THE STELLAR AGES OF ELLIPTICAL GALAXIES

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Abstract. Integrated broad-band colors and metallic lines cannot discriminate clearly between the effects of age and Z in old stellar populations. Such data are more sensitive to Z than to age. The $H\beta$ feature provides a way to break this degeneracy. New measurements indicate that the mean stellar ages of typical E galaxy nuclei are fairly young, ranging from 2 to $\sim$12 Gyr. The outer parts of E galaxies are both older and more metal-poor than nuclei, consistent with the formation of E galaxies via mergers and starbursts. Age effects contribute strongly to the classic color-line strength sequence of E galaxies.

1. Introduction

Population synthesis of elliptical galaxies has roots going back almost sixty years (Whipple, 1935) but has thus far yielded few *quantitative* conclusions. A major problem is that age and metallicity have extremely similar effects on the spectral-energy distribution of old stellar populations (Faber, 1972; O'Connell, 1976). This problem couples closely with the poor control over age and Z afforded by the stellar library method, it being difficult to sort

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stars well by these two parameters. Getting good coverage over the full range needed in both age and Z is also difficult with libraries.

The problem is worsened by the fact that abundances of at least some elements in E galaxies differ systematically from those in local stars. Such features as CN, Mg, and Na are too strong in many galaxies to be matched by local standards (Spinrad and Taylor, 1971; Faber, 1973; O'Connell, 1976). Given the near degeneracy between age and Z, any systematic failure to match metallic features could induce a *systematic* error in age. Hence, even though several workers have claimed to detect intermediate-age populations in certain giant E's (e.g., O'Connell, 1980; Pickles, 1985), the real error bars on such claims were unknown.

To progress, it is necessary to have much tighter control over model input age and Z. This involves going to an "evolutionary synthesis" approach (Tinsley, 1980), in which accurate evolutionary isochrones are computed as a function of age and Z. Spectral energy distributions (SED's) and spectral features are still needed at each point along the tracks, however. In this work we have taken a mixed approach to these two inputs. We use *empirical* fitting formulae derived from real stars for the line strengths, but a *theoretical* library of model stellar spectra for the SED's. The resultant models still have many flaws and uncertainties. Nevertheless, they are the first, we believe, to have the necessary level of detail to discriminate clearly between age and Z. When applied to new and highly accurate CCD spectra of elliptical galaxies, they confirm claims by earlier workers that significant intermediate-age populations exist in many E galaxies.

2. Models: Age versus Z

The models used here were computed by Worthey (1994). They are single-burst, coeval models, although we mention briefly the effects of mixtures in these quantities. The IMF is a power-law with Salpeter slope. No dead stellar remnants are presently included in the calculation of stellar M/L.

The equivalent width (EW) of a spectral feature j is given by:

$$EW^j_{model} = \frac{\sum_i N_i I_i(\lambda) EW^j_i}{\sum_i N_i I_i(\lambda)}, \qquad (1)$$

where i is a discrete index that runs in small bins along the stellar isochrone. The three quantites $N_i, I_i(\lambda)$, and EW^j_i have been taken from the following sources:

1) Numbers of stars, N_i, come from a set of stellar isochrones synthesized by Worthey (1994) by smoothly joining main-sequence and turn-off tracks from VandenBerg and collaborators (VandenBerg, 1985; VandenBerg and Bell, 1985; VandenBerg and Laskarides, 1987) with first-ascent giant

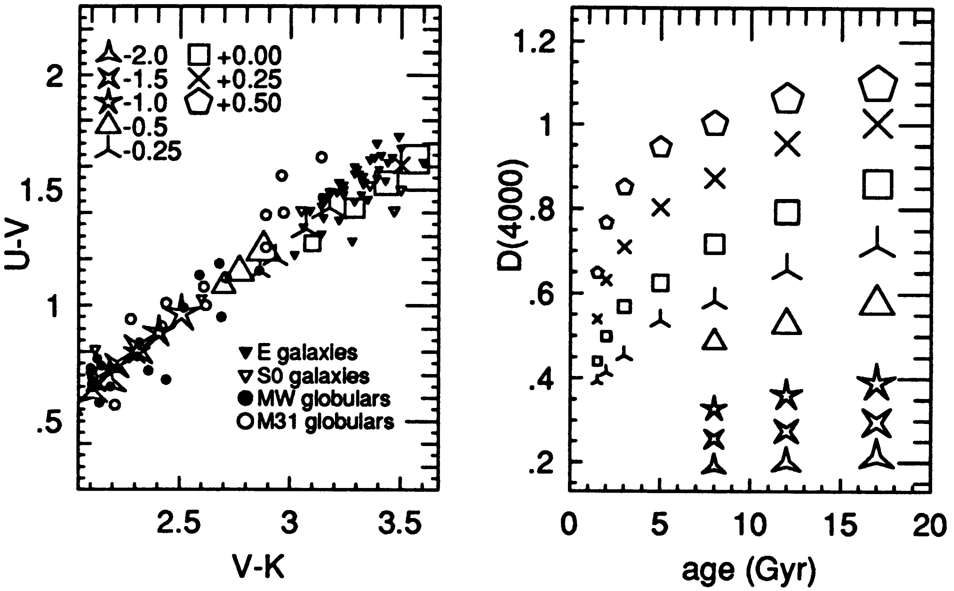

Figure 1. a) Worthey models and a variety of old populations in $U-V$ versus $V-K$. Model Z's are given by symbols, and ages by symbol size. Ages are 5, 8, 12, and 17 Gyr. b) "4000-Å break" versus age and Z. Near solar Z, an increase of $+0.25$ dex corresponds to a decrease in age from 17 Gyr to 7 Gyr.

branches from the Revised Yale Isochrones (Green *et al.*, 1987), appropriately adjusted in L and T_e to merge smoothly with VandenBerg. Further information on the merging and on the post-GB phases of evolution is found in Worthey (1994).

2) SED's, $I(\lambda)$, come from the theoretical libraries of Kurucz (1992) and Bessell *et al.* (1989,1991; below 3750 K). Tests show that the SED's match real stars to within 0.05 mag in B through K and 0.1 mag in U, after corrections to remove known systematic drifts in the Kurucz (1992) model fluxes.

3) Equivalent widths, EW_i^j, are computed from empirical fitting functions on the Lick line-strength system determined from a library of 400 Galactic field and cluster stars (Gorgas *et al.*, 1992; Worthey *et al.*, 1994). The functions cover a wide variety of temperatures, gravities, and metallicities. The method ties linestrengths firmly to real stars but hardwires in whatever *abundance-ratio trends* are present in the calibrating stars.

An extensive series of tests described in Worthey (1994) shows that the stellar isochrones, SED's, and luminosity functions match well many classic old stellar populations in the Galaxy.

The new models confirm strongly the difficulty of disentangling age and Z. All combinations of broad-band colors and *metallic* features are essentially degenerate in these two parameters. Fig. 1 illustrates $U - V$ versus $V - K$ and the "4000 Å break". Varying Z has exactly the same effect on $(U-V, V-K)$ as varying age. For $D(4000)$, increasing the assumed Z by only +0.25 dex (a small change in the context of E galaxy abundance uncertainties) decreases the derived age from 17 to 7 Gyr. Averaging over all combinations of colors and metallic features, Worthey finds the following equivalency between age and Z:

$$\Delta\log t = -2.2\ \Delta\log Z \qquad (2)$$

If Z is uncertain by 0.3 dex, the resultant age is uncertain by more than a factor of four, which makes it useless for cosmology. In fact, the conclusion from Equation 2 is that conventional broad-band features are really measuring Z *more than age.*

3. Breaking the Degeneracy: Hβ

The main difference in the HR-diagram between age and Z is the temperature of the turnoff stars: for similar broad-band colors, a younger population has a hotter turnoff than a more metal-poor population. Indices that discriminate age from Z should therefore key on F and G dwarfs. Rose (1994) has developed the age indicator Sr4077/Fe4063, which is sensitive to the amount of turnoff light. However, both lines are quite weak, and their ratio may also depend on composition.

In this work, we focus on Hβ. Hβ is extremely temperature sensitive among F and G dwarfs but is very *in*sensitive to Z (Gorgas *et al.*, 1993; Worthey *et al.*, 1994). The main disadvantage of Hβ is possible contamination by emission, which is severe in some galaxies. Moving to Hγ or Hδ would largely solve this problem.

Worthey's model grid for Hβ versus [Mg/Fe] is shown in Fig. 2a. [Mg/Fe] is the logarithmic mean of Lick Mgb and (Fe5270 + Fe5335)/2. We use this average because of the observed fact that [Mg/Fe] is often too strong compared to local-star models (O'Connell, 1976; Peletier, 1989; Worthey *et al.*, 1992). Evidently [Mg/Fe] is higher in some galaxies than in our metal-rich Galactic calibrating stars. The near-solar-ratio tracks of our models are then fundamentally *inconsistent* with the galaxies. There being no way to deal with this complication at present, we simply average Mg and Fe and hope that this represents an acceptable mean Z.

Fig. 2a compares Gonzalez's (1993) accurate nuclear index data to the models. Some Hβ values have been increased by a small amount to correct for emission based on the observed strength of [O III] 5007 Å. Galaxies with

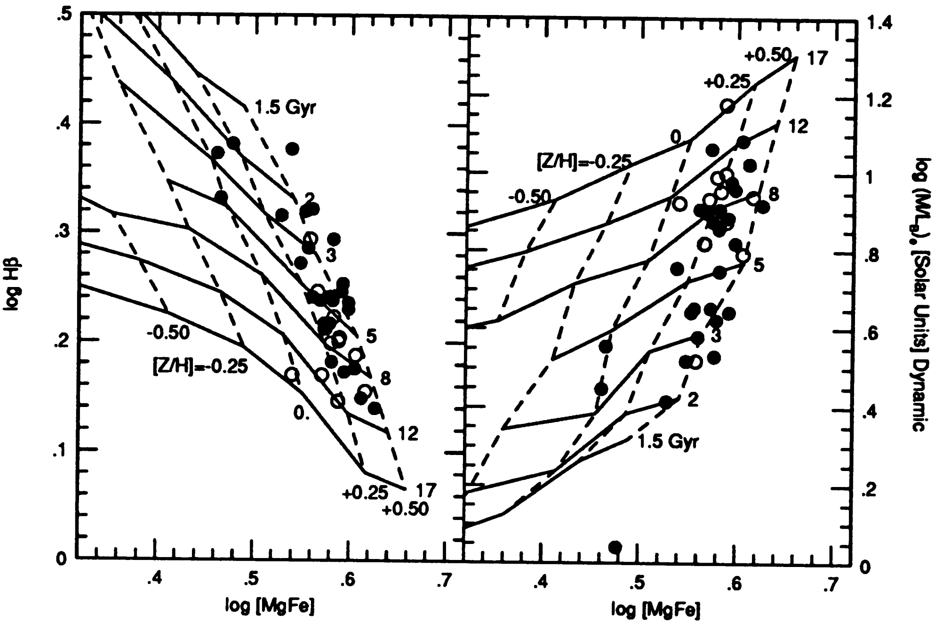

Figure 2. a) Nuclear Hβ versus [Mg/Fe] in normal E galaxies from Gonzalez (1993). Open circles show nuclei with emission corrections in excess of 0.07 dex. Lines show gradients within enclosed apertures out to radius $R_e/2$. Worthey models are overplotted. E galaxy nuclei on average have mean stellar ages that are substantially less than the age of the Universe. They are also younger and more metal-rich than the outer regions. b) Global M/L_B ratios (Gonzalez, 1993, see text) versus [Mg/Fe]. Worthey models are overplotted. Ages from M/L_B are generally consistent with those from Hβ (panel a).

large corrections ($>$ 0.07 dex) are shown as open circles. For the remaining galaxies, Hβ is if anything *higher* than shown.

The main conclusion from Fig. 2a is that the *mean stellar ages* of many E nuclei are rather young, $\leq$ 10 Gyr. A second conclusion is that *mean* nuclear Z is rather constant among this sample, at $\sim +0.3$ dex (although [Mg/Fe] does increase downward). The line attached to each nuclear point shows the gradient within a circular aperture out to a radius of $R_e/2$ (30% of total light). [Mg/Fe] weakens outward, but Hβ on average remains flat. When compared to models, this means that the outer parts of E galaxies are both *older and more metal-poor* than nuclei. This is consistent with a starburst/merger scenario for E galaxy formation, in which starbursts are both more intense and longer-lived at the centers of merging galaxies (Schweizer, 1983).

The ends of the lines in Fig. 2a measure the mean ages of the stellar populations within $R_e/2$. These ages are older than the nuclei, with several galaxies approaching 15 Gyr. If even larger radii could be measured, they might show still larger ages. The mean *global* stellar ages of E galaxies could therefore still be quite old on average.

Fig. 2b shows companion data on global M/L_B (also from Gonzalez, 1993) versus [Mg/Fe]. These are computed schematically from the quantity $\sigma_e^2 R_e$, assuming $H_0 = 75$ and using a constant of proportionality appropriate for a de Vaucouleurs' law (Gonzalez, 1993). Model $\log M/L$'s can be adjusted by an arbitrary constant to allow for missing mass in dead stellar remnants and for a change in H_0. However, the *trend* in observed M/L's follows the age loci closely, and the implied *relative* ages from M/L_B agree well with those Hβ in panel a. M/L_B, along with Hβ, may be a second way to break the age-Z degeneracy.

Related data on a larger sample of E nuclei from the Lick Image Dissector Scanner (IDS; Trager *et al.*, 1994) also show that E nuclei span a wide range of ages. The IDS data are much noisier than Gonzalez's data, but the sample is large enough to contain a good number of Virgo nuclei, which show the same age range as the rest of the sample. Several galaxies also have Σ disturbance parameters from Schweizer *et al.* (1990). High-Σ galaxies seem on average to have younger mean stellar ages, consistent with their status as recent post-merger candidates.

4. Discussion and Conclusions

We do not have space here to consider in detail other possible explanations for the strong Hβ line seen in many E galaxies. Briefly, we note that our models all have red horizontal-branch clumps. An Hβ excess could be produced by moving *most* of the clump stars to F spectral types or by blue stragglers. The former model does not agree with current thinking on the structure of metal-rich HBs, which says they should be either very red or extremely blue (Horch, Demarque and Pinsonneault, 1992; Dorman, O'Connell and Rood, 1994; Fagotto *et al.*, 1994 a,b; Lee, 1994). The latter explanation would require many more blue stragglers than seen in the outer parts of globular clusters, where the BS population is most likely to be pristine (Sigurdsson, Davies and Bolte, 1994). In the outer regions of M3 or M5, the luminosity-weighted ratio of blue stragglers to turn-off stars is ~ 0.007, not nearly large enough to account the Hβ strengths seen in E nuclei, even though the blue stragglers are ~ 0.1 magnitudes bluer (Ferraro *et al.*, 1993; Sandquist, private communication). Furthermore, the behavior of both M/L_B and Σ are more consistent with age than with these other models.

Since [Mg/Fe] is nearly constant in Gonzalez's CCD sample, it would be correct to say that the familiar line-strength/color sequence *in his sample* is due to more to age than it is to mean Z, which is the older interpretation (e.g., Spinrad and Taylor, 1971; Faber, 1973). Whether this conclusion applies also to the IDS sample is not as clear, as its scatter leaves room for greater intrinsic Z variations (but the data are also less accurate). Regardless, it would appear that age is playing, if not the dominant, then at least a major role in producing the classic E color/line-strength sequence. If that is so, several regularities among E galaxies that have commonly been interpreted in terms of metallicity should be re-examined with age as a possible factor. These include:

1) The slope and scatter about the Fundamental Plane and the Mg–σ relation (see also Renzini, this conference).

3) Trends in D_n-σ distances, planetary nebulae distances, and surface-brightness fluctuation distances.

4) The UV-rising branch versus Mg line strength.

5) What colors track stellar mass best *within* galaxies? *Among* galaxies?

6) The mass–metallicity relation among hot stellar systems: does any trace of it remain at all among giant E's, or does the relation set in only among smaller spheroidal systems?

We conclude by speculating on what E's might look like at high redshifts if these younger stellar populations are real. The answer depends critically on whether E populations are coeval. with ages close to the single-burst models, or episodic and formed in multiple bursts. We are investigating multi-burst models but are not currently hopeful that we will be able to distinguish clearly between the bursting and coeval scenarios. Basically, we find that populations tend to add vectorially in diagrams such as Fig. 2, and all that can be measured is a light-weighted mean. Protracted bursting will thus likely remain an option that cannot be ruled out, and indeed seems to be the natural prediction of hierarchical clustering/merging scenarios.

The point is that it takes only 2-3 Gyr after a merger for stellar population colors (and morphologies) to settle down to standard "E galaxy norms" (cf. Fig. 2). This is reasonably short compared to standard estimates of the age of the Universe (15 Gyr), providing time for multiple episodes to occur. Perhaps we should therefore begin to think of E galaxies as *mutable*: individual galaxies can come and go as E's, depending on whether they have been disturbed or not over the past $\sim$ 3 Gyr. If so, in examining E's at high redshift, we are simply identifying those galaxies that happen to be the reddest and most undisturbed at that epoch. A little thought will show that the statistical properties of the red members of such a bursting ensemble will differ drastically and systematically from a population of red galaxies evolving smoothly as $e^{-t/\tau}$ (e.g., Charlot and Silk, 1994; White, this meeting). It will be important to work out the predictions of the bursting scenario to compare with the observed properties of high-redshift field and cluster E galaxies.

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DORMAN: Our work has looked at a broad-band (2500Å–V) colour from the IUE data. We find that the bluest UVX galaxies are strong in 25–V, and so is M32 one of the bluest. We derive an age $\approx$ 4 Gyr for M 32 in good agreement with your models, while the bulk of the Burstein *et al.* galaxy sample has very similar 25–V colours (maybe all similar age?) Finally, it is interesting to note that the recent LWP IUE spectrum of NGC 1399 makes this UVX-strong, large galaxy very blue in this colour, which is puzzling.

FABER: We'll have to check whether we have a spectrum of NGC 1399 to see if we can derive an Hβ age, and hence estimate the main sequence 25–V color. Alternatively, since the far UV flux of NGC 1399 is so high, perhaps its 25–V color is influenced by the very hot component.

ELLIS: If the colour–luminosity relation is primarily an age relation rather than one of metallicity, how can you explain the observation that the colour–luminosity is already clearly in place at a redshift of $z = 0.5$ with the same slope as seen today? Over 5 magnitudes of luminosity, it appears things were the same 7 Gyr ago.

FABER: The main bulk of galaxies in our sample spans the range 7 to 13 Gyr in age and the models begin to look red enough to be called ellipticals at 3 Gyr. So you could get the requisite range of ages needed to generate the observed color range any time after the Universe is, say, 7 to 8 Gyr old. That's about where the color–luminosity relation begins to set in, as I understand it.

RENZINI: Virtually all your conclusions rely on detailed population synthesis models. I believe there are other evidences and arguments that are far less model dependent and that suggest a much different scenario for elliptical galaxy formation. But let me ask, in the frame of your picture, how you manage to reconcile with hierarchical clustering that big, high–σ, high–Mg_2 galaxies form several Gyr *before* small, low–σ, low–Mg_2 galaxies?

FABER: There actually is no correlation of age and luminosity at all in this sample, and only an extremely weak correlation with σ. If such correlations exist, I don't think this is impossible under hierarchical clustering. For example, the objects that come together to make big objects (or high–σ objects) may be the first to collapse (and thus make stars). Your question really relates to galaxy formation theory, which we don't understand in detail.

GERHARD: If there is only a weak trend of age with velocity dispersion, how then can we understand the very small scatter in the MG_2–σ relation?

FABER: An excellent question. I am not sure of the answer, but part of it is due, I think, to the fact that [Mg/Fe] also depends strongly on σ. This may play a large role in the apparent Mg_2–σ correlation.