Hot Stars in Old Stellar Populations: A Continuing Need for Intermediate Ages

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ABSTRACT

We investigate the effect of a small contamination of hot, old, metal-poor starlight on the inferred stellar populations of early-type galaxies in the core of the Coma Cluster. We find that the required correction to the Balmer and metal absorption-line strengths for old, metal-poor stars does not significantly affect the inferred age of the stellar population when the H\textbeta strength is large. Intermediate-aged populations are therefore still needed to explain enhanced Balmer-line strengths in early-type galaxies. This gives us increased confidence in our age estimates for these objects. For galaxies with weak Balmer-line strengths corresponding to very old populations (t > 10 Gyr), however, a correction for hot stars may indeed alter the inferred age, as previously suggested. Finally, the inferred metallicity [Z/H] will always be higher after any correction for old, metal-poor starlight than without, but the enhancement ratios [E/Fe] will strengthen only slightly.

Key words: galaxies: stellar content — galaxies: ellipticals and lenticulars — galaxies: clusters: individual (Coma)

1 INTRODUCTION

Stellar population analysis offers a powerful, if difficult to interpret, method of understanding the formation histories of nearby early-type galaxies (see Rose 1985; González 1993; Trager et al. 2000b; Caldwell, Rose & Concannon 2003; Mehlert et al. 2003, for just a few examples). This analysis relies primarily on the comparison of a hydrogen Balmer absorption-line strength to a metal absorption-line strength (or a combination of metal lines) to break the age–metallicity degeneracy (Worthey 1994), as the Balmer lines are (non-linearly) sensitive to the temperature of the main-sequence turnoff and the metal lines are sensitive to the temperature of the red giant branch. One can therefore determine accurate ages for the old stellar populations found in early-type galaxies. However, other hot star populations such as blue horizontal branch stars or blue straggler stars can significantly increase the observed Balmer-line strengths of old stellar populations (see, e.g., Burstein et al. 1984; Rose 1985; Rose & Tripicco 1986; Rose 1994).

In this paper we explore the effect of a specific kind of hot star population, that is, old, metal-poor populations containing blue horizontal branch stars, on the inferred stellar population ages and compositions of early-type galaxies in the Coma Cluster. These galaxies appear have significant intermediate-aged populations due to their enhanced Balmer lines. We use blue indexes first described by Rose (1985, 1994) to determine the level of contamination of the galaxy spectra by blue horizontal branch (BHB) stars. We then subtract model spectra representing populations containing these stars from the observed spectra and determine ages, metallicities, and enhancement ratios from the residual spectra. Finally these stellar population parameters are compared with those determined from the observed spectra to quantify the effect of a contaminating population of old, metal-poor stars on the spectra of early-type galaxies.

Throughout this paper, we refer to populations with metallicities [Z/H] ≤ −1.5 as ‘metal-poor’ (and thus possessing BHB stars) and populations with ages 1 < t < 10 Gyr as ‘intermediate aged’.

2 DATA

The line strengths discussed in this paper are derived from multi-slit spectra of twelve early-type galaxies in the Coma Cluster, centred
on the cD galaxy NGC 4874, taken with the Low-Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) on the Keck II 10-m Telescope. Details relevant to the current study are summarised here; for a complete description of the acquisition, reduction, and calibration of these spectra and the extraction of Lick/IDS absorption-line strengths we refer interested readers to Trager, Faber & Dressler (in preparation; hereafter TFD05).

2.1 Observations

Spectra were obtained in three consecutive 30-minute exposures on 7 April 1997 UT with the red side of LRIS, with seeing FWHM ≈ 0.8 arcsec, through clouds. A slit width of 1 arcsec was used in conjunction with the 600 line mm⁻¹ grating blazed at 5000 Å, giving a resolution of 4.4 Å FWHM (σ = 1.9 Å) and a wavelength coverage of typically 3500–6000 Å, depending on slit placement. Spectra of Lick/IDS standard G and K giant stars and F9–G0 dwarfs (Worthey et al. 1994) were observed on the same and subsequent nights through the LRIS 1 arcsec long slit using the same grating to be used for calibration to the Lick/IDS system (see Sec. 2.3 below).

Individual two-dimensional spectra of each galaxy were extracted from the multi-slit images after standard calibrations (overscan correction, bias removal, dark correction, and flat field correction), mapping of the geometric distortions, wavelength calibration, and sky subtraction. Both individual one-dimensional spectra and variance-weighted, combined spectra were then extracted from the two-dimensional spectra. In order to simulate an equivalent circular aperture to match with other line strength work in the Coma Cluster, the extracted spectra were weighted by distance from the object centre. For the present study the spectra were extracted with an equivalent circular diameter aperture of 2.7 arcsec, matching the Lick/IDS galaxy aperture (Trager et al. 1998) and the fibre diameter of the large sample of line strengths of Coma galaxies of Moore et al. (2002). Finally, the spectra were flux-calibrated using observations of spectrophotometric standard stars.

2.2 Line strengths on the Rose system

Rose (1985, 1994) has developed an absorption-line strength system, based on a combination of line-depth ratios and equivalent widths, which provides powerful tools for decomposing the hot-to-cool and giant-to-dwarf star ratios in composite populations. The Rose indexes of interest here are Ca II (= Ca II H+Hα/Ca II K) and Hn/Fe (= (∆Hβ/λ3859 + ∆Hδ/λ4045 + ∆Hγ/λ4325)/√3), which together indicate the presence of hot stars in old, metal-rich stellar populations (Rose 1985, 1994, Caldwell et al. 2003).

The LRIS spectra were first smoothed to a common velocity dispersion of 230 km s⁻¹ as suggested by Caldwell et al. (2003). For NGC 4874, which was left unsmoothed at its intrinsic velocity dispersion of 271 km s⁻¹, indexes were then computed by finding the minimum intensity of each absorption line using a cubic spline interpolation of a small region around the centre of each line.

Table 1. Observed line strengths of early-type galaxies in the Coma Cluster

| Name      | Ca II σ | Hn/Fe σ | Hβ σ | Mg b σ | Fe5270 σ | Fe5335 σ | O III σ |
|-----------|---------|---------|------|--------|----------|----------|--------|
| D127      | 1.165   | 0.016   | 1.878| 3.963  | 3.094    | 2.761    | 0.096  |
| D128      | 1.179   | 0.005   | 1.855| 3.564  | 2.788    | 2.542    | 0.028  |
| D154      | 1.178   | 0.003   | 1.247| 3.359  | 2.723    | 2.701    | 0.013  |
| D157      | 1.173   | 0.012   | 1.817| 3.940  | 2.839    | 2.670    | 0.054  |
| D158      | 1.154   | 0.007   | 1.217| 3.114  | 0.063    | 0.065    | 0.036  |
| GMP 3565  | 1.178   | 0.005   | 2.237| 3.114  | 2.484    | 2.309    | −0.007 |
| NGC 4864  | 1.197   | 0.005   | 1.738| 4.716  | 2.907    | 2.889    | 0.074  |
| NGC 4867  | 1.092   | 0.003   | 1.938| 4.589  | 2.909    | 2.897    | 0.146  |
| NGC 4871  | 1.160   | 0.006   | 1.832| 4.442  | 2.957    | 2.921    | 0.120  |
| NGC 4872  | 1.165   | 0.003   | 1.832| 4.442  | 2.957    | 2.921    | 0.120  |
| NGC 4873  | 1.177   | 0.002   | 1.867| 4.457  | 2.827    | 2.663    | 0.094  |
| NGC 4864  | 1.197   | 0.005   | 1.738| 4.716  | 2.907    | 2.889    | 0.074  |
| NGC 4872  | 1.165   | 0.003   | 1.832| 4.442  | 2.957    | 2.921    | 0.120  |
| NGC 4873  | 1.177   | 0.002   | 1.867| 4.457  | 2.827    | 2.663    | 0.094  |
| NGC 4874  | 1.192   | 0.005   | 1.572| 4.954  | 3.019    | 3.035    | 0.110  |
| GMP 3565  | 1.178   | 0.003   | 1.572| 4.954  | 3.019    | 3.035    | 0.110  |

All indexes observed within an aperture of 2.7-arcsec diameter.

and then dividing the appropriate combination of lines to determine the index value. For example, the H5/λ4045 index is determined by finding the minimum intensity of the Hβ absorption line and dividing it by the minimum intensity of the Fe I λ4045 absorption line. Indexes were determined independently from each of the three exposures after smoothing and the mean and sample standard deviations were used as the final index value and error, respectively. Within the errors of the two Rose indexes of interest (Hn/Fe and Ca II), the indexes determined from the variance-weighted combined spectra and from the mean of the individual exposures are identical. However, the uncertainties determined from the standard deviations of the indexes determined from the individual exposures appear to be more reliable than those determined from estimation of the photon noise in the combined spectra (cf. Caldwell et al. 2003).

Rose line strengths and errors for the current sample, measured in a synthesised circular aperture of 2.7-arcsec diameter, are presented in Table 1.

No correction for emission fill-in of the Hn/Fe index has been attempted. The fluxes of the Hα emission in each galaxy required to make the correction using the recipe of Appendix A of Caldwell et al. (2003) are unknown, although we expect that the corrections will be small: the typical correction to Hn/Fe in Caldwell et al. (2003) is 0.012, which is a correction of less than 1 Gyr for an 8 Gyr-old population. The precise value of Hn/Fe is however not used in the analysis that follows.

Furthermore, we cannot calibrate our index strengths on to a Rose ‘system’, as the Jones (1996) stellar library used by Caldwell et al. (2003) is smoothed to a velocity dispersion of 103 km s⁻¹ (the intrinsic resolution of our stellar spectra is roughly 150 km s⁻¹), and no published index strengths exist for the galaxies in the present study. However, the location of the Coma galaxies in the Hn/Fe–Ca II diagram is coincident with the distribution of

1 For NGC 4874, which filled its slitlet, and for D128 and NGC 4872, whose spectra were contaminated by that of NGC 4874, sky subtraction was performed first using the ‘sky’ information at the edge of their slitlets and then corrected by comparing this sky spectrum to the average sky from all other slitlets. The excesses in these slitlets were added back into the final extracted spectra.
Figure 1. The hot-star sensitive H\textsubscript{n}/Fe–Ca\textsc{ii} diagnostic diagram (cf. Caldwell et al. 2003). In this figure, grids are taken from the spectral models of Worthey (1994), where solid lines are isochrones (constant age) and dotted lines are isofers (constant metallicity). For old, metal-rich populations Ca\textsc{ii} saturates at a value of 1.24, while H\textsubscript{n}/Fe continues to increase with age. Galaxies with Ca\textsc{ii} below the saturated value are contaminated with hot stellar populations, most likely metal-poor stars (Rose 1985, 1994). In both panels open squares represent Coma galaxies, observed through a 2.7-arcsec diameter aperture. (a) The distribution of field and Virgo Cluster (small filled points Caldwell et al. 2003) galaxies in the H\textsubscript{n}/Fe–Ca\textsc{ii} diagram. Note the close overlap between the majority of field, Virgo, and Coma galaxies in this diagram, confirming that we are on a Rose-like “system” (see text). (b) To demonstrate the amount of contamination from a hot-star population, we have subtracted off a model spectrum of a 17 Gyr old, [Z/H] = −1.5 dex population from our Coma galaxies. Arrows point from the observed to the corrected line-strength values.

2.3 Line strengths on the Lick/IDS system

The Lick/IDS absorption-line strength system has been developed by Faber, Burstein, and their collaborators (e.g. Burstein et al. 1984; Worthey et al. 1994; Trager et al. 1998) to determine the stellar content of early-type galaxies (as seen in the models of, e.g., Worthey 1994; Thomas, Maraston & Bender 2003). For the purpose of breaking the age–metallicity degeneracy inherent in colours and line strengths of old stellar populations (see, e.g., O’Connell 1980), the H\textbeta, Mg\textsc{b}, Fe5270 and Fe5335 indexes are among the best-understood and best-calibrated (e.g., Trager et al. 2000a); we will use these four indexes to determine stellar population parameters in this study.

In order to measure Lick/IDS line strengths and then to place them on the Lick/IDS system, a series of spectral manipulations and calibrations are required. For the current observations, the complete series of steps performed is discussed in detail in TFD05; here we briefly review the process.

The first step in determining the line strengths of a galaxy is to measure its systemic velocity and velocity dispersion. These are needed to place the index bandpasses on the spectrum and to calibrate galaxy line strengths on to the Lick/IDS stellar system used by most stellar population models, including Worthey (1994). Both of these quantities are measured following the direct-fitting algorithm of Kelson et al. (2000) over the rest-frame wavelength range 4200–5100 Å.

Next, the spectrum is smoothed to the Lick/IDS resolution (Worthey & Ottaviani 1993) using a variable-width Gaussian filter. The Lick/IDS index bandpasses are then placed on the spectrum and indexes measured in either Å or magnitudes, depending roughly on the width of the central bandpasses (Trager et al. 1998). Errors are determined from the object spectrum and its associated variance spectrum.

For galaxies, a correction for fill-in of H\textbeta absorption by emission is required (González 1993). This is determined from the strength of the [O\textsc{iii}]λ5007 line as determined from the residual spectrum after subtracting the best-fitting spectrum from the models of Vazdekis (1999)2 from the observed spectrum. The correction to H\textbeta is then determined using the [O\textsc{iii}]λ5007–H\textbeta correction suggested by Trager et al. (2000a): ΔH\textbeta = 0.6 × [O\textsc{iii}], where the [O\textsc{iii}] index is defined by González (1993) and is positive for emission within the central bandpass. This correction never exceeds 0.09 Å for the present galaxies, or about 4% in H\textbeta strength.

2 We use the Vazdekis (1999) models for the emission correction because we achieve lower χ^2 values in the spectral fitting (i.e., better fits) when using these models instead of the Worthey (1994) models. This is due to the denser coverage in age of the Vazdekis (1999) models with respect to the Worthey (1994) models.
Finally, two corrections are required to bring the galaxy indexes on to the Lick/IDS stellar system: small offsets resulting from the fact that the Lick/IDS system is not based on flux-calibrated spectra, and a velocity dispersion correction to account for the velocity broadening of the galaxies (Gonzalez 1992, Trager et al. 1998). The former correction is performed using observations of the Lick/IDS stars taken in the run; the latter is performed using the polynomial corrections given in Trager et al. (1998). The final Lick/IDS index strengths of early-type galaxies in the Coma Cluster for the four lines of interest and for [O III] are given in Table 1.

3 ANALYSIS

Our goal is to determine the fractional contribution of hot stars, assumed to arise from the blue horizontal branch stars of an old, metal-poor population, to the light at 4000 Å of early-type galaxies in the Coma Cluster and then to correct their age- and metallicity-sensitive line strengths for this contamination. We then compute the metal-poor population, assumed to arise from the blue horizontal branch stars of an old, metal-poor population containing hot BHB stars. Our method is based on the suggestion of Rose (1985, 1994) and Caldwell et al. (2003) to use the Hn/Fe–Ca II plane to determine the presence and amount of hot-star light at 4000 Å in early-type galaxies. The W94 models predict an asymptotic Ca II strength of 1.24 for metal-rich populations with ages $t_{\text{SSP}} \gtrsim 2$ Gyr (Fig. 1). A hot-star spectrum is first smoothed to instrumental resolution of LRIS and to the velocity dispersion of the galaxy in question and then subtracted from the observed spectrum in increments of $f_{\text{hot}} = 0.005$ (where $f_{\text{hot}}$ is the fraction of light coming from the old, metal-poor population at 4000 Å) until the measured Ca II strength in the residual spectrum reaches the asymptotic old, metal-rich value. A demonstration of this process is given in Figure 2 for NGC 4867.

We choose three baseline hot-star models, whose line strengths are given in Table 2. The first is a 17 Gyr-old single stellar population model with $[Z/H] = -1.5$ dex and therefore an extended horizontal branch running from red to blue; the assumed $[E/Fe] = 0$ dex, that is to say, having the same $[E/Fe]$ as the metal-poor value. The modified W94 models for the analysis of the impact of the hot-star population on the stellar population parameters because these models (1) appear not to have the same flux calibration in the “blue” and “red” models and (2) have not been modified to account for enhancement-ratio variations.

Table 2. Line strengths of hot-star populations

| M      | Population | Hβ     | Mg b   | Fe5270  | Fe5335  |
|--------|------------|--------|--------|---------|---------|
| 1      | 17 Gyr, [Z/H] = −1.5 | 2.493  | 1.188  | 1.029   | 0.885   |
| 2      | 12 Gyr, [Z/H] = −1.5 | 2.814  | 1.185  | 0.896   | 0.778   |
| 3      | NGC 6254 (M10)      | 2.200  | 0.687  | 0.902   | 0.877   |

M is the model number in Table 1.

The presence and amount of hot-star light at 4000 Å in early-type galaxies. The W94 models predict an asymptotic Ca II strength of 1.24 for metal-rich populations with ages $t_{\text{SSP}} \gtrsim 2$ Gyr (Fig. 1). A hot-star spectrum is first smoothed to instrumental resolution of LRIS and to the velocity dispersion of the galaxy in question and then subtracted from the observed spectrum in increments of $f_{\text{hot}} = 0.005$ (where $f_{\text{hot}}$ is the fraction of light coming from the old, metal-poor population at 4000 Å) until the measured Ca II strength in the residual spectrum reaches the asymptotic old, metal-rich value. A demonstration of this process is given in Figure 2 for NGC 4867.

![Figure 2](image-url)

Figure 2. The correction of an observed early-type galaxy spectrum for contamination by an old, metal-poor population containing hot BHB stars. The upper (solid) spectrum is the observed spectrum of NGC 4867, an elliptical galaxy in the Coma Cluster. The lower (dotted) spectrum is that of NGC 6254 (M10), a globular cluster with a horizontal branch, from the compilation of Schiavon et al. (2003), after smoothing, shifting to the systemic velocity of NGC 4867, normalising at 4000 Å and multiplying by 0.3. The middle (dotted) spectrum is NGC 4867 after subtracting the spectrum of NGC 6254. This corrected spectrum has a Ca II strength of 1.24, as desired. Absorption lines used in this study are indicated.
calibrating stars [Thomas et al. 2003]. As described in [Trager et al. (2000a), the W94 model ages are older by 10–25 per cent than models based on isochrones from the Padova group [Bertelli et al. 1994]; this 17 Gyr-old model is equivalent in its line strengths to a 15 Gyr old model from, say, [Thomas et al. 2003]. The second is a younger, metal-poor single-star population with an age of 12 Gyr, [Z/H] = −1.5 dex, and [E/Fe] = 0 dex, also with an extended horizontal branch. The third is the observed spectrum of the globular cluster NGC 6254 (M10) from the compilation of Schiavon et al. (2003)4, which has [Fe/H] = −1.51 and an extended, blue horizontal branch (see, e.g., Rosenberg et al. 2000). The indexes given in Table 4 are derived from the spectrum of Schiavon et al. (2003) and corrected using the LRIC-based flux corrections.

We note here that Schiavon et al. (2004) present an alternative approach using the ratio Hβ/ [α] as a function of Fe4383. We have not attempted this method here, as it is dependent on knowing the response of H-[α] to α-enhancements, which have only just become available and are currently in the process of being incorporated into stellar population models [Thomas et al. 2004] [Korn et al. 2005; Lee & Worthey 2005].

4 RESULTS AND DISCUSSION

Figure 10 shows the results of the correction for hot-star light on the Hn/Fe and Ca II strengths for three of the Coma galaxies. Table 3 gives the required fractions to correct the spectra for hot-star light for all twelve galaxies: these range from 3 per cent of the total light within the 2.7 arcsec aperture at 4000 Å for NGC 4864 to 22 per cent for NGC 4867 when the hot-star light comes from the 17 Gyr old model, with a mean value of 7.9 per cent and an rms scatter of 2.9 per cent (here we use the bi-weight mean and scatter described in Beers, Pumplin, & Gebhardt 1999). When the 12 Gyr model is used, these fractions range from 3–19 per cent with a mean of 7.0 per cent and an rms scatter of 2.6 per cent, and when NGC 6254 is used, the range is 5–30 per cent with a mean of 10.2 per cent and an rms scatter of 3.7 per cent.

The inferred masses of the metal-poor components are also listed in Table 3, the bi-weight mean mass fractions of the metal-poor component are 8.3±6.1 per cent for the 17 Gyr old population and 5.4±3.9 per cent for the 12 Gyr old population. Note that the mass-to-light ratio of NGC 6254 is unknown and therefore the hot-star mass fractions are also unknown for this case. These average mass fractions are consistent with the conclusion of Worthey et al. (1992) that most or all elliptical galaxies have a metal-poor fraction ≤ 5 per cent, with a few exceptions depending on the age of the metal-poor population; GMP 3565, NGC 4867, and NGC 4873 are the most extreme cases. We have not fully explored alternative explanations in this short paper, but GMP 3565 is the most metal-poor of the galaxies, and thus may have a stronger metal-poor tail if it has the same abundance distribution as other galaxies shifted to lower mean abundance. The other two galaxies are candidates to violate the 5 per cent rule, but explanations such as UV-upturn populations, multiple-age populations, and blue stragglers have yet to be explored.

After the appropriate fraction of hot-star light has been subtracted from the observed spectrum, Lick/IDS line strengths are recomputed (including velocity dispersion, emission, and systemic corrections). The results are shown in Figure 8 as vectors pointing from the observed line strengths to the corrected line strengths. As is clear from this figure, the change in the line strength point along vectors of nearly constant age with an increase in metallicity [Z/H]SSP, and a slight increase in [E/Fe]SSP, being the major effects. This is borne out by the inferred stellar population parameters in Table 4 and the fractional changes in Table 4 only NGC 4867 changes its age by more than 1σ. However, NGC 4867 is extrapolated far off of the W94 grids after subtraction in all three cases, and so the inferred ages and metallicities are suspect.

We therefore find that the presence of even moderate amounts of light from hot stars does not significantly alter the inferred ages of early-type galaxies in the presence of intermediate-aged populations, provided that the hot-star light comes from an old, metal-poor population containing blue horizontal branch stars. We however do not claim that the ages of early-type galaxies are unaffected by hot stars. In fact, we reproduce in Fig. 3 the result of Maraston & Thomas (2000) that the oldest stellar populations (t > 10 Gyr) look younger by 2–5 Gyr when ancient, metal-poor populations are superimposed on ancient, metal-rich populations. Rather, we suggest that when an intermediate-aged population is present, i.e., when Hβ ≥ 1.5 Å, the influence of hot stars on the inferred age is nearly negligible (see also Thomas et al. 2005). The difference between the effect of hot-star light on intermediate-aged and old populations is mostly due to the change in slope of the W94 grids at old ages and high metallicities in the Hβ–[MgFe] diagram and to the high Hβ strengths of the observed galaxies due, presumably, to intermediate-aged stellar populations.

The increased inferred metallicity but nearly constant age in the corrected population can be understood in the context of the Appendix of Trager et al. (2000a), which demonstrated that stellar populations add as vectors in the Hβ–metal-line spaces (such as Hβ−[MgFe]). In effect, the ‘two’ populations in the Coma early-type galaxies—the metal-rich, intermediate-aged population with high Hβ and high [MgFe], and the metal-poor, old population with high Hβ (from the hot blue horizontal branch stars) and low [MgFe]–add to produce observed populations with high Hβ and moderate [MgFe] strengths. The strengthening of the Hβ line from the hot stars is compensated by a dilution of the continuum around the metal lines (Fig. 2), which weakens their measured equivalent widths. These weakened metal lines combined with the stronger Hβ line serve to preserve the inferred age of the galaxy while lowering the observed metallicity.

5 CONCLUSIONS

We have examined the effect of hot (horizontal branch) stars on the inferred stellar population parameters of early-type galaxies using observations of twelve Hβ-strong early-type galaxies in the Coma Cluster and spectra drawn from stellar population models.

| M | (Δt) | σΔt | ⟨Δ[Z/H]⟩ | σΔ[Z/H] | ⟨Δ[E/Fe]⟩ | σΔ[E/Fe] |
|---|------|------|----------|----------|----------|----------|
| 1 | 0.942 | 0.065 | 0.089 | 0.033 | 0.022 | 0.007 |
| 2 | 1.003 | 0.046 | 0.066 | 0.024 | 0.014 | 0.006 |
| 3 | 0.873 | 0.099 | 0.115 | 0.005 | 0.026 | 0.012 |

M is the hot-star population given in Table 3 and σΔt is the mean and rms scatter in fractional change in the age.
Figure 3. The impact of the contamination from metal-poor populations on the inferred ages and compositions of early-type galaxies (TFD05). Model grids again come from the W94 models, modified for [E/Fe] (cf. Trager et al. 2000, Thomas et al. 2003, TFD05). In both panels, solid lines are isochrones and dotted lines are isofers, as in Fig. 1. In the left panel, the models are for solar [E/Fe]; models with higher [E/Fe] are nearly identical. Therefore this is an appropriate grid from which to visually assess age and metallicity, although accurate determinations are made in ([Hβ, Mg b, Fe5270, Fe5335]) space. In the right panel, grids have [E/Fe] = 0 (black) and +0.3 (cyan). Open squares give the observed populations of the Coma galaxies; arrows point to the population after subtraction of enough of the old, metal-poor population to bring the Ca ii strength to the asymptotic value of old, metal-rich populations (Fig. 1). The black arrows represent the subtraction of a 17 Gyr old, [Z/H] = −1.5 dex population (black dot), the red arrows represent the subtraction of a 12 Gyr old, [Z/H] = −1.5 dex population (red dot), and the green arrows represent the subtraction of the metal-poor globular cluster NGC 6254 (green dot), which has a purely blue horizontal branch. The cyan triangles plot the positions of 17 Gyr old populations with metallicities (from left to right) of [Z/H] = −0.25, 0, +0.25, +0.5 dex that have been contaminated by 10 per cent by mass of a 18 Gyr old, [Z/H] = −1.5 dex population (cyan arrows) to replicate the experiment of Maraston & Thomas (2000).

as well as an observed spectrum of a metal-poor globular cluster with a purely blue horizontal branch. If the hot-star light comes from ancient, metal-poor populations (Rose 1985, 1994; Lee et al. 2004; Maraston & Thomas 2004; Caldwell et al. 2003) typically contributing <10 per cent of the light at 4000 Å (as detected in the Ca ii index), the ages of these galaxies are not significantly affected by the correction for this hot-star light. For the oldest, most metal-rich galaxies, this correction can be significant, as shown by Maraston & Thomas (2000) and Fig. 1. But this correction is insignificant for the intermediate-aged populations found in these early-type Coma galaxies, and likely also for the field and group galaxies studied by Maraston & Thomas (2000), many of which have similarly high Hβ line strengths. We suggest therefore that the claim that old, metal-poor stars can ‘explain away’ the strong Hβ lines in these early-type galaxies (e.g., Maraston & Thomas 2000) is overstated.

The presence of blue straggler stars in these galaxies is still a possibility to explain the enhanced Balmer-line strengths of early-type galaxies. However, as discussed by Rose (1985) and Trager et al. (2000b), populations of blue straggler stars are subject to the same constraints as other hot-star populations, as blue straggler stars typically have spectral types around mid-A. This is the same colour as the BHB stars that dominate the Balmer-line strengths of the old, metal-poor populations we have considered here. Using the same arguments we have already presented, therefore, we suggest that blue straggler stars are unlikely to affect the inferred ages of Hβ-strong galaxies. We conclude that intermediate-aged populations are still required to explain the strong Hβ lines in early-type galaxies.

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### Table 3. Stellar population parameters of early-type galaxies in the Coma Cluster before and after correction for hot-star contamination

| Name | Age (Gyr) | [Z/H] | [E/Fe] | $f_{\text{hot}}$ | $f_{\text{hot}}^M$ | Age (Gyr) | [Z/H] | [E/Fe] |
|------|-----------|-------|--------|----------------|-----------------|-----------|-------|--------|
| D127 | 5.3 ± 1.4 | 0.20 ± 0.07 | 0.07 ± 0.03 | 1 | 0.09 | 4.8 ± 1.0 | 0.29 ± 0.07 | 0.09 ± 0.03 |
|      |           |       |        | 2 | 0.08 | 5.1 ± 1.2 | 0.27 ± 0.07 | 0.08 ± 0.03 |
|      |           |       |        | 3 | 0.11 | 4.5 ± 1.0 | 0.32 ± 0.08 | 0.10 ± 0.03 |
| D128 | 8.8 ± 1.1 | −0.08 ± 0.03 | 0.03 ± 0.02 | 1 | 0.07 | 8.5 ± 1.2 | −0.02 ± 0.04 | 0.04 ± 0.02 |
|      |           |       |        | 2 | 0.06 | 9.0 ± 1.2 | −0.03 ± 0.04 | 0.03 ± 0.02 |
|      |           |       |        | 3 | 0.09 | 8.2 ± 1.1 | 0.00 ± 0.04 | 0.04 ± 0.02 |
| D154 | 4.0 ± 1.6 | 0.08 ± 0.12 | 0.01 ± 0.05 | 1 | 0.08 | 3.3 ± 1.3 | 0.19 ± 0.12 | 0.04 ± 0.06 |
|      |           |       |        | 2 | 0.07 | 3.6 ± 1.5 | 0.16 ± 0.12 | 0.03 ± 0.06 |
|      |           |       |        | 3 | 0.10 | 3.1 ± 1.2 | 0.22 ± 0.12 | 0.04 ± 0.05 |
| D157 | 7.6 ± 1.2 | 0.06 ± 0.05 | 0.09 ± 0.02 | 1 | 0.09 | 7.2 ± 1.5 | 0.15 ± 0.05 | 0.10 ± 0.02 |
|      |           |       |        | 2 | 0.08 | 7.6 ± 1.4 | 0.13 ± 0.05 | 0.10 ± 0.02 |
|      |           |       |        | 3 | 0.11 | 6.8 ± 1.4 | 0.17 ± 0.05 | 0.11 ± 0.02 |
| D158 | 4.7 ± 0.8 | −0.11 ± 0.06 | 0.05 ± 0.04 | 1 | 0.09 | 4.4 ± 1.1 | −0.03 ± 0.06 | 0.07 ± 0.04 |
|      |           |       |        | 2 | 0.08 | 4.6 ± 1.1 | −0.04 ± 0.06 | 0.06 ± 0.04 |
|      |           |       |        | 3 | 0.11 | 4.0 ± 1.1 | −0.01 ± 0.07 | 0.04 ± 0.04 |
| GMP 3565 | 4.5 ± 1.7 | −0.20 ± 0.14 | 0.00 ± 0.09 | 1 | 0.13 | 4.2 ± 2.2 | −0.08 ± 0.18 | 0.03 ± 0.10 |
|      |           |       |        | 2 | 0.12 | 4.3 ± 2.3 | −0.11 ± 0.17 | 0.02 ± 0.09 |
|      |           |       |        | 3 | 0.18 | 3.7 ± 1.8 | −0.03 ± 0.17 | 0.03 ± 0.10 |
| NGC 4864 | 5.8 ± 0.9 | 0.30 ± 0.04 | 0.21 ± 0.02 | 1 | 0.03 | 5.8 ± 1.0 | 0.33 ± 0.04 | 0.22 ± 0.02 |
|      |           |       |        | 2 | 0.03 | 5.9 ± 1.0 | 0.32 ± 0.04 | 0.21 ± 0.02 |
|      |           |       |        | 3 | 0.05 | 5.6 ± 0.9 | 0.34 ± 0.05 | 0.22 ± 0.02 |
| NGC 4867 | 3.0 ± 0.2 | 0.49 ± 0.03 | 0.25 ± 0.01 | 1 | 0.22 | 2.4 ± 0.3 | 0.81 ± 0.04 | 0.32 ± 0.01 |
|      |           |       |        | 2 | 0.19 | 2.9 ± 0.2 | 0.72 ± 0.04 | 0.30 ± 0.01 |
|      |           |       |        | 3 | 0.30 | 1.9 ± 0.2 | 0.95 ± 0.06 | 0.34 ± 0.01 |
| NGC 4871 | 4.4 ± 0.4 | 0.34 ± 0.04 | 0.17 ± 0.02 | 1 | 0.08 | 4.3 ± 0.5 | 0.45 ± 0.05 | 0.20 ± 0.02 |
|      |           |       |        | 2 | 0.08 | 4.5 ± 0.5 | 0.41 ± 0.05 | 0.19 ± 0.02 |
|      |           |       |        | 3 | 0.11 | 4.0 ± 0.5 | 0.48 ± 0.06 | 0.21 ± 0.02 |
| NGC 4872 | 5.2 ± 0.5 | 0.29 ± 0.03 | 0.20 ± 0.01 | 1 | 0.09 | 5.1 ± 0.6 | 0.39 ± 0.03 | 0.23 ± 0.01 |
|      |           |       |        | 2 | 0.08 | 5.5 ± 0.6 | 0.36 ± 0.03 | 0.22 ± 0.01 |
|      |           |       |        | 3 | 0.12 | 4.7 ± 0.4 | 0.43 ± 0.04 | 0.24 ± 0.01 |
| NGC 4873 | 4.8 ± 0.8 | 0.25 ± 0.05 | 0.22 ± 0.02 | 1 | 0.17 | 4.4 ± 0.7 | 0.45 ± 0.06 | 0.28 ± 0.02 |
|      |           |       |        | 2 | 0.15 | 5.0 ± 0.8 | 0.38 ± 0.05 | 0.25 ± 0.02 |
|      |           |       |        | 3 | 0.23 | 3.9 ± 0.7 | 0.53 ± 0.07 | 0.29 ± 0.02 |
| NGC 4874 | 8.0 ± 0.7 | 0.33 ± 0.03 | 0.19 ± 0.01 | 1 | 0.07 | 8.3 ± 0.9 | 0.40 ± 0.03 | 0.21 ± 0.01 |
|      |           |       |        | 2 | 0.06 | 8.5 ± 0.9 | 0.39 ± 0.03 | 0.21 ± 0.01 |
|      |           |       |        | 3 | 0.08 | 8.0 ± 0.7 | 0.41 ± 0.03 | 0.22 ± 0.01 |

All stellar population parameters are those in a 2.7-arcsec diameter aperture. M is the hot-star population given in Table 2. $f_{\text{hot}}$ is the fraction of light at 4000 Å contained in the ‘hot’ (i.e., old, metal-poor) stellar population as determined from CaII; $f_{\text{hot}}^M = f_{\text{hot}}(M/L_B)_{\text{hot}}/(M/L_B)_{\text{total}}$ is fraction of the total mass contained in the hot stellar population. Note that $(M/L_B)$ is unknown for NGC 6254 but is likely to be slightly higher than that of the 17 Gyr, $[Z/H] = −1.5$ dex population (cf. Fig. 3).
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