Star formation history in early-type galaxies – I. The line absorption indices diagnostics

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ABSTRACT

To unravel the formation mechanism and the evolutionary history of elliptical galaxies (EGs) is one of the goals of modern astrophysics. In a simplified picture of the issue, the question to be answered is whether they have formed by hierarchical merging of pre-existing substructures (maybe disc galaxies) made of stars and gas, with each merging event probably accompanied by strong star formation, or conversely, whether they originated from the early aggregation of lumps of gas turned into stars in the remote past via a burst-like episode ever since followed by quiescence so as to mimic a sort of monolithic process. Even if the two alternatives seem to oppose each other, actually they may both contribute to shaping the final properties of EGs as seen today. Are there distinct signatures of the underlying dominant process in the observational data? To this aim we have examined the line absorption indices on the Lick system of the normal, field EGs of Trager and the interacting EGs (pair- and shell-objects) of Longhetti et al. The data show that both normal, field and interacting galaxies have the same scattered but smooth distribution in the $H\beta$ versus [MgFe] plane even if the interacting ones show a more pronounced tail toward high $H\beta$ values. This may suggest that a common physical cause is at the origin of their distribution. There are two straightforward interpretations of increasing complexity. (i) EGs span true large ranges of ages and metallicities. A young age is the signature of the aggregation mechanism, each event accompanied by metal enrichment. This simple scheme cannot, however, explain other spectro-photometric properties of EGs and has to be discarded. (ii) The bulk population of stars is old but subsequent episodes of star formation scatter the EGs in the diagnostic planes. However, this scheme would predict an outstanding clump at low $H\beta$ values, contrary to what is observed. The model can be cured by supposing that the primary star formation activity lasted for a significant fraction of the Hubble time ($5 \leq T \leq 13$ Gyr) accompanied by global metal enrichment. The ‘younger’ galaxies are more metal-rich. The later burst of star formation should be small otherwise too many high-$H\beta$ objects would be observed. Therefore, the distribution of normal, pair- and shell-galaxies in the $H\beta$ versus [MgFe] plane is due to global metal enrichment. Even though the above schemes provide a formal explanation, they seem to be too demanding because of the many ad hoc ingredients that have to be introduced. Furthermore, they neglect the observationally grounded hint that the stellar content of EGs is likely to be enhanced in $\alpha$-elements with [$\alpha$/Fe] ranging from 0.1 to 0.4 dex. Here we propose a new scheme, in which the bulk dispersion of galaxies in the $H\beta$ versus [MgFe] plane is caused by a different mean degree of enhancement. In this model, neither the large age ranges nor the universal enrichment law for the old component are required and the observed distribution along $H\beta$ is naturally recovered. Furthermore, later bursts of stellar activity are a rare event, involving only those galaxies with very high $H\beta$ (roughly >2.5). Finally, simulations of the scatter in broad-band colours of EGs seem to confirm that the bulk stars have formed in the remote past, and that mergers and companion star formation in a recent past are not likely, unless the intensity of the secondary activity is very small.

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

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1 INTRODUCTION

Determining the age of the bulk stellar content of elliptical galaxies (EGs) is basic to reconstructing the past history of star formation and to setting clues on the galaxy formation process itself. Two competing scenarios are proposed: the monolithic picture in which a single dominant episode of star formation occurred in the past, ever since followed by quiescence and passive evolution (secondary episodes are, however, always possible); the hierarchical scheme, in which a series of mergers of smaller subunits has taken place over the billions of years, each of those is likely to be accompanied by star-forming activity (mergers of inert objects with no additional star formation cannot be excluded). Current ideas concerning the two competing pictures of galaxy formation have been critically reviewed by Ellis (1998) and Peebles (2002). In short the present-day view of structure formation suggests that roughly half of the large EGs were assembled at $z < 1$. However, observational evidence of variations with redshift of the colour–magnitude, fundamental plane, size–magnitude, K-magnitude–redshift relations indicate that large EGs have already formed in the distant past at $z > 2$.

In order to discriminate between the two schemes, the key question to be addressed and hopefully answered is what kind of signatures the stellar populations of a galaxy have inherited from the forming mechanism. The diagnostic to our disposal is mainly based on magnitudes, colours, integrated spectra, luminosity weighted line strength indices, estimates of chemical abundances and abundance ratios together with the spatial gradients in those quantities. As for the line absorption indices, gradients in Mg$_2$ and (Fe) (and others) observed in EGs (Worthey 1992; Carollo, Danziger & Buson 1993; Davies, Sadler & Peletier 1993; González 1993; Balcells & Peletier 1994; Carollo & Danziger 1994a,b; Carrasco et al. 1995; Fisher, Franx & Illingworth 1995, 1996) have often been interpreted as indicating that the abundances of $\alpha$-elements (Mg, O, etc.) with respect to iron are enhanced, $[\alpha/Fe] > 0$, in the central regions. Opposite conclusions, however, exist (Kuntschner 1998; Davies et al. 2001). Furthermore, limited to the nuclear regions, indices vary passing from one galaxy to another (González 1993; Trager et al. 2000b,a). Looking at the correlation between Mg$_2$ and (Fe) (or similar indices) for the galaxies in those samples, Mg$_2$ increases faster that (Fe), which is once more interpreted as due to enhancement of $\alpha$-elements in some galaxies. In addition to this, since the classical paper by Burstein et al. (1988), the index Mg$_2$ is known to increase with the velocity dispersion (and hence mass and luminosity) of the galaxy. Standing on this body of data the conviction arose that the degree of enhancement in $\alpha$-elements ought to increase passing from dwarf to massive EGs (Faber, Worthey & González 1992; Matteucci 1994, 1997; Worthey et al. 1994; Matteucci, Ponzoni & Gibson 1998).

Another point to consider is whether normal and interacting galaxies (i.e. shell- and pair-objects) show any systematic difference in colours and line absorption indices. The subject was addressed by Longhetti et al. (1998a,b, 1999, 2000), whose results will be briefly summarized below.

Using this body of data, can we infer the age, the metallicity and the degree of enhancement for the bulk stars in an EG? The task is not trivial because age and metallicity have similar effects on the spectrum of a galaxy, i.e. the spectrum and hence the colours of an old and metal-poor population may look like those of a young and metal-rich one, the so-called age–metallicity degeneracy pointed out long ago by Renzini & Buzzoni (1986). The degeneracy is also further complicated by effects both on the age and metallicity caused by the enhancement in $\alpha$-elements. A promising way-out is perhaps offered by the system of line absorption indices introduced by the Lick group (Worthey 1992; Worthey et al. 1994 and references therein), which have been extensively used to infer the age, metallicity and abundance ratios of EGs (Bressan, Chiosi & Tantalo 1996; Kuntschner 1998, 2000; Kuntschner & Davies 1998; Tantalo, Chiosi & Bressan 1998a; Jørgensen 1999; Trager et al. 2000b,a; Davies et al. 2001; Kuntschner et al. 2001; Poggianti et al. 2001; Vazdekis et al. 2001; Maraston et al. 2003; Thomas, Maraston & Bender 2003b,a; Thomas & Maraston 2003; Tantalo & Chiosi 2004).

Let us briefly summarize the key steps of these analyses, paying particular attention to the age, for which the conclusion that EGs show evidence of recent star formation either for the whole bulk stellar population or part it has often been drawn. The age youth has often been taken as the signature of the hierarchical mechanism.

(i) Starting from the pioneering study of González (1993) of ‘normal galaxies’ (i.e. those with no sign of dynamical interaction, accretion, etc.) in the local Universe, different groups analysed the distribution of galaxies in the H$\beta$ versus [MgFe] diagnostic plane and others of the same kind (Buzzoni, Garibaldi & Mantegazza 1992; Buzzoni, Mantegazza & Garibaldi 1994; Bressan et al. 1996; Tantalo 1998; Tantalo et al. 1998a) using the single stellar populations (SSP) approximation, i.e. the stellar content of a galaxy is reduced to an SSP of suitable age, metallicity and the degree of enhancement. The index H$\beta$ is considered to be a good age indicator, whereas [MgFe] is considered to be most sensitive to the metallicity. In reality both indices are sensitive to age, metallicity and the degree of enhancement (see also González 1993; Tantalo & Chiosi 2004 for similar remarks). Since EGs are more scattered in H$\beta$ than in [MgFe] and do not follow the relation expected for coeval old objects matching the colour–magnitude relation (Bower, Lucey & Ellis 1992a,b), it was argued that H$\beta$ traces the age of the bulk stars, thus suggesting that some galaxies are truly young objects. However, a closer scrutiny of the problem led Bressan et al. (1996) to suggest all galaxies in that sample should be old but with different histories of star formation. Some of them completed their stellar activity in the far past with no evidence of subsequent episodes. Others had a more prolonged star-forming history, perhaps in recurrent episodes of short duration. Looking at the galaxy-to-galaxy differences $\Delta H\beta$ and $\delta$[MgFe] in the nuclear values and their correlation with $\Sigma_0$, the suggestion was advanced that the global duration of the star-forming activity becomes longer at decreasing $\Sigma_0$ (galaxy mass). This was later confirmed by dynamical Tree-SPH simulations of early-type galaxies by Kawata (1999, 2001b,a); Chiosi & Carraro (2002). In addition to this, Bressan et al. (1996) and Longhetti et al. (2000) tried to understand the effect brought to the indices of a population of old stars by a recent episode of star formation. The results is that indices such as H$\beta$ are strongly affected by even small percentages of young stars: as long as star formation is active they jump to very high values and when star formation is over they fall back to the original value on a time-scale of approximately 1 Gyr. Other indices such as Mg$_2$, (Fe) are much less affected even if the companion chemical enrichment may somewhat change them. In diagnostics planes such as H$\beta$ versus (Fe) the galaxy performs and extended loop elongated towards the H$\beta$ axis, thus causing an artificial dispersion that could be interpreted as an age dispersion, whereas what we are really seeing is the transient phase associated to the temporary stellar activity. Consequently, the idea that the dispersion in H$\beta$ measures the age of the last episode of star formation instead of the age of the bulk population was commonly accepted. Finally, EGs probably have mean metallicities in the range of...
2 THEORY OF LINE ABSORPTION INDICES

2.1 Definition

The technique to calculate line-strength indices of SSPs is amply described in Worthey et al. (1994); Bressan et al. (1996); Bressan et al. (1998a); Maraston et al. (2003); Tantalo & Chiosi (2004). The reader is referred to these articles and references therein for a detailed description of the method. Here we limit ourselves to summarize a few basic points for the sake of clarity. Suffice here to recall that a line absorption index is constructed from the ratio $F_\lambda/F_c$ where $F_\lambda$ and $F_c$ are the fluxes in the line and pseudo-continuum, respectively. The flux $F_c$ is calculated by interpolating to the central wavelength of the absorption line, the fluxes in the mid-points of the red and blue pseudo-continua bracketing the line (Worthey et al. 1994).
2.2 Fitting functions

Since the Lick system of indices (Burstein et al. 1984; Faber et al. 1985; Worthey et al. 1994) stands on a spectra library with fixed resolution of $8\,\AA$, whereas most of the synthetic spectra in use have a different resolution, to overcome the difficulty, the so-called fitting functions ($\mathcal{F}\mathcal{F}_i$) have been introduced. They express the indices measured on the observed spectra of a large number of stars with known gravity, $T_{\text{eff}}$, and chemical composition ($[\text{Fe/H}]$) as functions of these parameters (Worthey et al. 1994). In the following we adopt the Worthey (1992) $\mathcal{F}\mathcal{F}_i$, extended, however, to high-temperature stars ($T_{\text{eff}} \approx 10^4$ K) as reported in Longhetti et al. (1998a).

2.3 Integrated indices of SSPs

They are derived in the following way. An SSP is described by an isochrone in the Hertzsprung–Russell (HR) diagram where the elemental bins (fixed by $\Delta\log L/L_\odot$ and $\Delta\log T_{\text{eff}}$) can be conceived as a ‘star’ of suitable luminosity (gravity), $T_{\text{eff}}$ and metallicity. Each elemental bin is in turn populated by a number $N_i$ of such stars given by

$$N_i = \int_{m_b}^{m_s} \phi(m) \, dm,$$

where $m_b$ and $m_s$ are the minimum and maximum star mass in the bin and $\phi(m)$ is the initial mass function in number. We start from the typical star of a bin for which we may derive the indices from the $\mathcal{F}\mathcal{F}_i$. The indices are then inverted to derive the flux in the absorption line, $F^{\mathcal{F}_i}_{\lambda}$, and in the pseudo-continuum $F^c_{\lambda}$. Knowing the index for a single star, we weight its contribution to the integrated value on the relative number of stars of the same type. We calculate the ratio

$$\frac{\sum F^{\mathcal{F}_i}_\lambda N_i}{\sum F^c_{\lambda} N_i},$$

where $N_i$ is the above number of stars in the generic bin, and finally insert the ratio into the definition of each index as appropriate.

2.4 $\alpha$-enhanced chemical compositions

2.4.1 Total enhancement

To distinguish the enhancement of individual species from the total one characterizing a given chemical mixture, Tantalo & Chiosi (2004) introduce the parameter $\Gamma$ defined as follows. Let us take a certain mixture of elements with mass abundances $X_i$ of each species, and total metallicity $Z$ (sum of the $X_i$ for all elements heavier than He). The ratio of the mass abundance of an element with respect to Fe and to the Sun is given by

$$\left[ \frac{X_i}{X_{\text{Fe}}} \right] = \log \left( \frac{X_i}{X_{\text{Fe}}} \right) - \log \left( \frac{X_{\text{Fe}}}{X_{\text{Fe}}} \right).$$

Let us now assume that the ratio $[X_i/X_{\text{Fe}}]$ of some elements is changed under the conditions that the abundance of Fe with respect to the Sun and the total metallicity $Z$ remain constant. The mass-abundances of all species in the new mixture are accordingly scaled to a new value $X'_{i}$. The total enhancement factor $\Gamma$ is

$$\Gamma = -\log \left( \frac{X'_{i}}{X_{i}} \right)$$

[see Tantalo & Chiosi (2004) for all other details].

2.4.2 The Tripicco & Bell (1995) response functions

A method designed to include the effects of enhancement online absorption indices has been suggested by Tripicco & Bell (1995, TB95), who introduce the concept of response functions. In brief, from model atmospheres and spectra for three stars of assigned effective temperature and gravity, i.e. a cool-dwarf (CD), a turn-off (TO) and a cool-giant (CG), they calculate the absolute indices $I_{\lambda}$, $I_{\lambda}^{\text{CD}}$, $I_{\lambda}^{\text{TO}}$, and $I_{\lambda}^{\text{CG}}$ in steps of $\Delta[X_i/H]$ from which the response function $R_{\lambda}(i)$ for any index corresponding to a variation of the element $i$ has $\Delta[X_i/H] = +0.3$ dex, can be derived:

$$R_{\lambda}(i) = \frac{1}{I_{\lambda}} \frac{\Delta I_{\lambda}}{\Delta[X_i/H]}.$$ 

The response functions for the cool-dwarf, turn-off and cool-giant stars constitute the milestones of the calibration.

The mathematical algorithm for correcting an index from solar to $\alpha$-enhanced element partitions is taken from Trager et al. (2000a) and Tantalo & Chiosi (2004) to whom the reader should refer for all details. In brief, starting from the assumption that fractional variation of an index to changes of the chemical parameters is the same as that for the reference index $I_{\lambda}$, the following expression is derived:

$$\frac{\Delta I_{\lambda}}{I_{\lambda}} = \frac{\Delta I_{\lambda}}{I_{\lambda}} = \left\{ \prod_i \left[ 1 + R_{\lambda}(i) \right] \right\}^{\frac{[X_i/H]}{0.3}} - 1,$$

where $R_{\lambda}(i)$ are the response functions tabulated by TB95. Relation (5) can be applied under the obvious condition that $I/I_{\lambda} > 0$.

The above algorithm is used to evaluate the fractional variations for the three calibrators, i.e. ($\Delta I/I$)$_{\text{CD}}$, ($\Delta I/I$)$_{\text{TO}}$ and ($\Delta I/I$)$_{\text{CG}}$. Since in general a star or elemental bin along an isochrone will have effective temperature and gravity different from those of the three calibrators, and the fractional variations for these latter are also different, to evaluate the total fractional variation to be used for the particular star (isochrone bin) under examination, we linearly interpolate both in effective temperature and gravity among the fractional variations of the calibrators weighting their contribution according to their distance from the current star in the HR diagram. For a detailed discussion of this topic and associated uncertainties see Tantalo & Chiosi (2004).

2.5 Stellar models and isochrones

The SSP indices are based on the Padova Library of stellar models and companion isochrones according to the version by Girardi et al. (2000) and Girardi (private communication). This particular set of stellar models/isochrones differs from the classical one by Bertelli et al. (1994) for the efficiency of convective overshooting and the prescription for the mass-loss rate along the asymptotic red giant branch (AGB) phase. For the reasons amply explained by Tantalo & Chiosi (2004), we prefer not to use the more recent stellar models by Salasnich et al. (2000) in which the effect of $\alpha$-enhancement is already included in the stellar opacity. Since indices are essentially a surface phenomenon in the sense that they are derived from the $\mathcal{F}\mathcal{F}_i$ linked to the stellar models only via the effective temperature, surface gravity and iron content $[\text{Fe/H}]$, details of the stellar models caused by patterns of abundances enhanced in $\alpha$-elements are of minor relevance. The point has been made clear by the systematic analysis of the issue made by Tantalo & Chiosi (2004). Therefore, the stellar models and companion SSPs by Girardi et al. (2000) and...
Girardi (private communication) are fully adequate to the purposes of the present study.

The stellar models extend from the zero-age main sequence (ZAMS) up to either the start of the thermally pulsing AGB phase (TP-AGB) or carbon ignition. No details on the stellar models are given here; they can be found in Girardi et al. (2000) and girardi et al. (2002). Suffice it to mention that: (i) in low-mass stars passing from the tip of red giant branch (T-RGB) to the horizontal branch (HB) or clump, mass-loss by stellar winds is included according to the Reimers (1975) rate with 

\[ \dot{\eta} \equiv \frac{M}{2 \pi \rho} \langle \frac{V}{c} \rangle \beta \text{erg cm}^{-2} \text{s}^{-1} \text{g}^{-1} \]

for the SSPs and (ii) the whole TP-AGB phase is included in the isochrones with ages older than 0.1 Gyr according to the algorithm of Girardi & Bertelli (1998) and the mass-loss rate of Vassilidias & wood (1993); (iii) four chemical compositions are considered as listed in Table 1.

### 2.6 Library of stellar spectra

The library of stellar spectra is taken from Girardi et al. (2002). It covers a large range of the log \( T_{\text{eff}} - \log g \) and [M/H] space. No details are given here. Suffice to mention:

(i) the basic spectra are from Kurucz ATLAS9 non-overshooting models (castelli, gratton & kurucz 1997; bessell, castelli & plez 1998) complemented with

(ii) blackbody spectra for \( T_{\text{eff}} > 50 \text{,000} \text{ K} \);

(iii) Fluks et al. (1994) empirical M-giant spectra, extended with synthetic ones in the infrared and ultraviolet, and modified shortward of 4000 Å so as to produce reasonable \( T_{\text{eff}} - \langle U - B \rangle \) and \( T_{\text{eff}} - \langle B - V \rangle \) relations for cool giants;

(iv) Allard et al. (2000) DUSTY99 synthetic spectra for M, L and T dwarfs.

The theoretical broad-band colours used in this study are in the Johnson–Cousins–Glass UBVRIJHK system, using filter response curves from Bessell & Brett (1988) and Bessell (1990).

### 3 LINE ABSORPTION INDICES FOR SSPS

In this study we essentially adopt the large grids of line absorption indices recently calculated by Tantalo & Chiosi (2004) for SSPs over large ranges of chemical abundances, enhancement factors \( \Gamma \) and ages. However, we have slightly changed the ratio \( [X/Fe] \) for some specific elements. More precisely, the abundance ratios for solar-scaled and \( \alpha \)-enhanced mixtures with \( \Gamma = 0.35 \) and 0.50 are taken from Tantalo & Chiosi (2004) but for Ti for which lower \([Ti/Fe]\) ratios have been adopted: either \([Ti/Fe] = 0 \) (case a) or \([Ti/Fe] = 0.20 \) (case b). See the text for details.

### Table 1. Chemical composition and \([Fe/H]\) as a function of \( \Gamma \) for the SSPs in use.

| \( Z \) | \( Y \) | \( X \) | \( \Gamma = 0 \) | \( \Gamma = 0.3557 \) | \( \Gamma = 0.50 \) |
|---|---|---|---|---|---|
| 0.008 | 0.248 | 0.7440 | −0.3972 | −0.7529 | −0.8972 |
| 0.019 | 0.273 | 0.7080 | 0.0000 | −0.3557 | −0.5000 |
| 0.040 | 0.320 | 0.6400 | 0.3672 | 0.0115 | −0.1328 |
| 0.070 | 0.338 | 0.5430 | 0.6824 | 0.3267 | 0.1715 |

\( X \) is the explanation in the strong response functions for elements such as \( N, O, Mg \) etc, found by Tripicco & bell (1995) in the different way enhancing those elements affects the ratio \( F_i / F_e \). In presence of enhancement, the spectrum over the three passbands defining the index \( H\beta \) is more absorbed. However, absorption in the blue wing is larger than in the central band and in the red wing. Owing to this,
the ratio $F_i/F_c$ becomes smaller so that $H\beta$ becomes stronger. This trend is also confirmed by the new response functions calculated by Tantalo et al. (2004) using high-resolution spectra (1 Å).

There is another important point to be addressed, which has already been touched upon by Tantalo & Chiosi (2004) and it is shown in Fig. 2 by the cases with the same $\Gamma$, either 0.35 or 0.5, and different [Ti/Fe]. In brief, at given metallicity $Z$, total enhancement factor $\Gamma$, and list of enhanced/depressed elements, the same $\Gamma$ can be obtained by many patterns of $[X_{el}/Fe]$. For instance Tantalo & Chiosi (2004) have shown that at given $\Gamma$ indices such as $H\beta$ are very sensitive to the abundance ratio [Ti/Fe]. In their calculations several values of [Ti/Fe] have been explored, i.e. [Ti/Fe]=0, 0.20 and 0.63. The first choice implies that Ti is not considered as an $\alpha$-element, the second one is based on the mean value measured by Gratton et al. (2003) for galactic metal-poor stars with accurate parallaxes, whereas the last choice comes from the old estimate by Ryan, Norris & Bessell (1991) for stars of the same type. In Fig. 2 we show the effect of varying [Ti/Fe] from 0 to 0.2. Test calculations show that other elements such as O, Mg, Ne, Ca, etc. have a similar effect. The explanation is the same as before.

Since there is no unique pattern of abundance ratios as clearly shown by the above-mentioned observational data, at given $Z$ and $\Gamma$ a sort of natural width for the indices has to be expected. The natural width we are talking about is provided by the difference $(I_{X_{el}/Fe}) - (I_{X_{el}/Fe})_{\alpha,\Gamma, Z}$. It is soon evident that models with the same $Z$, $\Gamma$ and age may have significantly different H$\beta$ and [MgFe] (indices in general) depending of the detailed pattern of $[X_{el}/Fe]$ in use.

4 COMPOSING SSPs

Since the stellar content of a galaxy can be approximated by a manifold of SSPs of different age and metallicity, each of which

Figure 1. Evolution of eight indices (Mg$b$, Mg$z$, H$\beta$, Fe, [MgFe], [MgFe]'', NaD and C$\lambda$4668) as a function of the age. The heavy lines show the indices for solar-scaled partition of elements ($\Gamma=0$), whereas the thin lines show the same but for the partition of $\alpha$-enhanced taken from Salasnich et al. (2000) ($\Gamma=0.3557$). Only two metallicities are displayed for the sake of clarity, i.e. $Z=0.008$ (solid lines) and $Z=0.07$ (dashed lines).

Figure 2. The $H\beta$ versus [MgFe] plane for different combinations of $\Gamma=0$, metallicity, and [Ti/Fe] as indicated in the legend. Looking at this diagram one can easily single out the separate effect of the four parameters: age, metallicity, $\Gamma$ and $[X_{el}/Fe]/[Ti/Fe]$ in this case. See the text for more details.
Figure 3. A burst of star formation of different intensity (as indicated) is let occur in an ideal galaxy represented by an SSP with \(Z = 0.019\) and \(\Gamma = 0\) at the age of 10 Gyr. The composite object is then followed up to the age of 16 Gyr. Left-hand panel, \((B - V)\) versus age. Right-hand panel, \(H\beta\) versus age.

For the sake of illustration we consider the case of an old galaxy, represented by an SSP with solar composition and no enhancement of \(\alpha\)-elements \((Z = 0.019\) and \(\Gamma = 0)\), which at the age of 10 Gyr suffers a burst of stellar activity represented by another SSP of the same \(Z\) and \(\Gamma\). The old galaxy is labelled by \(j = 1\) and the burst component by \(j = 2\). Three cases of the burst intensity are examined, i.e. \(\beta_1 = 0.98\) and \(\beta_2 = 0.02\), \(\beta_1 = 0.90\) and \(\beta_2 = 0.10\), \(\beta_1 = 0.80\) and \(\beta_2 = 0.20\). Once the burst has occurred the photometric properties of the composite object are described with the age step of the young SSP in order not to lose in the time resolution of magnitudes, colours and indices. In simulations of this type, both the old and the young component are let evolve with time from the burst epoch to the present. The results are shown in the panels of Figs 3 and 4. The left-hand panel of Fig. 3 is the colour \((B - V)\) versus age (in Gyr); whereas the right-hand panel is the \(H\beta\) versus age. The left-hand panel of Fig. 4 is the plane \((U - B)\) versus \((B - V)\), whereas the right-hand panel is the \(H\beta\) versus \([\text{MgFe}]\) plane. For the sake of clarity, the burst is displayed only for ages older than 0.1 Gyr because its path in the two colours and/or two indices planes for younger ages is quite complicated and difficult to describe in a simple fashion. In the left and right-hand panels of Fig. 3 the age structure of the bursting mode is clear. The colour \((B - V)\) and index \(H\beta\) are suddenly rejuvenated at the onset of the burst. (i) \((B - V)\) may become very blue, the peak value depends on \(\beta_2\), and then fade down toward the typical colour of an old object as the age increase from 10 up to 16 Gyr. The same for \(H\beta\). (ii) In all simulations both \(H\beta\) and \((B - V)\) keep memory of the bursting activity for long time. Both indeed tend to be lower and higher, respectively, than the pure passive evolution indicated by the solid heavy line. In the planes \((U - B)\) versus \((B - V)\) and \(H\beta\) versus \([\text{MgFe}]\) of Fig. 4, the composite object performs wide loops, the extension and width of which are functions of the intensity \(\beta_2\). The complete path of the bursting object is better shown in Fig. 5 below.

Another interesting plane to look at is the superposition of two SSPs, one old and the other young (in different percentages as above), but with the age of the old SSP kept fixed, whereas that of the young one is let vary from 0.01 Gyr to the age of the old component in suitable steps. These simulations allow us to span the whole range of possible combinations of ages for the two SSPs and the whole range of values in any two-indices plane at varying...
Table 3. Basic data for the Longhetti et al. (2000) sample of shell- and pair-galaxies. The velocity dispersion $\Sigma_0$ is km s$^{-1}$.

| Name   | $H\beta$ | $Mg_b$ | $Mg_b$ | Fe52 | Fe53 | [MgFe] | $\Sigma_0$ |
|--------|----------|--------|--------|------|------|--------|------------|
| RR24a  | −2.60    | 0.17   | 2.49   | 2.22 | 2.32 | 2.38   | 101        |
| RR24b  | −17.37   | 0.09   | 2.01   | 0.74 | 1.10 | 1.36   | 92         |
| RR62a  | 1.15     | 0.13   | 2.30   | 1.57 | 1.82 | 1.97   | 81         |
| RR101a | 1.86     | 0.23   | 3.53   | 3.10 | 2.76 | 3.22   | 162        |
| RR101b | 2.35     | 0.23   | 3.67   | 2.83 | 2.35 | 3.08   | 210        |
| RR105a | 1.32     | 0.27   | 4.23   | 3.21 | 2.26 | 2.34   | 130        |
| RR187b | 2.87     | 0.22   | 3.42   | 2.69 | 2.34 | 2.92   | 144        |
| RR210a | 0.80     | 0.33   | 4.97   | 2.71 | 2.24 | 2.37   | 281        |
| RR210b | 1.50     | 0.31   | 4.62   | 2.99 | 2.44 | 3.54   | 212        |
| RR225a | 1.76     | 0.34   | 4.96   | 3.41 | 2.40 | 3.80   | 357        |
| RR225b | 1.18     | 0.31   | 4.42   | 2.80 | 2.59 | 3.45   | 186        |
| RR287a | −1.67    | 0.20   | 4.14   | 2.20 | 2.44 | 3.10   | 184        |
| RR282b | 1.53     | 0.33   | 5.17   | 2.78 | 2.16 | 3.57   | 290        |
| RR287b | 1.61     | 0.28   | 4.57   | 3.08 | 2.43 | 3.55   | 205        |
| RR297a | 1.97     | 0.27   | 4.08   | 2.89 | 2.32 | 3.62   | 277        |
| RR297b | 2.37     | 0.26   | 4.81   | 2.92 | 2.60 | 3.64   | 147        |
| RR298b | 1.42     | 0.31   | 4.48   | 3.24 | 2.44 | 3.57   | 130        |
| RR307a | 0.08     | 0.21   | 3.73   | 1.59 | 1.53 | 2.41   | 92         |
| RR317a | 1.56     | 0.28   | 4.36   | 3.06 | 2.90 | 3.60   | 189        |
| RR317b | 2.33     | 0.13   | 1.80   | 2.47 | 1.74 | 1.95   | 91         |
| RR381a | 1.64     | 0.31   | 5.01   | 2.63 | 2.62 | 3.63   | 276        |
| RR387a | 2.20     | 0.29   | 4.48   | 3.08 | 2.74 | 3.61   | 187        |
| RR387b | 1.83     | 0.31   | 4.51   | 3.13 | 2.55 | 3.58   | 215        |
| RR397b | 1.33     | 0.29   | 4.39   | 3.21 | 2.87 | 3.65   | 198        |
| RR405a | 1.45     | 0.28   | 4.68   | 2.92 | 2.39 | 3.52   | 192        |
| RR405b | 1.89     | 0.34   | 4.81   | 2.72 | 2.76 | 3.63   | 207        |
| RR409b | 1.89     | 0.29   | 4.51   | 3.02 | 2.28 | 3.77   | 187        |
| RR409b | 1.17     | 0.31   | 4.56   | 2.89 | 2.36 | 3.46   | 150        |

intensity and age of the burst. In other words, any point in these plane is a picture of the composite galaxy taken at a certain age of the burst. Simulations of this type are shown in Fig. 5 for the typical age of the old SSP of 13 Gyr. The apparently strange behaviour of the SSP path at increasing age of the burst deserves some explanation. The bell-shaped trend of $H\beta$ has already been explained by Buzzoni et al. (1994). In brief for strong $H\beta$ absorption (as in young SSPs and/or burst of star formation), the Stark wings of the feature overflow the Lick wavelength window, and enter the side bands depressing the pseudo-continuum. As a result, the $H\beta$ index peaks when the SSP is dominated by B5–A0 stars and fades for earlier and later spectral types. This is mirrored in the path of the composite SSP with the contribution from each component weighted on its percentage. It is worth noticing that a galaxy caught at the very early stages of its bursting activity would appear as an object with unusually low indices. We will come back to this later on.

5 INDEX–INDEX DIAGNOSTICS: AGE OR CHEMISTRY?

The sample of galaxies we intend to analyse is derived from two sources of data, namely the ‘IDS Pristine’ catalogue by Trager (1997) for the central regions of normal galaxies, it contains also the González (1993) list, and the catalogue by Longhetti et al. (2000) for pair- and shell-galaxies (i.e. only objects with clear signs of interaction). The latter sample is given in Table 3. The $H\beta$ versus [MgFe] plane for all the galaxies in question is shown in the left-hand panels of both Figs 6 and 7 to facilitate the comparison with the theoretical simulations we are going to present. It is worth calling attention to the striking similarity between normal and interacting galaxies, and the very smooth but steeper slope of the data as compared with that of SSPs of given metallicity (see Fig. 2). In the following we will refer to it as the nearly vertical distribution along the $H\beta$ axis.

5.1 A toy galaxy model

Bressan et al. (1996) and Longhetti et al. (2000) suggested that the distribution of galaxies in the $H\beta$ versus [MgFe] plane may reflect secondary episodes of star formation superposed to an old stellar component. In the following, we intend to explore further this idea by means of Monte Carlo simulations based on the Longhetti et al. (2000) toy model of galaxy evolution.

The complex star formation history of an early-type galaxy is reduced to a burst of relatively recent star formation superposed to the bulk population made of old stars. These latter are in turn represented by an SSP where the age is randomly selected between the ages $T_1$ and $T_2$. The young stellar component, formed during the recent burst of star formation, is represented by an SSP where the age is randomly selected between $T_2$ and a lower limit $T_1$. Typical values for the age limits are: $T_1 = 13$, $T_2 = 10$ and $T_1 = 0.1$ Gyr. The time-scale of the two star-forming event are always assumed to be short compared with all other relevant time-scales (ages and Hubble time).

Since we are interested in guessing the minimum threshold above which the secondary episode becomes important in affecting the line strength indices, we will consider only the case in which the
secondary episode involves a minor fraction of the galaxy mass. Typical values for the strength of the primary and secondary burst $\beta_1$ and $\beta_2$, respectively, measuring the percentage of the total galaxy mass turned into stars, are $\beta_1 = 0.98$ and $\beta_2 = 0.02$.

The metallicity $Z_1$ of the old stellar component is randomly selected between 0.008 (50 per cent of the solar value) and 0.07 (3.25 the solar value). We have also built a set of simulations in which the metallicity of the old component is forced to linearly increase from 0.008 and 0.07 over the age range $T_1-T_2$. The metallicity $Z_2$ of the young component is randomly chosen over the whole range (i.e. from $Z = 0.008$ to 0.07), thus simulating the widest range of possibilities, going from acquisition of external less processed gas to chemical enrichment during the burst.

The simulations are first performed for solar partitions of elements, i.e. $\Gamma = 0$ and then for $\Gamma \neq 0$ (another dimension is added to the problem).

Finally, random errors are applied to the model indices to better simulate the observations. Using the data by Trager (1997) we calculate the mean relative errors $\langle \Delta I/I \rangle_0$ as reported in Table 4. The error affecting an index is randomly evaluated according to

$$\Delta I = -\left\langle \frac{\Delta I}{I} \right\rangle_0 I + 2 \times \epsilon \left\langle \frac{\Delta I}{I} \right\rangle_0 I,$$

where $\epsilon$ is a random number between 0 and 1.

### 5.2 Large scatter in age and metallicity of the bulk population

This is the simplest interpretation of the distribution of the galaxies in the H$\beta$ versus [MgFe] plane. Neglecting important effects due to enhancement in $\alpha$-elements and recent stellar activity, matching the observational range of the data would require the bulk population of early-type galaxies being formed in different epochs from galaxy to galaxy over a time-scale comparable to the Hubble time. In the central panel of Fig. 6 we show a simulated sample of 100 objects for which the following parameters are assumed: $T_1 = 13$, $T_2 = 2$ Gyr, $\beta_1 = 1$, no increase of the metallicity in this time interval, no later bursts of stellar activity, and finally $\Gamma = 0$. The models galaxies distribute along the SSP lines of different.
metallicity according to their age. The simulation significantly differs from the observational data shown in left-hand panel of Fig. 6. Even if this view could be fitted into the classical hierarchical scheme of galaxy formation, it can be hardly sustained because it would predict spectro-photometric properties not fully compatible with the observational data for EGs.

### 5.3 Random bursts of star formation

Bursts of star formation (from one to several) superposed to an old dominant population of stars seem to be more plausible and yield better results. Galaxies are conceived as old, nearly coeval systems, their population being approximated by a single SSP with age between 10 and 13 Gyr; this age range agrees with the current age estimate of EGs in rich clusters (Bower, Kodama & Terlevich 1998). A burst of stellar activity is added at an age randomly chosen in the interval $T_2 - T_3$. Two different prescriptions for the metallicity are adopted as described in Section 5.1 above. Finally, all the simulations are for $\Gamma = 0$. The maximum intensity of the superposed burst amounts to 2 per cent of the total mass, i.e. $\beta_1 = 0.98$ and $\beta_2 = 0.02$.

The simulations of this type are made at increasing complexity. Since they essentially confirm what already found by Longhetti et al. (2000) we limit ourselves to discuss the results and to highlight the point of disagreement with the observational data without showing any simulation in detail.

(i) Stronger bursts of star formation (i.e. engaging more than 2 per cent of the mass) are nor suited as they would predict too high values of $H_\beta$ and too many young objects.

(ii) The expected distribution of objects with respect to the $H_\beta$ index is at variance with the observational one. Indeed, models of this type predict a bimodal distribution, whereby the old galaxies (those for which the burst is almost as old as the bulk of their stellar content) are redder than the young ones.
populations) clump together in the lower portion of the diagram, whereas the ‘young’ objects (those with very young bursts) form a tail extending to high values of Hβ.

(iii) Nevertheless, the burst alone cannot explain the smooth distribution observed at low-Hβ values. This is because the Hβ index of a stellar population for which the 2 per cent of the mass is composed by ‘young’ stars and the remaining 98 per cent by an old component, reaches the observed high values, but, fading very rapidly with the age of the ‘young’ component, has low probability to match the intermediate observed values. Slowing down the index decrease (corresponding to the ageing of the ‘young’ component) by increasing the percentage of mass involved by the young burst produces an uncomfortably large fraction of objects in the upper part of the diagram. A complex interplay between burst intensity and mean age of the stellar population should then take place, with the old bursts being on average stronger than the recent ones. It must be said, however, that when the burst itself is larger than a few per cent of the total mass, the definition of the average age of the bulk of the stellar population becomes a problem.

(iv) The difficulty is partially cured assuming that the old population has an average age spreading over a significant fraction of the Hubble time (perhaps down to $T_2 \simeq 5$ Gyr). This is meant to indicate that either the object has been growing for such a long time with a low star formation rate, or that its major star formation activity was not confined to an early epoch. The young component is left to occur. It appears immediately that the observed smooth distribution in the Hβ index together with the young tail can be much better reproduced with such a kind of models, see Longhetti et al. (2000) for details.

(v) Another problem arises if the metallicity is randomly selected. The distribution of the models galaxies in the left-hand panel of Fig. 6 strictly follows the path of an SSP, whereas the data run much steeper. We take this point to invoke the existence of a relation between the age of the bulk stellar population and its average metallicity and to apply the ULMF. The simulations better fit the data.

The right-hand panel of Fig. 6 shows our final experiment incorporating all the hints we have been discussing so far. The simulations are based on the following parameters and assumptions: $T_1 = 13$, $T_2 = 5$, $T_{\alpha} = 0.1$ Gyr, $\beta_1 = 0.98$, $\beta_2 = 0.02$, average metallicity of the bulk of the stellar population forced to linearly increase from $Z = 0.008$ to $0.070$ over the time interval $T_1$ to $T_2$. Thanks to the combined effect of the large age and metallicity spread for the bulk population, the distribution in Hβ versus [MgFe] plane is nearly vertical. The larger range of metallicity is necessary to maintain a significant dispersion in [MgFe], because age differences tend to compensate metallicity differences. If the latter interpretation is correct, it suggests that young early-type galaxies in the field are on average more metal-rich than old systems, with an average metallicity gradient of approximately $\Delta\log(Z)/\Delta\log(t) \simeq 0.7$, the latter value being very dependent on the younger limit of the bulk age.

The main conclusion out of these simulations is that in addition to the mass dominating old population, which, however, has to be built up over a large time interval and under a suitable age–metallicity relationship, sprinkles of stellar activity in the recent or very recent past ought to considered in nearly all galaxies to reconcile theory and observations. However, that all galaxies have to go through recent star-forming activity is perhaps too demanding and other alternatives should be explored.

5.4 The $\alpha$-enhancement alternative

The results obtained by Tantalo & Chiosi (2004) for SSPs of the same age and metallicity but different degrees of enhancement in $\alpha$-elements offer a third plausible explanation. The bottom line of the model is best explained by comparing the theoretical models in the Hβ versus [MgFe] plane of Fig. 6 (central and right-hand panels), with the observational data (left-hand panel). Several points are soon evident.

(i) The majority of galaxies (those with $H \beta \leq 2$) are fully compatible with being very old objects of the same age (approximately 13 Gyr) but a different degree of enhancement in $\alpha$-elements going from $\Gamma = 0$ to 0.5 (taking the so-called natural width caused by a possible variation in single elemental species into account). As a matter of fact, an old galaxy (perhaps a 10–13 Gyr object) being shifted to higher Hβ by high $\Gamma$ and/or $[X_{\alpha}/Fe]$ ([$Ti/Fe$] as a prototype) could lie in the same region occupied by a galaxy of significantly younger age and solar abundance ratios. At least part of the scatter along the Hβ axis could be due to a different degree of enhancement in $\alpha$-elements.

(ii) Only for galaxies with $H \beta > 2$, unless their enhancement factor $\Gamma$ and abundance ratios $[X_{\alpha}/Fe]$ (such as [$Ti/Fe$]) are larger than the above limits, the presence of secondary star-forming activity ought to be invoked.

(iii) Looking at the position of models of constant metallicity and age but different $\Gamma$ and/or $[X_{\alpha}/Fe]$ (for instance [$Ti/Fe$]), they scatter along a nearly vertical line. This implies that the metallicity relationship invoked for the bulk old population is no longer required. The vertical distribution of the data is simply caused by the compensatory effect of different combinations of $Z$, $\Gamma$ and $[X_{\alpha}/Fe]$ ($[Ti/Fe]$ in our case).

(iv) Secondary episodes of star formation are no longer a common feature to all galaxies, but an exceptional event limited to a small number of them. This agrees with the age distribution obtained by Tantalo & Chiosi (2004).

The $\alpha$-model is confirmed by the Monte Carlo simulations shown in the central and right-hand panels of Fig. 7. In the central panel we show the case of old galaxies with no secondary activity: the bulk population spans the age range given by $T_1 = 13$ and $T_2 = 10$ Gyr with $\beta_1 = 1$, whereas the metallicity and $\alpha$-enhancement span the whole range for the parameters $Z$, $\Gamma$ and $[X_{\alpha}/Fe]$ ($[Ti/Fe]$ taken as a measure of the natural width). Since there is no further star formation activity $T_1 = 10$ Gyr and $\beta_2 = 0$. The models essentially match the bulk of data, i.e. galaxies with Hβ ≲ 2, and yield a distribution in the Hβ versus [MgFe] plane which is nearly vertical (no memory of the SSPs path). In the right-hand panel we show the same but allowing for recent burst to occur, i.e. $T_3 = 0.1$ Gyr. The burst intensity is for $\beta_2 = 0.02$. However, for the few galaxies clearly caught in the burst mode (those with $H \beta > 2$), the two theoretical distributions are nearly identical and both fairly well reproduce the observational data.

These simulations open the gate to an interesting alternative explanation, i.e. that the large scatter in Hβ and [MgFe] is predominantly caused by a spread in the chemical parameters metallicity Z and enhancement factor $\Gamma$ rather than metallicity and age in the bulk population of a galaxy. Secondary activity of star formation is unavoidable only for a minority of objects.

The scatter in Z, $\Gamma$ and also individual $[X_{\alpha}/Fe]$ of the dominant old stellar component could be attributed to different kinds of star formation at the very early epochs, perhaps related to the physical conditions in the protogalaxy affecting not only the intensity
and duration of the star formation process, but also the initial mass function of the stars and the abundance ratios in turn. We will touch upon this point later.

6 DISCUSSION

6.1 Testing the α-model

To corroborate the suggestion that the scatter in the Hβ versus [MgFe] plane for most galaxies is due the chemical parameters Γ, Z, and perhaps [Ti/Fe] we perform here a few ad hoc experiments.

First of all, we test a model with a very narrow age range for the old component and no subsequent star formation. The test is meant to isolate the sole effect of the chemical abundances. The model is characterized by the parameters: \( T_1 = 13, T_2 = 12, \beta_1 = 1, T_3 = 12 \) Gyr, and \( \beta_2 = 0 \). While no UMLE is considered, the metallicities, Γ’s and \([X_{el}/Fe]\)s (at present \([Ti/Fe]\)) are let span the whole range. The simulations are shown in left-hand panel of Fig. 8 correlating Mg, with [MgFe]. The choice of these two indices is based on the notion that [MgFe] is nearly independent on Γ, whereas Mg, does. Both are sensitive to the age and metallicity even if some degree of degeneracy is present. On purpose we avoided Hβ because of its equal sensitivity to all the parameters in question. In this plane we also displays the theoretical areas corresponding to the different combinations of Γ and [Ti/Fe], metallicities, and ages. Each area is bounded by the SSPs with the lowest (Z = 0.008) and highest (Z = 0.070) metallicities, the two heavy lines along which four values of the age are marked (2, 3, 8 and 13 Gyr). It is worth noticing the good resolving power of Mg, only for Γ and large insensitivity to all remaining parameters. Different values of \([X_{el}/Fe]\) ([Ti/Fe] in this case) have in practice no effect. Furthermore, the age and metallicity are nearly degenerate. The open circles are the simulations, the filled squares are the data by Longhetti et al. (2000), and finally the open triangles are those by Trager (1997). Secondly, we re-examine in the same plane the simulations shown in Fig. 7, in which a wider age range for the old component is adopted. All remaining ingredients are the same as above. These model are shown in the right-hand panel of Fig. 8. Comparing data with theory, we would conclude that in both cases Γ in the range 0–0.35 and Z \( \leq 0.07 \), probably 0.05, are best suited, the only difference between the two type of models is that in presence of a burst the left-lower corner of the panels is populated (i.e. Mg, \( \leq 2 \) and [MgFe] \( \leq 3 \)). In any case the large dispersion of the bulk population in the Hβ versus [MgFe] plane is once more compatible with all galaxies being old and spanning a large range of Γs and Zs. The large age dispersion (perhaps from 13 to 5 Gyr) and the occurrence of a later burst of activity are no longer unavoidable results and/or hypotheses. Only a few galaxies seem to require a later burst of star formation.

However, the upper limits suggested by the Mg, versus [MgFe] plane are not firmly established as different conclusions would be derived by looking at another diagnostic plane such as (Fe) versus Mg, shown in Fig. 9. All the symbols have the same meaning as in Fig. 8. From this diagram one would indeed conclude that Γ falls in the range 0.35–0.5, that high metallicities (up to Z = 0.07) are likely to occur, and finally that galaxies with Γ = 0 and metallicities larger than solar or so are not there. Since Mg, seems not to depend on Γ and (Fe) is likely to be more sensitive to both Γ and Z than other indices, we would favour the hints arising from this diagnostic plane with respect to the previous ones.

6.2 Two template galaxies

It may be of interest here to closely inspect some of the galaxies in the samples paying major attention to those with unusually high Hβ and/or very low [MgFe]. To this end three sources have been used: Trager (1997), Longhetti et al. (2000) for the...
Table 5. Selected galaxies: seven indices on the Lick system; $M$ is the mass in solar units inside the effective radius; $L_B$ is the B-luminosity in solar units; $\Sigma_0$ is the central velocity dispersion in km s$^{-1}$.

| Name       | H$\beta$ | $M_{\text{g2}}$ | $M_{\text{gb}}$ | Fe52  | Fe53  | (Fe) | [MgFe] | $(B - V)$ | log $M$ | $L_B$  | $\Sigma_0$ |
|------------|----------|-----------------|-----------------|-------|-------|------|--------|----------|--------|--------|-----------|
| NGC 2865   | 3.12     | 0.220           | 3.28            | 2.34  | 2.22  | 2.28 | 2.73   | 0.83     | 10.517 | 10.241 | 208       |
| NGC 5018   | 2.68     | 0.220           | 3.31            | 2.89  | 2.24  | 2.56 | 2.91   | 0.85     | 11.094 | 10.736 | 247       |
| E2400100b  | 2.79     | 0.210           | 3.79            | 3.12  | 2.33  | 2.71 | 3.21   | 0.82     | 122    | 223    |           |
| RR101b     | 2.35     | 0.230           | 3.67            | 2.83  | 2.35  | 2.64 | 3.08   | 0.88     | 210    |        |           |
| RR187b     | 2.80     | 0.220           | 3.40            | 2.69  | 2.34  | 2.51 | 2.92   | 0.93     | 144    |        |           |
| NGC 2863   | 3.02     | 0.208           | 3.12            | 2.65  | 2.20  | 2.43 | 2.88   | 0.87     | 87     |        |           |
| NGC 4742   | 3.32     | 0.185           | 2.83            | 2.50  | 1.97  | 2.23 | 2.51   | 1.05     | 105    |        |           |
| NGC 5061   | 2.65     | 0.275           | 3.93            | 2.97  | 2.83  | 2.90 | 3.38   | 0.86     | 10.925 | 10.586 | 191       |
| NGC 2865   | 3.12     | 0.220           | 3.31            | 2.89  | 2.24  | 2.56 | 2.91   | 0.85     | 11.094 | 10.736 | 247       |
| RR187b     | 2.80     | 0.220           | 3.40            | 2.69  | 2.34  | 2.51 | 2.92   | 0.93     | 144    |        |           |
| NGC 2863   | 3.02     | 0.208           | 3.12            | 2.65  | 2.20  | 2.43 | 2.88   | 0.87     | 87     |        |           |
| NGC 4742   | 3.32     | 0.185           | 2.83            | 2.50  | 1.97  | 2.23 | 2.51   | 1.05     | 105    |        |           |
| NGC 5061   | 2.65     | 0.275           | 3.93            | 2.97  | 2.83  | 2.90 | 3.38   | 0.86     | 10.925 | 10.586 | 191       |

(iii) From the position of a galaxy suspected to be in the burst or post-burst activity because of its unusual indices in planes for composite systems such as those presented in Fig. 5 on one hand we may find another estimate of the burst age, on the other hand we may check the consistency of the whole picture. For the sake of illustration, we discuss here the case of NGC 5018, a giant elliptical galaxy with total mass $M = 1.24 \times 10^{11} M_{\odot}$, luminosity $L_B = 5.43 \times 10^{10} L_{\odot}$, central velocity dispersion $\Sigma_0 = 223$ km s$^{-1}$, H$\beta = 2.30$ and Mg2 = 0.211. Long ago, Bertola, Burstein & Buson (1993) have classified NGC 5018 as a giant, chemically unevolved galaxy consisting of M32-like stars, and Leonard & Worthey (2000) have suggested that the central regions of NGC 5018 are dominated by an intermediate-age population. Along the same vein, is the very recent study by Buson et al. (private communication) who have stressed the close similarity between M32 (NGC 221) and NGC 5018. The similarity concerns the indices as shown by the entries of Table 5, the $(B - V)$ colours, and the spectrum from 2000 to 4700 Å (Buson et al., private communication). They have also made the point that since M32 (at least in the central regions) is commonly considered to...
Figure 10. Age estimate of the last episode of star formation in a few galaxies with unusual values of H$\beta$ and/or [MgFe] (left-hand panel) and Mg$_{2}$ (right-hand panel). The galaxies indicated with different symbols are listed in the right-hand panel. In each panel we plot three SSPs with different metallicity, Z = 0.008, 0.019, and 0.040 as indicated, along which five values of the age are marked, i.e. 13, 8, 5, 3 and 1 Gyr, and the corresponding lines of constant age are drawn (thin dotted lines). Finally, we show the locus expected for composite galaxies, in which to a population with the age of 13 Gyr and metallicity Z = 0.019, a burst of arbitrary age and different intensity is added. The metallicity of the young component is, however, the same as the old one (Z = 0.019). The intensities are $\beta_2 = 0.005$ (long dashed line), 0.01 (heavy dotted line), and 0.02 (solid line). Along each curve the age increases from the minimum plotted value 0.1 to 13 Gyr. The position of M32 is compatible with various combinations of $T_B$ and $\beta$, for instance $T_B \simeq 1$ Gyr and $\beta_2 = 0.005$ or $T_B \simeq 2$–3 Gyr and $\beta_2$ in the range 0.01–0.02. At given $\beta_2$, the burst age will increase if higher metallicities for the young component are considered.

be dominated by a population where the age is approximately 3 Gyr (Freedman 1989, 1992; Longhetti et al. 2000; Trager et al. 2000b,a) the same should occur for NGC 5018. However, the reality may be more complex than this simple scheme. Studies of the stellar content and other properties of M32 have pointed out that the bulk population could be as old as that of globular clusters, e.g. see the discussion by Bressan, Chiosi & Fagotto (1994) and references therein, and by Grillmair et al. (1996). Bressan et al. (1994, 1996) have argued that the young stellar component in M32 could result from a recent burst of activity superposed to the pre-existing, old stellar content. Is NGC 5018 experiencing the same? To check this possibility, in Fig. 10 we plot M32, NGC 5018 and other galaxies of Table 5 on to the H$\beta$ versus [MgFe] and Mg$_{2}$ planes and compare them with single SSPs of different age and metallicities and composite SSPs in which bursts of different intensity and age are superposed to an old dominant component. In the first case we recover the standard solution, i.e. M32 is an object where the stellar content is approximately 3–4 Gyr, whereas in the second case M32 is an old object (perhaps 10–13 Gyr) on the top of which a young component (1–2 per cent of the total mass) is present. The age of this is approximately 1 Gyr. An old galaxy, which underwent a burst of activity perhaps 1 Gyr ago, would appear as a brand newly formed galaxy with the age of approximately 3–4 Gyr. The same analysis can be extended to other galaxies of Table 5. A special remark is due to the three galaxies with very low [MgFe]: we exclude RR317b because it shows evidence of emission [OII] (3712 Å) as already pointed out by Longhetti et al. (2000). The case of NGC 3156 is trivial because of its strong H$\beta$: it is indeed fully compatible with theory if undergoing a burst of star formation. We are left with RR62a for which not very much can be said: it follows the same $\mu_\alpha$–$R_e$ relationship as ordinary galaxies, but it deviates from the Hamabe–Kormendy relationship (Hamabe & Kormendy 1987). It could be an old, low-metallicity galaxy which according to Gorgas et al. (1993) should fall into the bottom left corner of the H$\beta$ versus [MgFe] plane. Alternatively, it could be old galaxy which is just starting (or undergoing) a burst of star formation as indicated by the results for composite SSPs shown in Fig. 5.

6.3 The Coma EGs

We have already mentioned that EGs in Coma (Jørgensen 1999) have systematically higher values of H$\beta$ than the local galaxies. The minimum value is H$\beta = 1.5$. Repeating the same analysis we have made for the Trager (1997) and Longhetti et al. (2000) samples we would come up with the following conclusions. (i) The $\alpha$-model may hold good even in this case. (ii) The Coma galaxies have a higher degree of enhancement than the local ones. A rough estimate is $T \geq 0.3$. Supporting this idea is the estimate for the age of the Coma EGs by Poggianti et al. (2001) who find a mean age older than approximately 9 Gyr; the estimate of the ratio [Mg/Fe] by Jørgensen (1997, 1999) who finds [Mg/Fe] = 0.3–0.4 as the central velocity dispersion log $\Sigma_0$ increases of 0.4 dex; and finally the recent study by Mehler et al. (2003) who find $[\alpha/Fe]$ ratios in the range 0.15–0.4. The mean degree of enhancement in EGs of the Coma Cluster seems to be at least 0.1 dex higher than in the local field galaxies.

6.4 $\alpha$-enhancement in EGs: data and theory

The occurrence of the $\alpha$-enhancement in early-type galaxies is currently attributed to the duration of the star-forming period and the different contribution to chemical enrichment by Types Ia and II supernovae (see Matteucci 1997 for a review of the subject). In brief, $\alpha$-elements are mainly ejected by Type II together with some Fe, whereas Fe is essentially expelled by Type Ia supernovae (via the carbon ignition in binary white dwarfs reaching the Chandrasekhar limit by mass accretion). As long as Type Ia supernovae do not intervene in a significant manner, the chemical composition of the gas and newly formed stars in turn will be enhanced in $\alpha$-elements. Since Type Ia supernovae are expected to start contaminating the intergalactic medium through Type II (Greggio & Renzini 1983), within the framework of the standard supernova driven galactic wind model by Larson (1974) and the standard initial mass function, the timescale of star formation and galactic wind must be shorter than approximately 0.5 Gyr not to decrease the initial $[\alpha/Fe] > 0$ (when $\alpha$-elements are mostly produced) to $[\alpha/Fe] \leq 0$ (when iron is predominantly ejected). In other words, to reproduce the observed trend of the $[\alpha/Fe]$–mass relationship, the total duration of the star-forming activity ought to scale with the galaxy mass according to $\Delta t_{SF} \propto M_\star^{-1}$. This is the main drawback of the standard model because it requires a mass-star-formation–time-scale correlation which is the opposite of what is implied by the colour–magnitude relationship (Bower et al. 1992a) as amply discussed in Bressan et al. (1996); Chiosi (2000); Chiosi & Carraro (2002); Tantalo & Chiosi (2002). This point of difficulty has been overcome by the $N$-body
Tree–SPH model of Chiosi & Carraro (2002). In brief: (i) independently of the total mass, galaxies of high initial density undergo a prominent initial episode of star formation followed by quiescence. (ii) The same applies to high-mass galaxies of low initial density, whereas the low-mass ones undergo a series of burst-like episodes that may stretch over a considerable fraction of their lifetime. (iii) The mean and maximum metallicity increase with the galaxy mass. Therefore, these models can account for the CMR of EGs. (iv) Finally, the occurrence of galactic winds does not follow the simple Larson (1974) model, but takes place continuously in lumps of gas as soon as their thermal kinetic energy exceeds the gravitational energy of the galaxy. In other words, the scheme on which the Larson (1974) model rests, i.e. longer star formation period, higher metallicity, lower degree of $\alpha$-enhancement at increasing galaxy mass, is reversed but for the metallicity. Therefore, the CMR and $\alpha$-enhancement constraints are met at the same time. See Chiosi & Carraro (2002) and Tantalo & Chiosi (2002) for all details. Given these premises, the existence of various degrees of $\alpha$-enhancement in different EGs finds a natural explanations thanks to the sensitivity of the star-forming process and its duration to the initial conditions (mean density) and total mass of the protogalaxy. By the same token we may also explain the systematic higher abundance ratios $[\alpha/Fe]$ passing from field to cluster galaxies.

7 WHAT IS THE MAXIMUM COLOUR DISPERSION OF EGs?

Our aim here is to check at what extent a past episode of star formation would reflect on to broad-band colours, such as $(B - V)$, of the host galaxy as we see it today. To this aim we adapt the toy model of galaxy formation we have been using in so far. The analysis below applies both to the monolithic (isolation) and hierarchical scheme.

For the sake of simplicity let adopt a model with the minimum number of parameters: solar scaled abundances, fixed age for the old stellar component, here indicated as $T_F \simeq 12$ Gyr, fixed mean metallicity. With no further stellar activity, passive evolution of the galaxy would imply that at the present time $(B - V) \simeq 1.00 \pm 0.05$ whereby the uncertainty reflects the spread in metallicity and abundance ratios.

Now suppose that at a certain age $T_B$ the model galaxy undergoes an additional episode of star formation of short duration and arbitrary intensity $\beta_2$ (this immediately fixes also the intensity $\beta_1$ of the old component, their sum being equal to unity). The burst can be of internal origin (e.g. gas left over by the previous activity and then turned into stars) or the result of a merger with some gas-rich object. In the first case, the galaxy will be made by an old and a young component. In the second case, the galaxy will consist of two subunits harbouring old populations (in principle, of different age and metal content) plus the younger component born during the burst.

The colour evolution of the composite galaxy is followed up to the present time and its broad-band colours are tested against observations. The results are displayed in the large panel of Fig. 11 as a function of the age and intensity of the secondary activity. Let us now read off the age $T_B$, at which a galaxy which underwent a burst of star formation of intensity $\beta_2$ at the age $T_B$ is able to recover the same colour it had before the burst. This is simply given by the intersection of any line labelled $\beta_2$ with the horizontal bar. The ages $T_B$ as a function of the $\beta_2$ are shown in the small panel of Fig. 11. It turns out that for many combinations of $T_B$ and $\beta_2$, the resulting $(B - V)$ colour would be too blue as compared with the typical colours of EGs, $(B - V) = 1.00 \pm 0.05$. Stellar activities engaging 5–10 per cent of the total mass and taking place as early as 5–6 Gyr ago would be detectable. The situation becomes even worse for higher $\beta_2$ and/or lower $T_B$. This implies that only remote or minute star-forming events are allowed. Therefore, either mergers occur very early on in the history of a galaxy or only captures of small bodies and little companion star formation can take place at later epochs. This is a rather strong constraint that should be taken into account by any model of hierarchical assembling of big galaxies. It is plausible to suggest that the main body of a galaxy was assembled early on and that all subsequent activity we infer from the observational data is limited to the capture of small objects (probably satellites of the dominant galaxy).

8 SUMMARY AND CONCLUDING REMARKS

The present-day challenge with EGs is to unravel their formation and evolution history. In a simplified picture of the issue, the problem can be cast as follows. Do EGs form by hierarchical merging of pre-existing substructures (maybe disc galaxies) made of stars and gas? Was each merging event accompanied by strong star formation? Or conversely, they originate from the early aggregation of lumps of gas turned into stars in the remote past via a burst-like episode ever since followed by quiescence so as to mimic a sort of monolithic process? Even if the two alternatives seem do oppose

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Figure 11. Simulations of the $(B - V)$ colour of EGs in which a burst of star formation of arbitrary intensity ad age $T_B$ is superposed to an old population with the age of 13 Gyr. In these simulations for both components we assume $Z = 0.019$ and $\Gamma = 0$. The burst intensity is $\beta_2 = 0.001, 0.002, 0.005, 0.01, 0.02, 0.08, 0.10, 0.20, 0.30, 0.40, 0.50$, going from bottom-left to top-right as indicated. The horizontal bar visualizes the typical colour of EGs with the uncertainty $\Delta(B - V) = \pm 0.055$. The insert shows the time $T_B$ in Gyr elapsed from the epoch of the burst to the stage at which the composite galaxy recovers the typical red colours of EGs as a function of the burst intensity. $T_B$ is given by the intersection of each colour curve with the horizontal bar.
each other, actually they may concur to shaping the final properties of EGs as seen today. The question is to unravel the signature of the forming mechanism from the observational data. To this end we have examined the line absorption indices on the Lick system of normal, field EGs of Trager (1997) and of interacting EGs (pair- and shell-objects) of Longhetti et al. (2000). Occasionally, we have also looked at the EGs in the Coma clusters of Jørgensen (1999) and other more specific cases taken from literature. The main aim of this study was: (i) to check whether normal (quiescent) and interacting have a different behaviour in the popular diagnostic planes such as Hβ versus [MgFe] (and others); (ii) to seek whether the signature of interaction may mirror in some specific changes of the indices that could unequivocally hint for bursts of stellar activity; (iii) to evaluate the intensity of those bursts or secondary episodes of star formation; (iv) to explore whether other alternatives can exist, i.e. distinct from obvious ones resting on large age range and/or bursts of star formation (from one to several) at various epochs.

From the various observational issues we have been examining in so far, we gather the following picture.

(i) Both normal, field and interacting galaxies have the same scattered distribution in the Hβ versus [MgFe] diagnostic plane even the interacting ones show a more pronounced tail toward high-Hβ values. This may suggest that a common physical cause is at origin of their distribution.

(ii) The distribution of normal and interacting galaxies is smoothly elongated in Hβ. While for the interacting objects an easy, however, not fully satisfactory, explanation can be found invoking a late burst of activity, in the case of normal galaxies an explanation can be found only invoking a large age range for the bulk population together with the existence of a universal law of metal enrichment. Adding a late burst of star formation to an old system without invoking the large age range and the universal law of chemical enrichment would not yield the desired trend. Therefore, normal galaxies have to be built up not only over a large time interval but also at increasing total metallicity. The occurrence of a late star-forming episode is a side detail.

(iii) More specifically, a typical model based on classical SSPs with solar partition of elements and where the burst is superimposed to an old and coeval population is not able to reproduce the smooth distribution of galaxies in the Hβ versus [MgFe] plane. This kind of model would predict an outstanding clump at low-Hβ values, contrary to what is observed. Models in which star formation lasted for a significant fraction of the Hubble time (4 \( \leq t_{\text{ds}} \leq 16 \) Gyr) better match the observed diagram. In this context, the peculiar, almost vertical distribution of galaxies (normal, shell- and pair-objects) in the Hβ versus [MgFe] plane is interpreted as the trace of increasing the average metallicity accompanying all star-forming events. This could be the signature of a metal enrichment happening on a cosmic scale.

(iv) However, the above scheme is first too demanding because of the many ad hoc ingredients that have to be introduced, secondly it neglects important effects given by the observationally grounded hint that the stellar content of EGs is probably enhanced in α-elements with Γ ranging from 0.1 to 0.4 dex. We would like to propose a new scheme, in which the bulk dispersion of galaxies in the Hβ versus [MgFe] plane is caused by a different mean degree of enhancement. Indeed, two old galaxies of the same age (perhaps 13 Gyr) but different Γ and |[X]/[Fe] for some important species (C, N, O, . . ., Ti) would have different values of Hβ. For instance passing from a 13 Gyr old galaxy with Γ = 0 to an object with the same age but Γ = 0.3 would increase Hβ by as much as 0.2–0.3 or more (depending on the abundance ratios for some specific elements such as Ti). The effect is comparable to the mean observational dispersion. The majority of EGs can be pretty old (10–13 Gyr). Furthermore, neither large age range nor universal enrichment law are required. The nearly vertical smooth distribution for coeval galaxies is secured by the compensatory effect of different combinations of Γ and ζ. Finally, the occurrence of a late burst of activity is not an unavoidable ingredient of the recipe, but a rare event interesting only those galaxies with very high Hβ (roughly \( > 2.5 \)). The possibility that EGs span large ranges of Γ and metallicitities but narrow ranges of ages for the bulk population favours the monolithic scheme and can be derived from N-body Tree–SPH models of galaxy formation as a consequence of the dependence of the star formation efficiency and temporal history on the initial mean density and total mass of the protogalaxy.

(v) As far as we can tell, from simulations of broad-band colours, EGs are compatible with the notion that the bulk stars have formed in the remote past. Galaxy mergers and companion star formation in a recent past are not likely, unless the intensity of the secondary activity is very small (i.e. engaging less than a few per cent of the total mass). Were merging the only possible mechanism to form massive EGs, this should have occurred in a remote past (half of the Hubble time at least). In any case merging of smaller units without star formation even in a recent past cannot be excluded. Is it likely?

(vi) Finally, prolonged or secondary stellar activity seem to be also more probable in field and loose groups EGs than in those belonging to compact groups and clusters. The physical cause could once more be the mean density of the environment out of which protogalaxies are formed.

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