

History of Star Formation of Early Type Galaxies from Integrated Light: Clues from Stellar Ages and Abundances

Ricardo P. Schiavon

Gemini Observatory, 670 N. A'ohoku Place, Hilo, HI 96720, USA

ABSTRACT

I briefly review what has been recently learned from determinations of mean stellar ages and abundances from integrated light studies of early-type galaxies, and discuss some new questions posed by recent data. A short discussion of spectroscopic ages is presented, but the main focus of this review is on the abundances of Fe, Mg, Ca, N, and C, obtained from comparisons of measurements taken in integrated spectra of galaxies with predictions from stellar population synthesis models.

Subject headings: galaxies: elliptical and lenticulars — galaxies: stellar content — galaxies: abundances — galaxies: evolution

1. Introduction

How galaxies form—and the stars within them—is one of the major open questions of modern cosmology. Early-type galaxies (ETGs) host a large fraction of the stellar mass in today's universe, and typically show no evidence for major ongoing star formation, so they are natural targets for the investigation of how and when galaxy assembly and star formation occurred in the past. The task is a difficult one, which has consumed a large amount of observational and theoretical effort in the past several decades. All that work cannot be fairly summarized in a such short article. This review is thus narrowly focused on what has been learned from stellar ages and abundances based on integrated light studies, and the new questions raised by recent evidence. Apologies go to many hard-working colleagues for any important omissions.

2. Stellar Ages

Historically, the debate on the star formation history of ETGs was framed in terms of two competing scenarios: hierarchical clustering (e.g., White & Rees 1978, Searle & Zinn 1978), according to which these galaxies were assembled through the merging of less massive structures

formed at high redshift; and monolithic dissipative collapse (e.g., Eggen et al. 1962, Larson 1974), whereby massive ETGs were formed at very high redshift by means of a rapid gravitational collapse. Deciding between these two scenarios was one of the main motivations behind attempts to measure stellar ages and abundances in ETGs. Today there is little question that galaxies formed hierarchically in a Λ -CDM universe, and while that historical debate has been settled, studies of unresolved stellar populations have acquired renewed importance, as they provide much needed constraints to increasingly sophisticated galaxy formation models.

Early attempts at dating stellar populations from applications of stellar population synthesis models to observations of integrated light were based on photometric or low-resolution spectrophotometric observations (e.g., O'Connell 1980, Gunn et al. 1981, Renzini & Buzzoni 1986) and high-resolution photographic spectroscopy (e.g., Rose 1985). They led to promising, yet not entirely conclusive results, due to limitations of the early models and/or uncertainties associated with the age-metallicity degeneracy (e.g., Renzini 1986, Worthey 1994). The latter is a manifestation of the similar dependence of the temperatures of main sequence and giant stars of a given stellar

population on age and metallicity, which causes the integrated colors of stellar populations, particularly in the optical and near-UV, to respond in similar ways to variations of these two parameters.

It was only after the systematic modeling of Balmer lines as (relatively) clean age indicators, initiated by Worthey (1994), that reliable quantitative estimates of mean luminosity-weighted¹ stellar ages became available. The method relies on the dependence of Balmer lines, such as $H\beta$ λ 486 nm, on the temperatures and luminosities of turnoff stars—which are higher in younger stellar populations. For A-type stars and cooler, Balmer line strength is positively correlated with temperature, so that the lines in integrated spectra of stellar populations older than a few 100 Myr are stronger for younger ages. Spectroscopic ages based on $H\beta$ for large numbers of ETGs, both in the field and in clusters, suggest that many of them have undergone recent star formation events (e.g., Trager et al. 2000, Kuntschner 2000, Caldwell et al. 2003, Denicoló et al. 2005, Thomas et al. 2005). Trager et al. proposed a scenario where the bulk of the stars in their sample galaxies were old, and only a very small fraction of their stellar populations had young ages (~ 1 Gyr). Because the latter are brighter in the optical, they weight the mean ages towards lower values. Although plausible, this schematic scenario could not be verified by the Trager et al. data because of the degeneracy between the age of the young component and its relative contribution to a galaxy’s total stellar mass budget, which cannot be broken on the basis of $H\beta$ and metal-line indices alone.

With the inclusion of additional age indicators, such as higher-order Balmer lines in the blue (Leonardi & Rose 1996, Worthey & Ottaviani 1997, Schiavon 2007), stronger constraints were placed on the age distributions of stars. These studies confirmed early suggestions that a small fraction of the stellar mass budget (few %) is required to be young in order to match the data. They also ruled out claims that Balmer line strengths in the spectra of ETGs required the presence of metal-poor stars with blue horizontal branches (e.g., Freitas Pacheco & Barbuy

1995, Maraston & Thomas 2000, Lee et al. 2000). Models including metal-poor stars cannot simultaneously match all Balmer and metal lines in the 400-530 nm range (see also Trager et al. 2005).

Perhaps the cleanest evidence for the presence of young/intermediate-age stellar populations was provided by Galex observations of ETGs by Yi et al. (2005). Analyzing UV–optical colors of ETGs from the Sloan Digital Sky Survey, Yi et al. found that approximately 2/3 of their sample present strong UV fluxes which cannot be explained by hot horizontal branch stars. They estimate that approximately 1–2% of the stellar mass is in the form of young stars. Because they constitute a tiny fraction of the stellar mass budget, young stars are vastly outshone by older populations in the optical, where they can only be detected on the basis of accurate spectrum synthesis of very high S/N spectra (e.g., Schiavon et al. 2004, Schiavon 2007, Graves et al. 2007)—while being relatively easy to detect in the UV.

More recent estimates based on a combination of Galex photometry with larger SDSS samples indicate that as much as 10% of all stellar mass in ETGs today were formed since $z \sim 1$ (S. Yi, this volume). While a fascinating debate is ongoing regarding what triggered and quenched this relatively recent star formation (e.g., Kuntschner et al. 2010, Zhu et al. 2010, Sánchez-Blázquez et al. 2009, Serra et al. 2008, Schawinski et al. 2007, Kaviraj et al. 2007, Graves et al. 2007), information on the history of formation of the remaining $\sim 90\%$ of the stellar mass is relatively scanty, possibly because it requires observations of large samples at higher redshifts than so far possible and/or a far more thorough assessment of the fossil record in the abundance patterns of stars in the nearby ETGs. The latter is the topic of the next section.

3. Stellar Abundances

Crucial information about the star formation history is encoded in the chemical composition of stars. The key observables are mean (luminosity-weighted) metallicities, abundance ratios, and the run of these quantities with σ . It has long been known that the central regions of nearby massive galaxies are metal-rich (e.g., Spinrad & Taylor 1971). It was only far more recently that reliable metallicity estimates became possible for

¹See Trager & Somerville (2009) for a discussion of the relation between luminosity- and mass-weighted ages/abundances with those obtained from comparison of line indices with single stellar population synthesis models.

massive ETGs at cosmological distances, showing that they have comparably high metallicities, (e.g., Spinrad et al. 1997, Jørgensen et al. 2005, Schiavon et al. 2006), implying a relatively rapid early chemical enrichment. A more detailed knowledge of the history of star formation requires accurate estimates of detailed abundance patterns in a range of redshifts, but work on abundance ratios has so far been restricted to relatively nearby samples (but see Jørgensen et al. 2005 and Kelson et al. 2006).

3.1. Magnesium

The Mg I 517-518 nm doublet has been the chief metallicity indicator in early studies of the chemical composition of ETGs from integrated light, due to its strength and location in a spectral region where astronomical detectors were very sensitive. Early studies found evidence for an overabundance of Mg relative to Fe in ETGs (e.g., Peterson 1976). When Mg and Fe lines were finally compared with models of stellar population synthesis, it was found that $[\text{Mg}/\text{Fe}]^2$ is above solar in the centers of massive ETGs (Worthey et al. 1992). This was arguably one of the most influential results in the history of the field, and it has guided theoretical work to this day. Further studies showed that Mg enhancement is correlated with central velocity dispersion (σ) and metallicity (e.g., Jørgensen 1999, Trager et al. 2000, Thomas et al. 2005, Schiavon 2007, Smith et al. 2009). At least three scenarios have been invoked to explain this finding, all involving the balance between Mg enrichment by SN II and Fe enrichment by SN Ia: short star formation timescale, top-heavy IMF, and selective winds (Faber et al. 1992). One popular interpretation of the data invokes the existence of a relation between star formation timescale and galaxy mass (e.g., Thomas et al. 2005). The data, however, did not allow one to rule out scenarios based on selective winds or IMF variations.

Some exciting new results have been presented

²More often than not, this result is phrased in the literature in terms of an overabundance of α elements relative to iron. Despite the many theoretical reasons in favor of the assumption that all α elements should vary *in tandem*, there is so far no firm evidence that any α element other than Mg is enhanced in ETGs, except perhaps for Ti (Milone et al. 2000).

in a series of papers, by G. Graves and collaborators. Analyzing a large sample of stacked SDSS³ spectra, they mapped the spectroscopic ages, $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$ of ETGs onto the fundamental plane (FP) with particular attention to how these parameters are distributed along and across the FP (Graves et al. 2009, Graves & Faber 2010, Graves et al. 2010). Besides recovering the well known trends of age and abundances with σ , Graves et al. showed that, at fixed σ , star formation histories of ETGs correlate strongly with galaxy surface brightness. Galaxies with higher surface brightness have lower spectroscopic ages, higher $[\text{Fe}/\text{H}]$ and $[\text{Mg}/\text{H}]$, but lower $[\text{Mg}/\text{Fe}]$. Graves & Faber (2010) contend that the thickness of the FP is accounted for by departures of a constant dynamical-mass-to-light ratio (M_{dyn}/L), which may be due to variations in either dark-matter fraction or IMF, and not to effects due to passive evolution of the stellar populations. At fixed M_{dyn} , galaxies with higher surface brightness (located "above" the FP) have a higher surface stellar density and therefore are characterized by either a lower dark matter fraction or by a bottom-heavier IMF. They formed stars during a longer timescale, so that their metallicities are higher, but both their spectroscopic ages and $[\text{Mg}/\text{Fe}]$ s are lower than their low-surface-brightness counterparts. Graves et al. propose a scenario where star formation in galaxies with same M_{dyn} was truncated at different times, with longer/shorter star formation timescales resulting in higher/lower stellar surface mass density and surface brightness, higher/lower metallicity, lower/higher $[\text{Mg}/\text{Fe}]$, and younger/older spectroscopic ages. In short, these new results single-handedly explain the thickness of the FP and establish possible (and testable) correlations between the star formation histories of ETGs and such measurable quantities as dark-matter fraction and the shape of the low-mass end of the stellar IMF. Further progress will be determined by observational tests of these predictions, as well as more sophisticated chemodynamical modeling of ETG formation.

³Sloan Digital Sky Survey

3.2. Calcium

Past studies suggest that Ca does not behave like Mg, with $[\text{Ca}/\text{Fe}]$ being possibly solar (or lower) and not correlated with σ . Trager et al. (1998) found the Lick/IDS Ca4227 index to be essentially independent of σ . Accordingly, Thomas et al. (2003) concluded that $[\text{Ca}/\text{Fe}]$ in their sample galaxies was also essentially constant with σ . Saglia et al. (2002), on the other hand, found the Ca II triplet (CaT, 849, 855, 862 nm) to be mildly decreasing with σ . Vazdekis et al. (2003) and Cenarro et al. (2004) compared new single stellar population synthesis models for the CaT with data for field and Coma galaxies, again finding very low $[\text{Ca}/\text{Fe}]$. While difficult to understand, given that both Ca and Mg are α elements manufactured in similar (though not identical) nucleosynthetic sites, the implications of these results are potentially important, giving theorists ample room for a wide range of speculations.

The unexpected behavior of Ca seems to be instead most likely caused by difficulties in the interpretation of the measurements, particularly because the two Ca indices employed in these studies do not respond to Ca abundance variations in a clean fashion. Prochaska et al. (2005) showed that the Ca4227 index is severely affected by a CN bandhead which contaminates the blue pseudo-continuum of the index, making it lower. Because CN is strongly correlated with σ (Trager et al. 1998), the effect is stronger for higher σ galaxies, offsetting any dependence of the Ca line strength itself on σ , thus making the index σ -independent. Prochaska et al. demonstrated this by defining a new index, Ca4227_r, which is less affected by CN contamination. They showed that Ca4227_r is as strongly correlated with σ as Mg *b*.

While the issue of the slope of the Ca4227- σ relation is seemingly resolved, models that account for the effect of CN on the Ca4227 index still indicate $[\text{Ca}/\text{Fe}] \sim 0$ in massive ETGs (Schiavon 2007, Graves et al. 2007). At face value, this confirms the abundance ratios found by previous studies. However, there may be non-negligible systematics in the Ca abundances derived by application of the Schiavon (2007) models. They are affected by uncertainties in age, and in the abundances of Fe, C, and N. They are also affected by uncertainties in the way models account for the contamination

of Ca4227 by CN. So the matter should be considered far from settled.

Regarding the results based on CaT, one should bear in mind that the integrated spectra of metal-rich stellar populations in the CaT region is dominated by M giants (Schiavon & Barbuy 1999), and that fact has implications for both the zero point and the slope of the $[\text{Ca}/\text{Fe}]$ - σ relation. First let us consider the zero point. The stellar libraries employed in the models used to analyze CaT data in the past contain hardly any M giants with known metallicity, let alone known $[\text{Ca}/\text{Fe}]$ (Cenarro et al. 2001a). Therefore, $[\text{Ca}/\text{Fe}]$ in the models themselves is uncertain, which obviously makes it very hard for one to infer reliable $[\text{Ca}/\text{Fe}]$ from comparison of those models with the data. As regards the slope of the CaT- σ relation, we recall that the CaT lines are located in a region where opacity in the spectra of M giants is dominated by TiO lines. While the definition of the CaT* index employed in these studies is partly meant to account for TiO contamination (Cenarro et al. 2001b), the index has not been shown to be immune to variations in $[\text{Ti}/\text{Fe}]$ ⁴ which may be important, given that there is evidence that Ti is enhanced in ETGs (Milone et al. 2000). Regarding the negative slope of the CaT* $\sim \sigma$ relation, that could be due to the effect of TiO opacity on the pseudocontinuum, because: 1) TiO is well correlated with σ (Trager et al. 1998), and 2) TiO lines are more sensitive to metallicity than CaT lines (Schiavon et al. 2000, Schiavon & Barbuy 1999, Jørgensen et al. 1992). Finally, CN contamination of the CaT indices may also be important (Erdelyi-Mendes & Barbuy 1991).

In summary, we suggest that Ca abundances are far from well known in ETGs, and there is no compelling motivation to resort to extreme scenarios to account for the numbers currently available in the literature. More work is needed to produce reliable $[\text{Ca}/\text{Fe}]$ measurements in ETGs.

3.3. Nitrogen & Carbon

While the behavior of C- and N-sensitive indices such as Lick CN₁, CN₂, G4300 and C₂4668 in ETG spectra has been well documented for over a decade, it was only after the Schiavon (2007) mod-

⁴TiO lines are very sensitive to variations in the abundance of Ti.

els and their implementation in EZ_Ages (Graves & Schiavon 2008) that these indices could be interpreted in terms of $[N/Fe]$ and $[C/Fe]$ (see also Kelson et al. 2006). Both abundance ratios are found to be super-solar and correlate strongly with σ and metallicity (Schiavon 2007, Graves et al. 2007, Smith et al. 2009). This result has been called into question recently by Toloba et al. (2009), who found no correlation between the strength of the near-UV NH3360 feature and σ in a sample of nearby galaxies. They argue that the NH3360 band is a clearer indicator of N abundance than the Lick CN features used by EZ_Ages, because the latter are also dependent on C abundance. The absence of a slope in the NH3360- σ relation may be explained by the presence of metal-poor stars, whose contribution to the integrated light is highest in the UV. In fact, multiple stellar population models show that the inclusion of a small fraction of a metal-poor population flattens the NH3360- σ relation, even in the presence of a $[N/Fe]$ - σ correlation (G. Worthey, 2010, private communication).

The existence of a steep slope in the $[N/Fe]$ - σ relation, if confirmed, is an important result, as it may indicate secondary enrichment of N by stars ranging from 4–8 M_{\odot} (Chiappini et al. 2003). Because these stars last for $\sim 10^8$ years, the presence of a secondary-enrichment signature in the chemical composition of stars in ETGs may constrain the lower limit for the duration of star formation in the systems that formed the stars that live today in those galaxies, (Schiavon 2007) and, perhaps most importantly, their characteristic masses. The increasing evidence for the presence of multiple stellar populations in globular clusters (Piotto 2009) may be an important clue in this regard. It has been long known that there is a marked spread in N and C abundances in globular cluster stars (e.g., Smith & Norris 1982, Cannon et al. 1998, Carretta et al. 2005), which is roughly consistent with enrichment by intermediate mass stars going through the AGB phase (Ventura & D’Antona 2008). The presence of such CN inhomogeneities seems to be a function of both cluster mass and environment (Martell & Smith 2009), as predicted by recent models (Conroy & Spergel 2010).

One may reasonably speculate that the evidence above indicates that the stars we see in

nearby ETGs were formed in the precursors of today’s Galactic globular clusters. In that scenario, the signature of secondary N enrichment we see in ETGs today would have been established in those early systems, before they merged to form the massive, dynamically hot galaxies we see today. The Galactic halo can be used as a resolved proxy to test this scenario. The recent identification of CN bimodality in a sample of halo field stars by Martell & Grebel (2010) argues for a similar process in operation during the formation of the Galactic halo. Because CN-strong stars have almost certainly been formed in globular clusters (or their precursors in the distant past), their presence in the halo field is evidence of the early dissolution of those systems in the formation of the Galactic halo. Martell & Grebel estimate that as much as 50% of the halo mass may have been contributed by globular clusters and their precursors. If a similar process was responsible for the assembly of stellar mass in ETGs, one might wonder whether a similar fraction of the total mass would have been contributed by the globular cluster precursors. Could the slope of the $[N/Fe]$ vs. $[Fe/H]$ or σ be used to constrain that number? What were the characteristic masses of those systems? Would it be possible to construct chemodynamical evolution models for those low-mass systems that are capable of reproducing all the abundance ratios measured in today’s ETGs?

Inclusion of C and N in abundance analyses of ETGs is bringing interesting new insights on their star formation histories, which could potentially even lead to a reinterpretation of the data on $[Mg/Fe]$. Smith et al. (2009) analyzed a large data set for galaxies from the Coma cluster and Shapley supercluster, spanning a very wide range of σ . They determined the abundances of several elements using EZ_Ages, then performed biparametric fits to the relation between $[Mg, Ca, C, N/Fe]$ and both $[Fe/H]$ and σ , thus disentangling the dependence of abundance ratios on these two variables. Smith et al. found that both $[Mg/Fe]$ and $[Ca/Fe]$ decrease with $[Fe/H]$, whereas $[N/Fe]$ and $[C/Fe]$ do not correlate with it. They suggest that the run of $[Mg/Fe]$ and $[Ca/Fe]$ with $[Fe/H]$ indicates a short time scale for star formation. They consider that the lack of correlations of $[N/Fe]$ and $[C/Fe]$ with $[Fe/H]$ is expected since, unlike Mg and Ca, C and N are contributed by low(er) mass

stars, so that these elements should scale with Fe, not with Mg and Ca. Interestingly, on the other hand, all abundance ratios show a strong correlation with σ . Smith et al. contend that this result is difficult to interpret in terms of a simple dependence of star formation timescale on galaxy mass (e.g., Thomas et al. 2005), because that would preclude a correlation between [C/Fe] and [N/Fe] with σ . Clearly, more work is needed to clarify this issue.

4. Concluding remarks

The discussion above highlights the power of stellar population synthesis to infer mean stellar properties from integrated light, and constrain galaxy formation models. Presently, well tested stellar population synthesis models can be used to determine mean stellar ages and abundances of Fe, Mg, Ca, C, and N. The recent addition of the latter two elements may spark the emergence of a more complex picture of galaxy formation. In order for that to happen, more work is needed to refine chemodynamical models used to interpret the abundance measurements and their relation with global galaxy properties in terms of the physics of galaxy formation. There has been very promising recent progress on this front, which, due to space limitations, could not be reviewed here (e.g., Arrigoni et al. 2010, Pipino et al. 2009a,b). More theoretical work is also needed to develop better stellar population synthesis models to ascertain the reality of current abundance determinations, and to include more elements in the pool of reliable abundances. On this front as well, different groups are making steady progress (Lee et al. 2009, Coelho et al. 2007, Peterson 2007). In that regard, it is particularly desirable to extend stellar population synthesis modelling towards the UV, in order to match the upcoming observing capabilities that will make possible collection of large samples of galaxy spectra at redshift beyond 2. With the expected developments in theory and observations, this field will likely go through very exciting times in the next decade.

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