cold dark matter dominated universe, in which large haloes form late by coalescence of smaller ones.

These facts lead us to consider models with an ‘inverted hierarchy’ by assuming that less-massive galaxies are assembled later than massive ones and, as a consequence, being constituted by a stellar population mix relatively younger than that of bright galaxies. In practise, this means we have abandoned the previous idea in which the starting points for mass assembly and for the beginning of the star formation activity are the same whatever be the mass of the galaxy. The departure time for assembly and the beginning of star formation activity was then adjusted in order to improve the location of modelled galaxies in the Hβ–Mg2 diagram. Moreover, observations suggest that some dust may be mixed with the residual gas in E galaxies (e.g. Leeuw et al. 2004; Temi, Brighenti & Mathews 2007). A small internal extinction will in particular affect the bluer colours, requiring a slightly higher star formation efficiency to compensate for such a reddening and produce an increase in the Hβ strength. This effect goes in the same sense as downsizing. Thus, we have included this possibility in our models by assuming that dust is homogeneously mixed with stars. The transfer equation was solved by considering a plane–parallel geometry and, under these conditions, the reddened magnitude in a given filter is given by

$$M_\lambda = M_{\lambda,0} - 2.5 \log \left[ \frac{1}{\tau_{\text{eff}} (\sqrt{1 - \omega_2} + \coth \tau_{\text{eff}})} \right]$$

$$= M_{\lambda,0} + A_\lambda,$$

where $M_{\lambda,0}$ is the unreddened magnitude, $\omega_2$ is the albedo of the dust grains and the effective optical depth $\tau_{\text{eff}}$ is given by

$$\tau_{\text{eff}} = 2 \int \left[ 1 - \omega_2 \pi a^2 Q_{\text{e}}(\lambda) n_d \right] ds,$$

where $a$ is the mean radius of the dust grains, supposed to be spherical, $Q_{\text{e}}(\lambda)$ is the extinction (absorption + scattering) efficiency and $n_d$ is the dust number density. In our calculations, we have assumed that the extinction efficiency and the albedo of the grains have the same properties as those of galactic dust taken from Cardelli, Clayton & Mathis (1989) and Li & Draine (2001), respectively.

3 RESULTS

If previous evolutionary models such as, for instance, those of Kodama & Arimoto (1997) and IMP03 constrained the free parameters by fitting the CMD of ellipticals, these models were unable to adequately reproduce the trend either in the Hβ–Mg2 or in the Mg2–[Fe] diagrams. The behaviour of our best models in these diagrams is illustrated in Fig. 1 (middle and lower panels). Indices for the same object measured by different authors, in spite of being transformed into the Lick system, may differ significantly among them which, besides the intrinsic (cosmic) dispersion, explains the scatter of data points in these diagrams. Even so, the trend of data points in both diagrams is now well reproduced by our model sequence.

Table 1 gives the model parameters found to best describe the mean integrated properties of our galaxies. The first column identifies the model and the second gives the mass parameter $M_0$ in units of $10^{11} M_\odot$. The actual mass of the galaxy is $M_0 (1 - f_w)$, where the mass fraction $f_w$ lost by the galaxy through the wind is given in the seventh column. As expected, because of large potential wells, the mass-loss fraction decreases for more massive galaxies. The star formation efficiency is given in the sixth column and, as in IMP03, it increases for higher masses. A measure of the downsizing
We emphasize again that downsizing was introduced because in the luminosity range up to three times solar for the brightest galaxies. The [Mg/Fe] ratio differs on the average by 0.50 for the most-massive galaxies, as X-ray observations indicate, while for galaxies differing on the average by 0.003 for the less-massive galaxy up to 0.02, for the most-massive modelled objects. These values indicate that the relative amount of dust is compatible with the derived metallicities or, in other words, with the amount of metals expected to be in the solid phase.

Using the derived properties of our models, we have derived relations between the mean age of stellar population mix and observed integrated properties such as the indices $\text{H}$β, Mg2 and the colour $(U − V)$. These are
\begin{align*}
\tau_1 &= -19.230 + 3.884 \beta + 7.516 \beta^2, \\
\tau_2 &= 3.122 - 3.243 (U − V) + 1.226 \beta^2,
\end{align*}
where ages are in Gyr. The mean iron abundance and the mean magnesium-to-iron ratio of the stellar population mix can be

\begin{align*}
\text{Table 1. Model parameters. The columns give the model identification (1),} \\
\text{the mass parameter $M_0$ in units of } 10^{11} \text{ M}_\odot (2), \text{ the infall time-scale in Gyr} \\
\text{(3), the wind time-scale in Gyr (4), the redshift at which 80 per cent of} \\
\text{the mass was assembled (5), the star formation efficiency in Gyr}^{-1} (6), \text{the mass} \\
\text{fraction lost by the wind (7) and the exponent of the IMF (8).}
\end{align*}

\begin{align*}
\text{Table 2. Model properties. The columns give the model identification (1),} \\
\text{the residual gas fraction (2), the fraction of hot gas (3), the mean iron abundance (4),} \\
\text{the mean stellar magnesium-to-iron ratio (5), the mean metallicity (6) and} \\
\text{the mean population age in Gyr (7).}
\end{align*}

\begin{align*}
\text{Table 3. Photometric properties I. The columns give the model identification (1),} \\
\text{the absolute B-magnitude (2), the stellar mass-to-luminosity ratio (3),} \\
\text{the dust effective extinction (in mag) (4) and the Lick indices H}_\beta, M_{g2} \text{ and} \\
\text{the colour (5–7).}
\end{align*}

\begin{align*}
\text{Table 4. Photometric properties II. The columns give the model identification (1) and} \\
\text{the integrated colours (2–6).}
\end{align*}
estimated from the relations
\[ [\text{Fe/H}] = -1.694 - 3.220 [\text{Mg} / \text{Fe}] + 0.963 [\text{Fe}] \]  
(10)
and
\[ [\text{Mg/Fe}] = -0.674 + 0.363 [\text{Fe}] - 0.318 [\text{Mg}]. \]  
(11)
Once the mean iron abundance and the mean magnesium-to-iron ratio are calculated from the relations above, the mean metallicity can be derived from
\[ [Z/\text{H}] = -0.313 + 0.399 [\text{Fe/H}] + 1.242 [\text{Mg/Fe}]. \]  
(12)
The scatter of data observed in Fig. 1 is due essentially to measurement errors and to intrinsic variations in physical parameters among galaxies of similar mass. We have estimated the dispersion of data with respect to our models, correcting for measurement errors. From simple error propagation, we have then estimated the uncertainties in the calibrations above. These correspond to about 1.5 and 1.0 Gyr for ages estimated from equations (8) and (9), respectively, 0.17 dex for metallicities and 0.1 dex for the \([\text{Mg/Fe}]\) ratio. Systematic errors may certainly increase these estimates.

In order to perform an application of the present models and compare with the results derived by using the SSP approach, we have selected 42 galaxies whose ages and metallicities were estimated by Howell (2005). For some of these galaxies, Thomas et al. (2005) have also derived ages and metallicities, which will also be used in our comparative analysis. Mean population ages and mean metallicities derived from our calibrations are given in Table 5. Ages are the average value resulting from the aforementioned calibrations and are followed by an index \(a\) or \(b\). The former implies that the average age value differs by less than 1 Gyr from the individual determinations, whereas the latter means that the difference is in the range 1–2 Gyr. Age differences in this range implies that data points are not close to the mean theoretical relations and, consequently, the resulting age or metallicity values are more uncertain.

It is important to mention that ages derived from SSP models either by Howell (2005) or by Thomas et al. (2005) are consistent but with values given by the latter authors being systematically higher by \( \sim 1.5 \) Gyr than those by the former author. The same remark is valid for metallicities, excepting that for \([\text{M/H}] > 0.5\) the values derived by Howell are higher than those by Thomas et al. In Fig. 2 (upper panel), we have plotted metallicities as a function of age derived from an SSP, using the results by Howell and including those by Thomas et al. for the same objects. In spite of the significant scatter, we note that ‘young’ objects, with ages \(< 5\) Gyr are those with the highest metallicity while galaxies with lower metallicities are generally old. This behaviour is completely different when a similar plot is performed with values obtained from our evolutionary models (Fig. 2, lower panel). In this case, a robust correlation between the mean metallicity and the mean population age is observed, indicating that the most-massive galaxies are those which have been more enriched in chemical elements, thanks to the higher star formation efficiency. The most-discrepant object in this plot is NGC 3610, for which the mean population age determination gives values discrepant by \( \sim 2.5\) Gyr, indicating that the model parameters which characterize this galaxy are far from those describing the mean trend. This galaxy is likely to be a merger remnant, and merits more detailed structural modelling (cf. Strader, Brodie & Forbes 2004), beyond the scope of this paper. However, if an important merger event stimulates the star formation activity, this can roughly be simulated in our approach by a higher star formation efficiency. In fact, with \( k = 3.96\) Gyr\(^{-1}\) (instead of 1.33 Gyr\(^{-1}\) for a galaxy of same luminosity) it is possible to reproduce quite well the observed

| NGC  | Age  | [Mg/Fe] | [Z/H] | Age  | [Z/H] |
|------|------|---------|-------|------|-------|
| 0315 | 10.7 (a) | +0.35 | +0.23 | 5.0 | +0.44 |
| 0584 | 11.3 (a) | +0.35 | +0.26 | 2.4 | +0.61 |
| 0596 | 8.2 (a) | +0.22 | +0.26 | 4.4 | +0.22 |
| 0636 | 10.5 (a) | +0.33 | +0.23 | 3.8 | +0.44 |
| 1052 | 8.3 (a) | +0.27 | +0.03 | 16.0 | +0.42 |
| 1172 | 7.8 (a) | +0.18 | -0.07 | 4.8 | +0.13 |
| 1209 | 9.3 (a) | +0.33 | +0.17 | 15.6 | +0.28 |
| 1400 | 8.1 (a) | +0.26 | +0.02 | 14.2 | +0.31 |
| 1700 | 12.0 (a) | +0.38 | +0.33 | 2.3 | +0.63 |
| 2300 | 10.3 (a) | +0.36 | +0.22 | 5.5 | +0.48 |
| 2768 | 8.2 (a) | +0.28 | +0.18 | 10.0 | +0.14 |
| 2778 | 8.8 (a) | +0.29 | +0.12 | 5.0 | +0.40 |
| 3115 | 11.7 (a) | +0.41 | +0.36 | 3.9 | +0.65 |
| 3193 | 8.3 (a) | +0.26 | +0.02 | 11.8 | +0.20 |
| 3377 | 7.8 (a) | +0.20 | -0.02 | 3.5 | +0.30 |
| 3379 | 10.3 (a) | +0.35 | +0.23 | 8.0 | +0.32 |
| 3607 | 8.6 (a) | +0.27 | +0.05 | 10.6 | +0.27 |
| 3608 | 7.9 (a) | +0.23 | +0.00 | 6.1 | +0.38 |
| 3610 | 10.8 (b) | +0.31 | +0.00 | 1.7 | +0.76 |
| 3640 | 9.4 (a) | +0.29 | +0.15 | 4.9 | +0.26 |
| 4168 | 8.9 (a) | +0.29 | +0.06 | 5.0 | +0.24 |
| 4365 | 11.3 (a) | +0.40 | +0.36 | 5.9 | +0.59 |
| 4374 | 10.0 (a) | +0.34 | +0.22 | 11.1 | +0.24 |
| 4472 | 11.9 (a) | +0.44 | +0.42 | 7.8 | +0.36 |
| 4473 | 10.5 (a) | +0.35 | +0.24 | 4.0 | +0.46 |
| 4486 | 8.8 (b) | +0.32 | +0.14 | 19.6 | +0.27 |
| 4489 | 9.1 (a) | +0.22 | +0.14 | 2.3 | +0.24 |
| 4552 | 11.1 (a) | +0.39 | +0.29 | 10.5 | +0.32 |
| 4621 | 10.5 (a) | +0.36 | +0.22 | 15.8 | +0.29 |
| 4697 | 8.4 (a) | +0.23 | -0.02 | 7.1 | +0.19 |
| 5576 | 10.2 (a) | +0.30 | +0.17 | 2.5 | +0.60 |
| 5638 | 8.6 (a) | +0.27 | +0.05 | 7.8 | +0.32 |
| 5813 | 9.3 (a) | +0.30 | +0.12 | 14.9 | +0.07 |
| 5831 | 7.6 (a) | +0.25 | +0.04 | 2.7 | +0.61 |
| 5846 | 8.3 (a) | +0.27 | +0.06 | 12.2 | +0.25 |
| 6702 | 9.2 (b) | +0.24 | +0.07 | 1.4 | +0.80 |
| 6703 | 9.6 (a) | +0.29 | +0.11 | 3.9 | +0.39 |
| 7454 | 7.3 (a) | +0.15 | -0.15 | 4.7 | +0.04 |
| 7562 | 10.2 (a) | +0.35 | +0.25 | 7.1 | +0.31 |
| 7619 | 12.2 (a) | +0.45 | +0.41 | 13.5 | +0.31 |
| 7626 | 10.7 (a) | +0.37 | +0.24 | 12.0 | +0.27 |
| 7785 | 10.6 (a) | +0.36 | +0.26 | 7.9 | +0.31 |

It is worth mentioning a further aspect when comparing results derived from SSP models and EVMs. The present sequence of models were built by varying different parameters in order to adequately reproduce the integrated properties such as luminosities, colours and metallicity indices. In this sense, the present models are ‘self-consistent’. In general, analyses based on SSP models use only metallicity indices but not colours. If ages and metallicities derived
4 CONCLUSIONS

In this study, new models for E galaxies are presented. The 'canonical' one-zone model was revised by including a simplified two-phase ISM, in which stars are formed only in cold regions and a galactic wind removes hot gas from the galaxy. The mass of the galaxy increases with time as a consequence of infall, here represented by either continuous accretion or discrete minor merger events. The possibility that some dust is mixed with the residual gas was also taken into account. The different parameters of the model were varied in order to adequately reproduce integrated properties such as the CMD and the trends of indices such as H$_\beta$ versus Mg$_2$ and Mg$_2$ versus (Fe)$_2$. The fundamental characteristic of these models concerns the beginning of stellar assembly and star formation activity. The start-up time was adjusted in order to give a better description of data in the H$_\beta$–Mg$_2$ diagram and this requires that the less-massive galaxies are assembled later, in agreement with the downsizing effect. In order to characterize this effect, we have defined the quantity $z_{10}$, corresponding to the redshift at which 80 per cent of the (baryonic) mass was assembled. Galaxies in the luminosity range $-18.8 > M_\text{B} > -20.2$ were assembled in the redshift range $0.7 < z_{10} < 1.1$ whereas brighter objects $-21.2 > M_\text{B} > -22.2$ were assembled earlier, for example, $1.8 < z_{10} < 3.9$.

Our models predict an increasing fraction of hot gas for massive galaxies, a consequence of gravitational trapping, in concordance with X-ray observations. The derived amount of dust mixed with the residual gas also increases with galaxian masses and the dust-to-gas ratio varies from 0.003 for faint up to 0.02 for bright galaxies. However, these numbers depend on the adopted grain dimension and composition. Thanks to downsizing, the resulting mean stellar population ages span a range of 6.4–12.8 Gyr, considerably wider than our previous models (IMP03). Metallcities vary from half to about three times solar, increasing with the mass of the galaxy. These results imply that the CMD is not either a pure metallicity or a pure age sequence, but a combination of these two quantities.

From the present models, different calibrations were obtained allowing estimates of mean properties of the stellar population mix like the age, the metallicity and the [Mg/Fe] ratio, from the knowledge of integrated parameters like the $(U - V)$ colour and the Lick indices H$_\beta$, Mg$_2$ and (Fe)$_2$. These calibrations were applied to a sample of early-type galaxies, whose spectral indices were interpreted in terms of SSP models. From these studies based on SSC models, galaxies with stellar population ages as young as 2.5 Gyr can be found, while the corresponding ages derived from our model calibrations are significantly higher, ranging from 7.5 up to 12 Gyr. The mean values for metallicities and ages concern the bulk of the stellar population mix constituting ellipticals. However, the residual gas originated either from the stellar evolution or from infall can presently be converted into stars. In fact, Ferreras & Silk (2000) studied a sample of early-type galaxies in Abell 851 and found that the slope and scatter in the near-UV–optical plane are consistent with some objects having $\sim 10$ per cent of their stellar mass in stars younger than $\sim 0.5$ Gyr. The study of a large sample by Kaviraj et al. (2006) confirms such a conclusion. They have noted that about
30 per cent of the galaxies in their sample (∼2100 objects) have UV–optical colours consistent with some star formation activity within the last Gyr. This recent activity represents, according to their estimates, about 1–3 per cent of the stellar mass in stars less than 1 Gyr old. Using the fraction of residual cold gas and the star formation efficiency of our models, we have estimated the mass fraction of stars formed in the last 0.8 Gyr, which are in the range 2.3–5.7 per cent, fully consistent with UV and near-UV observations.

As mentioned, the present models describe mean integrated properties and some uncertainties are certainly present in the resulting calibrations of age and metallicity, because of cosmic scatter and observational errors. In a future paper, we will report the application of the present model to individual galaxies, deriving the relevant parameters from the best fit of the integrated parameters of each object. This approach will possibly give information about the cosmic scatter and will eventually reveal any possible correlations with the environment.

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