The Stellar Populations of Early-Type Galaxies in the Fornax Cluster

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Abstract. We have measured central line strengths for a complete sample of early-type galaxies in the Fornax cluster, comprising 11 elliptical and 11 lenticular galaxies, more luminous than $M_B = -17$. We find that the centres of Fornax ellipticals follow the locus of galaxies of fixed age in Worthey's models and have metallicities varying roughly from half solar to 2.5 times solar. The centres of (relatively low luminosity) lenticular galaxies however exhibit a substantial spread to younger luminosity weighted ages indicating a more extended star formation history.

Our conclusions are based on two age/metallicity diagnostic diagrams in the Lick/IDS system comprising established indices such as [MgFe] and Hβ as well as new and more sensitive indices such as Fe3 and Hγ_A. The inferred difference in the age distribution between lenticular and elliptical galaxies is a robust conclusion as the models generate consistent relative ages using different age and metallicity indicators even though the absolute ages remain uncertain. The absolute age uncertainty is mainly caused by the effects of non-solar abundance ratios which are not accounted for in the stellar population models. We find that Es are generally overabundant in magnesium where the most luminous galaxies show stronger overabundances. The luminosity weighted stellar populations of young S0s are consistent with solar abundance ratios or a weak Mg underabundance. Two of the faintest lenticular galaxies in our sample have blue continua and extremely strong Balmer-line absorption suggesting starbursts < 2 Gyrs ago.

1. Introduction

As pointed out by Worthey (1994) the determination of the ages or metallicities of old stellar populations is complicated by the similar effects that age and metallicity have on the integrated spectral energy distributions. Broad band colours and most of the line strength indices are degenerate along the locus of $\Delta\,\mathrm{age} \approx -3/2\,\Delta\,\mathrm{Z}$. In other words the integrated SED of an old (> 2 Gyrs) stellar population looks almost identical when age is doubled and total metallicity reduced by a factor of three at the same time. In the optical wavelength range only a few narrow band absorption line-strength indices have so far been identified which can break this degeneracy. In terms of age, the Balmer lines, Hβ, Hγ and Hδ are the most promising features, being clearly more sensitive to age than metallicity. Features which are more metal sensitive, and thus less age sensitive are e.g., Fe5270, Fe5335 and Fe4383. By plotting an age sensitive index and a metallicity sensitive index against each other one can break the degeneracy and estimate the luminosity weighted age and metallicity of a integrated stellar population (see e.g., Figure 1).

2. The Ages and Metallicities

In this Section Worthey (1994) single-burst stellar population models are compared to observed central ($2\farcs3 \times 3\farcs85$ aperture) line-strength indices of a complete sample of Fornax early-type galaxies obtained at the Anglo–Australian–Telescope in Dec 1996. All indices have been accurately calibrated to the Lick/IDS system taking into account resolution differences, velocity dispersion corrections and small systematic offsets. For details see Kuntschner & Davies (1998) and Kuntschner (1998). In Figure 1 we show a plot of Hβ equivalent width *vs* [MgFe] equivalent width, where [MgFe] is defined as

$$[\mathrm{MgFe}] = \sqrt{\mathrm{Mgb} \cdot \frac{\mathrm{Fe5270} + \mathrm{Fe5335}}{2}} \quad . \tag{1}$$

The error bars on the individual data points represent the photon noise and the error in the velocity dispersion correction. Overplotted are model predictions by Worthey (1994). The elliptical galaxies in Fornax (filled circles) have weak Hβ absorption spanning a modest range in [MgFe]. The more metal rich Es tend to have larger central velocity dispersions as indicated by the symbol size. The S0s (open circles) on the other hand span a larger range of values in this diagram, typically having stronger Hβ absorption. The central regions of two bright S0s (NGC 1380 and NGC 1381) show Hβ absorption similar to the Es. Fornax A, however, often cited as the product of a recent merger, shows a young luminosity weighted age. We note that apart from Fornax A all young galaxies are rather faint having velocity dispersion < 100 kms^{-1}. The two lenticular galaxies with the lowest [MgFe] values and strong Hβ absorption (ESO359-G02, cross and ESO358-G25, open triangle) show extraordinary blue spectra for early-type galaxies with only weak metal absorption lines. These galaxies are likely to be post-starburst or starburst galaxies.

The spectrum of ESO358-G25 even exhibits nebular emission in Hβ and Hγ_{A} along with weak [O III] emission. The nebular emission can fill in the stellar Hβ absorption leading to an underestimate of the real stellar absorption and thus to an overestimate of the mean age. The arrow in Figure 1 indicates a rough emission correction. To reduce contamination by nebular emission we use Hγ_{A} as an improved age indicator because it is less affected by the nebular emission (Osterbrock,

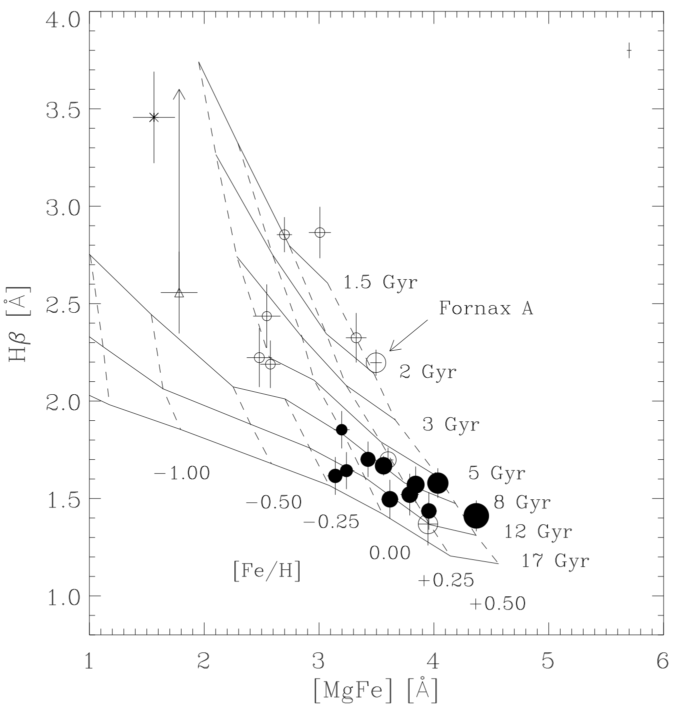

Figure 1. Hβ equivalent width *vs* [MgFe] equivalent width diagram for the complete sample of Fornax early-type galaxies (central 2.3 arcsec$\times$3.85 arcsec aperture). Overplotted are models by Worthey (1994). The solid lines represent isoage lines whereas the dashed lines are lines of constant metallicity. Filled circles and open circles represent ellipticals and S0s respectively. The cross and open triangle represent possible post-starburst and starburst galaxies respectively. The area covered by the symbols is proportional to the central velocity dispersion of the galaxy. The cross in the right upper corner indicates the rms uncertainty in the transformation to the Lick/IDS system. The arrow attached to the galaxy ESO358-G25 (open triangle) indicates an emission correction.

1989). Furthermore we have defined a new metal sensitive index, Fe3. This index is designed to maximize its sensitivity to Fe-abundance and at the same time minimize photon noise. Fe3 is defined as

$$\mathrm{Fe3} = \frac{\mathrm{Fe4383} + \mathrm{Fe5270} + \mathrm{Fe5335}}{3} \qquad (2)$$

Figure 2 shows a plot of Hγ_{A} equivalent width *vs* Fe3 equivalent width. The first thing to notice is that the effects of age and metallicity are not as well separated as in the previous diagram, i.e., the model grid is more "squeezed". However, the galaxies occupy very similar positions relative to the model grid as shown in Figure 1. Thus we have confirmed

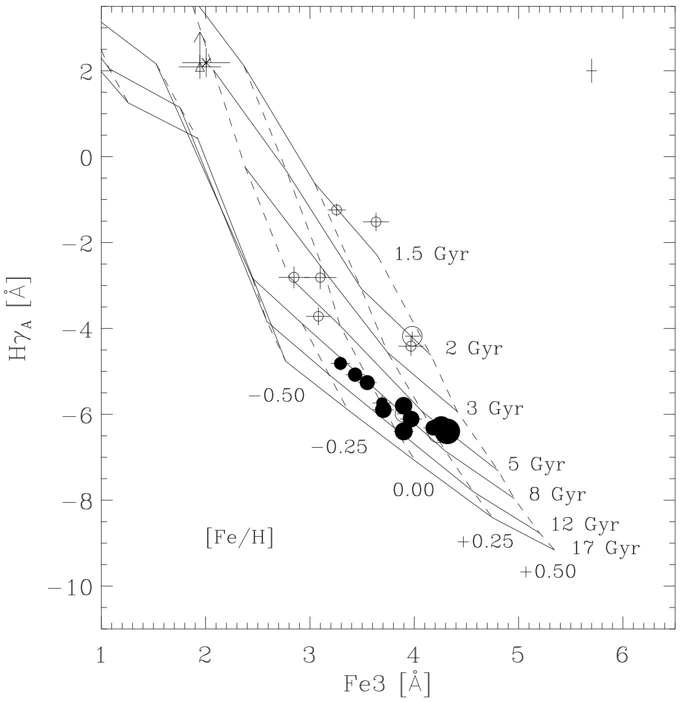

Figure 2. Fe3 equivalent width *vs* $H\gamma_A$ equivalent width diagram. Overplotted are models from Worthey (1994) and Worthey & Ottaviani (1997). The symbol sizes are scaled such that the area of the symbol is proportional to the central velocity dispersion of the galaxy. The cross in the right upper corner indicates the rms uncertainty in the transformation to the Lick/IDS system. Note that two bright S0s are hidden in the sequence of Es.

our previous findings with an independent index combination. Furthermore the galaxy with nebular emission has moved to much younger ages, supporting the advantage of using $H\gamma_A$ as an age indicator which is relatively robust against emission.

Inspecting Figure 2 in detail we find that the most luminous galaxies appear less metal rich in the $H\gamma_A$ *vs* Fe3 diagram compared to the $H\beta$ *vs* [MgFe] diagram. This behaviour was previously reported and recently reviewed by Worthey (1998). It is now widely accepted that this discrepancy in the model predictions is caused by non-solar abundance ratio effects. For example Mg as measured by the Mg_2 index is overabundant compared to Fe in luminous elliptical galaxies, i.e., [Mg/Fe]>0 (Peletier, 1989; Worthey, Faber & González, 1992; Davies, Sadler & Peletier, 1993).

3. Non-Solar Abundance Ratios

The Mg overabundance can be more clearly demonstrated in a Mg-index *vs* Fe-index plot. In such a diagram the model predictions cover only a narrow band in the parameter space as effects of age and metallicity degenerate. If the model predictions accurately resemble the galaxies properties they should trace the observed relation. For this analysis we assume that the models have solar abundance ratios, i.e., [Mg/Fe]=0. This might not be entirely true as the Lick/IDS stellar library, on which the models are based, probably contains stars which are Mg-overabundant at low metallicities (McWilliam, 1997).

Figure 3 shows a plot of Fe5270 equivalent width *vs* Mg_2 for the Fornax sample. Overplotted are model predictions from Worthey (1994). The measured line-strength of the young S0s in our sample roughly agrees with the model predictions with 2–3 galaxies having slightly low Mg_2 compared to Fe5270. However, for most of the ellipticals, the models predict too weak Mg-absorption at a given Fe-absorption strength. There is also a trend apparent that the most metal rich galaxies are the furthest away from the models. Using the Mg-overabundance correction by Greggio (1997) we conclude that the stellar populations of Fornax ellipticals are Mg-overabundant relative compared to Fe. The overabundance ranges between [Mg/Fe]=0.0 to ∼0.4. S0s are generally consistent with solar abundance ratios or maybe slightly underabundant in Mg.

As previously noted the Mg-overabundance, which is not accounted for in the models, can affect the age and metallicity estimates. It is important to notice that a trend in Mg-overabundance, i.e. the more luminous galaxies being more overabundant than low luminosity ones, as seen in the Fornax sample, influences not only the inferred relative metallicity distribution but also can change the relative age distribution in diagrams such as Figure 2. This is caused by the residual age/metallicity degeneracy in the diagrams. Only if the index-combination breaks the degeneracy completely, i.e., if lines of constant age and constant metallicity are perpendicular, would the age estimates not be affected by non-solar abundance ratios.

Introducing non-solar abundance ratios in model predictions is rather complicated as accurate model predictions do need a stellar library covering the whole parameter space of T_e, log g, [Fe/H] *and* [Mg/Fe]. Furthermore new isochrone calculations are probably needed for each [Mg/Fe] bin as recent research by Salaris & Weiss (1998) shows that scaled-solar isochrones cannot be used to replace Mg-enhanced ones at the same total metallicity. The latter will not only change the model predictions for indices such as Mg_2 but may affect all indices and in

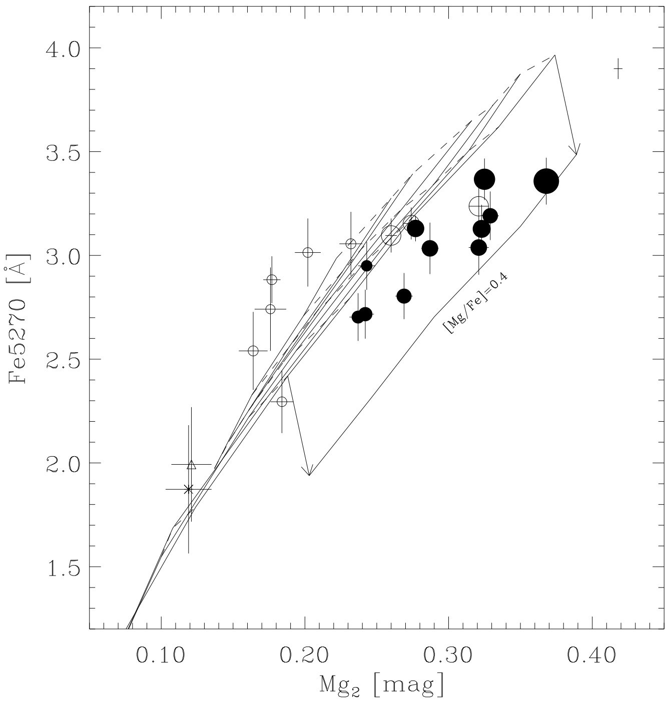

Figure 3. Mg_2 *vs* Fe5270 equivalent width diagram for the complete sample of Fornax early-type galaxies. Overplotted are models by Worthey (1994) and a correction for [Mg/Fe]=0.4 for the 17 Gyrs isoage line (taken from Greggio 1997). The symbol sizes are scaled such that the area covered by the symbol is proportional to the central velocity dispersion of the galaxy. The cross in the right upper corner indicates the rms uncertainty in the transformation to the Lick/IDS system.

particular the age sensitive ones such as Hβ and Hγ_A (see also Worthey, 1998).

4. Conclusions

We have measured the central line strength indices in a complete sample of early-type galaxies brighter than $M_B = -17$ in the Fornax cluster and have applied the models of Worthey (1994) and Worthey & Ottaviani (1997) to estimate their ages and metallicities. We find that:

1. **Elliptical Galaxies** appear to be roughly coeval forming a sequence in metallicity varying roughly from -0.25 to 0.30 in [Fe/H]. This result is consistent with the conventional view of old, coeval

elliptical galaxies where the metallicity scales roughly with the luminosity of the galaxy.

2. **Lenticular Galaxies** have luminosity weighted metallicities in the range $-0.5 \lesssim [\mathrm{Fe/H}] \lesssim 0.5$. Their *luminosity weighted ages* are on average much younger than those of the ellipticals. However, the centres of the bright lenticular galaxies NGC1380 and NGC1381 resemble the properties of ellipticals suggesting that they experienced similar star formation histories. The peculiar S0 galaxy Fornax A (NGC1316), which is the brightest galaxy in the sample, has extremely strong Balmer lines implying a very young luminosity weighted age, yet the metallicity is equal to the most metal rich Es. We interpret this as sign of a recent merger in which new stars were formed.

3. Our conclusions are based on two independent age/metallicity diagnostic diagrams which give very consistent results. Furthermore we demonstrate the advantage of using emission robust age indicators such as $\mathrm{H}\gamma_{\mathrm{A}}$ when analysing the stellar populations of extragalactic objects.

4. We have discovered that two of the fainter and very metal poor lenticular galaxies appear to have undergone major star-formation in the last 2 Gyrs (in one case very much more recently). We note that, like Fornax A, these galaxies lie on the periphery of the cluster.

5. Not all galaxies in the Fornax cluster have solar abundance ratios. The elliptical galaxies exhibit overabundances up to 0.4 dex in Mg. There is a trend that the most metal rich galaxies are the most overabundant, whereas the faintest Es approach solar ratios. Young S0s on the other hand seem to be consistent with roughly solar abundance ratios, and may even be slightly underabundant. Furthermore we note that varying abundance ratios, which are not included in the models, can lead to a change of relative age and metallicity estimates depending on which index combination is used in the analysis.

6. As long as the non-solar abundance ratios are not properly incorporated into the models the estimation of absolute ages of integrated stellar populations remains insecure.

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