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Abundances from the Integrated Light of Globular Clusters and Galaxies

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Abstract

It is currently impossible to determine the abundances and ages of the stellar populations of distant, dense stellar systems star by star. Therefore, methods to analyze the composite light of stellar systems are required. I review the modeling and analysis of integrated spectra of the stellar populations of individual globular clusters, globular cluster systems, early-type galaxies, and the bulges of spiral galaxies, with a focus on their abundances and abundance ratios. I conclude with a list of continuing difficulties in the modeling that complicate the interpretation of integrated spectra, as well as a look ahead to new methods and new observations.

1.1 Introduction

The reviews presented in this volume demonstrate that the nucleosynthetic history of the Milky Way and its satellites can now be probed in exquisite detail, revealing a wealth of information about the processes by which our own Galaxy and its neighbors have formed. Such star-by-star analysis of the abundances of distant globular clusters and distant and/or dense galaxies is, however, currently beyond the reach of current telescopes. Although this situation might change with the advent of overwhelmingly large telescopes of the 30–100 m class with high-precision adaptive optics systems, during the 20th century and at the beginning of the 21st, we have been limited to studying the *integrated* stellar populations of distant globular clusters and galaxies.

In this review, I will discuss spectroscopic techniques for determining abundances from the integrated light of galaxies and globular clusters. I will begin with a discussion of the ingredients of the models required to interpret the integrated-light spectra, the calibration of those models, and a few of their pitfalls. I will then discuss the abundances determined from integrated-light spectroscopy of globular clusters in our Galaxy, the Local Group, and the globular cluster systems of early-type galaxies. I will then consider the abundances of nearby early-type galaxies and the bulges of early-type spirals determined from integrated-light spectroscopy, including recent results on abundance anomalies in these systems. Although I will focus on deriving abundances from optical spectra, these results necessarily depend on the *ages* of the systems (through the age-metallicity degeneracy; §1.2.1), and so I must briefly discuss the ages of these systems. Finally, I will summarize the current state of the observations, the current problems in understanding stellar populations from integrated-light spectroscopy, and current and future directions in this subject.

Perusal of this outline reveals that there are a number of topics I will not discuss, due either to space constraints or to difficulties in interpretation. I will not be able to discuss the fascinating history of this subject in detail. I will not discuss purely photometric methods of determining abundances, such as attempts to derive abundances of globular clusters and early-type galaxies from broad-band colors, as the interpretation of broad-band optical colors is seriously compromised by the age-metallicity degeneracy. I will not have space to discuss abundances derived from wavebands other than the optical; there have been excellent recent reviews and studies of the stellar populations of globular clusters and early-type galaxies determined from, for example, UV spectroscopy (O'Connell 1999; Dorman, O'Connell, & Rood 2003; Peterson et al. 2003, 2004). Last, but not least, I will not discuss stellar abundances of irregular or dwarf galaxies themselves (apart from M32), as this subject is ably covered elsewhere in this volume, and I will touch only lightly on abundances derived from the integrated *stellar* light of bulges of early-type spiral galaxies. Garnett (2004) thoroughly and cogently discusses the *gas-phase* abundances of such galaxies.

1.2 Stellar Population Modeling of Integrated-light Spectra

The interpretation of the integrated light of globular clusters and galaxies requires astrophysically constrained models. In this section, I outline the basic purpose and ingredients of such models and the steps required to calibrate them.

1.2.1 The Basic Problem

O'Connell (1986) gives a clear physical explanation of the *age-metallicity degeneracy* that plagues the study of the integrated light of stellar populations. Because the emergent flux from a stellar atmosphere is a superposition of spectra that are characterized by different temperatures weighted by a function of opacity, increases in opacity in a stellar atmosphere due to increased metallicity are equivalent to a decreased mean temperature for the emergent flux. Therefore, a metal-rich population can be simulated by decreasing the mean temperature—that is, decreasing the age—of a more metal-poor population (Fig. 1.1).

The key breakthrough in the analysis of integrated stellar populations was made by Rabin (1980, 1982) and Gunn, Stryker, & Tinsley (1981), who noticed independently that the strengths of the Balmer lines of hydrogens derived from evolutionary population synthesis models allow an accurate age of a single-burst stellar population to be measured. Rabin expressed this idea in a powerful graphical form: the "hydrogen-metals diagnostic diagram," in which the strength of Balmer lines are plotted as a function of a metal line (in this case, Ca II K) for the integrated spectra and stellar population models. Using this diagram, he could break the age-metallicity degeneracy. Applying this method to clusters in the Magellanic Clouds, Rabin confirmed that the Searle, Wilkinson & Bagnuolo (1980; hereafter SWB) ranking of those clusters was indeed an age ranking.

Worthey (1994) and Worthey & Ottaviani (1997) quantified the age-metallicity degeneracy for a large number of absorption-line strengths and broad-band colors. Metal lines (like Mgb and $\langle\mathrm{Fe}\rangle$) and broad-band colors are slightly more sensitive to metallicity than age, in the ratio $\partial \log t / \partial \log Z = 3/2$ (Worthey 1994; Fig. 1.1). This means that a factor of 3 change in age looks like a factor of 2 change in metallicity for a simple stellar population. Clearly, age-sensitive indices are desired—lines that preferentially measure the

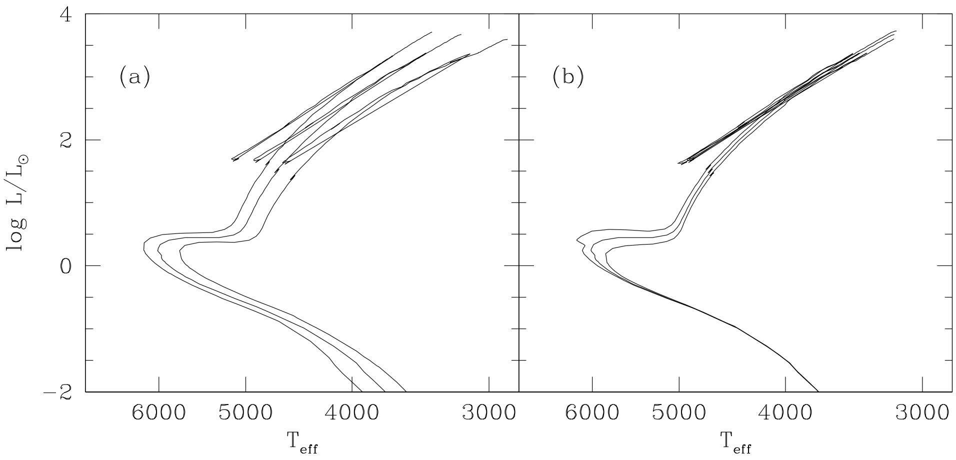

Fig. 1.1. The age-metallicity degeneracy. (*a*) Varying metallicity at fixed age: 12 Gyr old Padova (Girardi et al. 2000) isochrones with metallicities of [Fe/H] = –0.68, –0.38, 0 (left to right). (*b*) Varying age at fixed metallicity: [Fe/H] = –0.38 Padova isochrones with ages of $t = 7$, 10, 14 Gyr (left to right). Note that in this view of the age-metallicity degeneracy, the main sequence turnoff (MSTO) varies in temperature roughly equally in each case, but the red giant branch (RGB) varies little with age at fixed metallicity. To break the degeneracy, one needs to measure the temperature of both the MSTO and the RGB to decouple the age and metallicity.

(luminosity-weighted) temperature of the MSTO. Following Rabin (1980, 1982), Worthey (1994) showed that $\partial \log t / \partial \log Z \approx 2/3$ for Hβ (and ~ 1 for Hδ and Hγ; Worthey & Ottaviani 1997). Thus, a Balmer-line index *combined* with a metal-line index *breaks* the age-metallicity degeneracy.

1.2.2 Ingredients

The first attempt to synthesize the spectral lines and colors of a galaxy appears to have been made by Whipple (1935). Whipple developed population synthesis, in which arbitrary permutations of stellar types are combined to make a synthetic galaxy spectrum and colors; this method was highly influential on many later workers (e.g., de Vaucouleurs & de Vaucouleurs 1959; Spinrad 1962a,b; Spinrad & Taylor 1969, 1971; Lasker 1970; Faber 1972; O'Connell 1976; Williams 1976). Tinsley (1968, 1972; Tinsley & Gunn 1976) invented the method that has generally superseded population synthesis: *evolutionary* population synthesis. In this method, populations are modeled from the starting point of an isochrone and a luminosity function and then matched to the observations, instead of attempting to extract a color-magnitude diagram (CMD) and luminosity function from the observations. Tinsley's method has become the basis for modern stellar population models (e.g., Bruzual 1983; Buzzoni 1989; Charlot & Bruzual 1991; Bruzual & Charlot 1993; Worthey 1994; Bressan, Chiosi, & Fagotto 1994; Maraston 1998).

To build a model of a *simple stellar population* (SSP)—that is, a single-age, single-metallicity stellar population—that can be used to analyze the integrated spectrum of a given object, four major ingredients are required.

Isochrones An isochrone set that is best calibrated against the populations of interest (young, intermediate-aged, or old; metal poor or metal rich) is needed as the basic astrophysical constraint. Popular choices for the intermediate-aged and old populations considered here are currently the Padova set (Girardi et al. 2000; Salasnich et al. 2000), the set from Cassisi, Castellani, & Castellani (1997) and Bono et al. (1997), and the set of Salaris & Weiss (1998) and more recent extensions (see, e.g., Schiavon et al. 2002b).

Initial mass function An IMF populates the isochrones as needed. Typically, a Salpeter (1955) IMF is chosen, although other choices are possible (Vazdekis et al. 1996).

Stellar fluxes While it may be preferable to have a set of observed stellar fluxes covering a comprehensive range in temperature, gravity, and metallicity (and even $[\alpha/\mathrm{Fe}]$), such a set is not currently available (although see Vazdekis 1999 for another approach and Le Borgne et al. 2003 for a hint of what is to come). We therefore are reliant on the theoretical flux library of Kurucz (1993), which covers a broad range of parameter space, or modifications of that library to attempt to bring its colors into better agreement with real stars (Lejeune, Cuisinier, & Buser 1997, 1998; Westera et al. 2002).

Stellar spectra or absorption-line strengths Because we require the strengths of Balmer-line and metal-line indices to break the age-metallicity degeneracy, a library of either stellar spectra (e.g., Jones 1998) or stellar absorption-line strengths (e.g., Worthey et al. 1994) is required. Given the difficulties in matching the Lick/IDS system precisely (Worthey & Ottaviani 1997; Trager, Faber, & Dressler 2004), we would like to find new libraries for population syntheses. Such libraries are on their way (Peletier, Rose, Schiavon, and Worthey, private communications).

Once these ingredients are available, one can construct a stellar population model, as shown in Figure 1.2. However, such models clearly have a problem: ages and metallicities derived from different pairs of Balmer- and metal-line indices are different for giant elliptical and many S0 galaxies. These discrepancies result from the nonsolar abundance ratios of these objects (Faber & Jackson 1976; O'Connell 1976; Peterson 1976; Peletier 1989; Worthey, Faber, & González 1992; Greggio 1997; Worthey 1998; Trager et al. 2000a). Although we refer to these nonsolar abundance ratios by the shorthand phrase "α-enhancements," we stress that the proper interpretation of these discrepancies is actually as "Fe-deficiencies," because the "α-elements" O and Mg dominate the metallicity determinations (Greggio 1997; Trager et al. 2000a). Correcting for $[\alpha/\mathrm{Fe}]\neq 0$ (or more generally, for $[X_i/\mathrm{Fe}]\neq 0$ for any element X_i; Thomas, Maraston & Bender 2003a, hereafter TMB03) requires either an empirical stellar library with the needed enhancements or stellar atmosphere models in which synthetic spectra with the needed enhancements can be generated, as well as isochrones with $[\alpha/\mathrm{Fe}]\neq 0$, such as those available in the Padova and Salaris & Weiss sets (cf. Trager et al. 2000a; but see Maraston & Thomas 2003). The empirical approach was attempted first by Weiss, Peletier, & Matteucci (1995), who coupled fitting functions for Mg_2 and $\langle\mathrm{Fe}\rangle$ from the Galactic bulge giants of Rich (1988) with α-enhanced isochrones; unfortunately, the Rich library was not complete enough for a reasonable coverage of parameter space and, more importantly, did not include the crucial Hβ index. Trager et al. (2000a) and TMB03 have chosen to use the stellar atmosphere computations of Tripicco & Bell (1995), who modeled the response of the Lick/IDS index system to changes in individual elements,

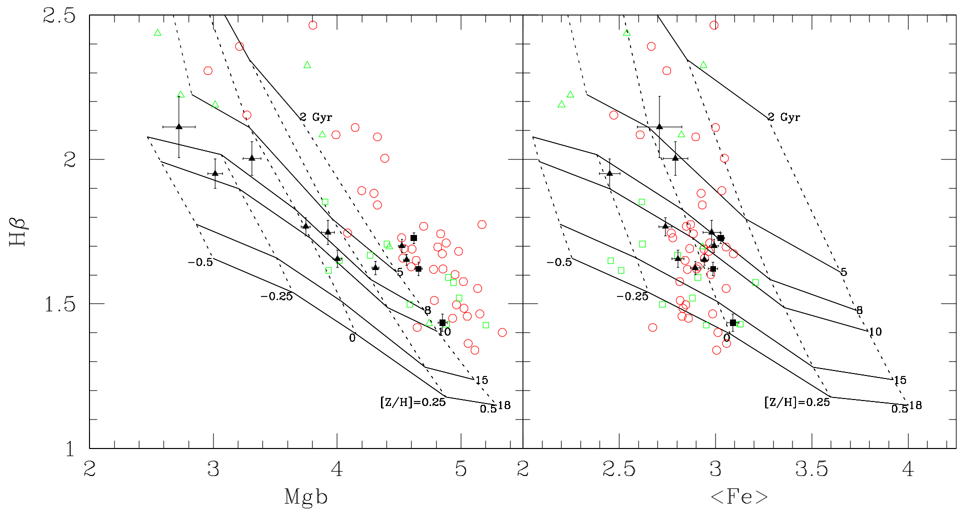

Fig. 1.2. The line strengths of local early-type galaxies compared with stellar population models from Worthey (1994). Solid lines: constant age. Dashed lines: constant metallicity. Solid squares and triangles: elliptical and S0 galaxies in Coma (Trager, Faber, & Dressler 2004). Open squares and triangles: elliptical and S0 galaxies in Fornax (Kuntschner 2000). Open circles: elliptical galaxies in Virgo, groups, and the field (González 1993). *Left*: Hβ as a function of Mgb. *Right*: Hβ as a function of $\langle$Fe$\rangle$. Note the significant difference in derived age and metallicity for most galaxies from each pair of indices; this is indicative of $[\alpha/\mathrm{Fe}] \neq 0$ for these galaxies.

in a differential sense, and ignore the α-enhanced isochrones (Maraston & Thomas 2003). While more flexible for analyzing populations that may not resemble local stars, calibration of these theoretical corrections is required.

1.2.3 Calibrations

I show the results of α-enhanced models (TMB03) in Figure 1.3. It is clear that if these models are indeed properly calibrated, then it is possible to determine uniquely age, metallicity, and $[\alpha/\mathrm{Fe}]$ for a single-burst population. Galaxies are unlikely to be SSPs, but globular clusters are (except maybe ω Cen: Smith 2004). I note here that the "metallicities" measured by the Trager et al. (2000a) technique are total metallicities [Z/H], not [Fe/H]. However, [Z/H] can be converted to [Fe/H] on the Zinn & West (1984) scale with the following (model-dependent) scaling: $[\mathrm{Fe/H}] = [\mathrm{Z/H}] - 0.94[\alpha/\mathrm{Fe}]$ (Tantalo, Chiosi, & Bressan 1998; Trager et al. 2000a; TMB03).

I will now exploit this fact and turn to a model of an individual cluster: 47 Tuc. Gibson et al. (1999) pointed out that the stellar population models of Jones & Worthey (1995) predicted an age in excess of 20 Gyr from Hγ and the Ca4227 or $C_2$4668 indices for 47 Tuc, a cluster with a CMD-based age of 11–14 Gyr (depending on the isochrone set used; Schiavon et al. 2002b). Vazdekis et al. (2001) brought the spectroscopic age down by using α-enhanced isochrones with He diffusion (from the Salaris & Weiss 1998 set). Schiavon et al. (2002a,b) used a two-pronged approach to solve this problem. First, they synthesized the

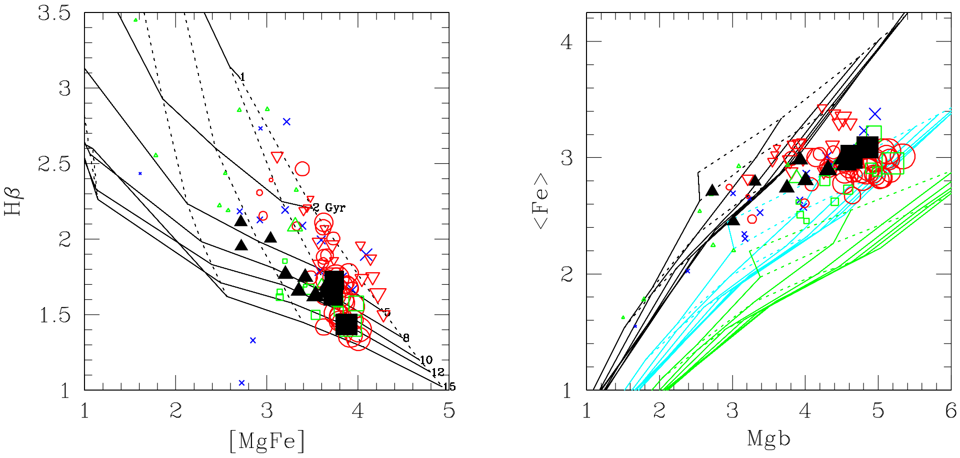

Fig. 1.3. The line strengths of the nuclei of local early-type galaxies compared with stellar population models from TMB03. Points and line types as in Fig. 1.2, except inverted triangles (S0s in groups and Virgo; Fisher, Franx, & Illingworth 1996) and crosses (bulges of S0/a–Sbc spirals in various environments; Proctor & Sansom 2002). Point sizes for all samples are proportional to velocity dispersion. *Left*: Ages and metallicities. Note that the metallicity (left to right: [Fe/H] = −1.35, −0.33, 0, 0.35, 0.67 dex) and age scales have changed. Note that field ellipticals (circles), nearly all S0s, and bulges span a large range in Hβ strength and thus in SSP age, while cluster ellipticals (squares) are quite old and vary more in metallicity. *Right*: [α/Fe] (from left to right: [α/Fe] = 0, +0.3, +0.5 dex). In this plot, note that ellipticals tend to have [α/Fe] $\approx$ +0.3—in fact, this varies with velocity dispersion, with small ellipticals being more "solar" and large ones being more enhanced (Trager et al. 2000b)—while S0s and bulges tend to be more "solar."

spectrum directly from the CMD (Schiavon et al. 2002a), which was meant to reveal any problems with the stellar libraries. Schiavon et al. uncovered several: (a) it is necessary to have a strictly *homogeneous* set of atmospheric parameters for the stars in the library; (b) the metallicities of the library stars used in the synthesis must be that of the cluster to less than 0.05 dex, and must be on the same metallicity scale; and (c) the line strengths need to account for the CN bimodality of the cluster (which extends to at least the MSTO: Hesser 1978), in which roughly half the stars are CN-strong. Now that the necessary corrections to the line strengths are understood, the second step is to synthesize the line strengths from the best-fitting isochrone (Schiavon et al. 2002b). A significant problem arises in this step: the observed luminosity function does not match that of the model, due to a lack of AGB stars (in the Salaris isochrones) and a strong deficit of RGB stars (in both the Salaris and Padova isochrones). Once all of these problems are corrected for, nearly all of the synthesized spectral indices match the observations at the correct age (11–13 or 12–14 Gyr using the Salaris and Padova isochrones, respectively) and metallicity ([Fe/H] = −0.75 dex).

Now that we have confidence in our stellar population models to predict the age and metallicity of a single globular cluster (finally; Searle 1986), we turn to the calibration of the corrections for [α/Fe] $\neq 0$. Maraston et al. (2003) have done this by comparing the Lick/IDS globular cluster data and the Galactic bulge cluster data of Puzia et al. (2002)

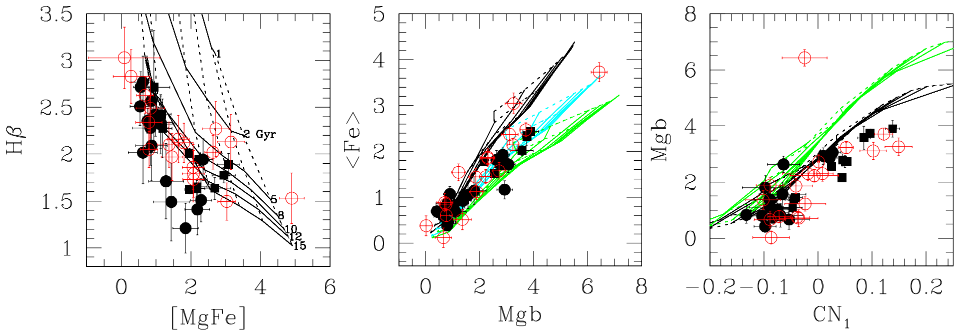

Fig. 1.4. The stellar populations of Milky Way (solid circles: halo clusters from Trager et al. 1998; solid squares: bulge clusters from Puzia et al. 2002) and M31 (Trager et al. 1998; halo clusters only) globular clusters. Left: ages and metallicities. Grids as in Fig. 1.3, although here extended down to [Fe/H] = −2.25 dex. The two Hβ-strong M31 clusters (V87, V116) are likely to be intermediate-aged, but the slightly "younger" Milky Way clusters are the anomalous blue horizontal branch clusters NGC 6388 and NGC 6441 (Rose & Tripicco 1986; Rich et al. 1997), which are as old as the other Galactic clusters. Center: [α/Fe] ratios; grids as in Fig. 1.3. Right: The "CN anomaly" (Burstein et al. 1984) in the Galactic and M31 clusters; grids are [α/Fe] = 0 (lower) and [α/Fe] = +0.5 (upper) from TMB03. Clearly, the Galactic and M31 clusters do not differ significantly in Mg*b*/CN_1, but as a whole are too strong in CN_1 at fixed Mg*b* given their typical [α/Fe] (middle panel; Maraston et al. 2003; TMB03). The highly aberrant M31 "cluster" V204 is likely to be one of the brightest stars in M31 (Berkhuijsen et al. 1988) rather than a globular cluster.

with the TMB03 stellar population models, index by index. I show Puzia et al.'s data for a few indices below (Fig. 1.4) but comment here that several indices do not match the models: CN_1 and CN_2 (Burstein et al. 1984); Ca4455 (this difficult index probably should be dropped from the Lick/IDS system); strikingly, $C_2$4668, an index with a large dynamic range at fixed temperature but varying metallicity (Worthey et al 1994; Worthey 1994); Na D; and the TiO indices (although this is not surprising, as Tripicco & Bell 1995 did not model TiO properly). TMB03 have solved the discrepancies in the CN indices and $C_2$4668 by allowing [N/α] = +0.5 (cf. Brodie & Huchra 1991; Smith et al. 1997), but Na D remains a mystery (Spinrad 1962a,b; Cohen, Blakeslee, & Côté 2003).

1.3 Globular Cluster Systems

Now that the required tools are in hand, I turn to what has been learned about the abundances and ages of the stellar populations of globular cluster systems of the Milky Way and M31 (§1.3.1), dwarf galaxies in the Local Group (§1.3.2), and early-type galaxies (§1.3.3).

1.3.1 The Globular Cluster Systems of the Milky Way and M31

Van den Bergh's (1969) spectroscopy of globular clusters in M31, the Fornax dwarf spheroidal galaxy, and the Milky Way opened the field of extragalactic globular cluster systems. He found that the metallicities of M31 globular clusters were on average more metal rich than those in the Milky Way with a similar or slightly larger metallicity spread, but the

Fornax clusters were more metal poor and had a much smaller metallicity spread. Interestingly, van den Bergh also found that the Balmer line strengths of globular clusters may differ at fixed metallicity, even in the most metal-rich clusters (see the discussion in Rose 1985); this suggests that age may play a role in the stellar populations of some globular cluster systems or that blue horizontal branches may exist at much higher metallicities than seen in the Milky Way globular clusters.

In Figure 1.4 I plot the line strengths of globular clusters in the Milky Way and M31. Three primary results can be read from this figure.

(1) The mean metallicity and spread in metallicity of the globular cluster systems in the two dominant spirals of the Local Group are nearly identical when the bulge clusters of the Milky Way are included.*
(2) The M31 clusters are slightly more "solar" in their $[\alpha/\mathrm{Fe}]$ ratios at the highest metallicities.
(3) The CN strengths at fixed Mgb are very similar in both systems but are significantly higher than the strength predicted by the models at the $[\alpha/\mathrm{Fe}]$ ratios derived from the Mgb–$\langle\mathrm{Fe}\rangle$ diagram.

Point (1) implies that metallicities of M31 clusters from integrated-light spectra interpreted using the TMB03 models can be assumed to be well calibrated onto the Zinn & West (1984) scale as long as $[\alpha/\mathrm{Fe}]$ can be measured. Point (2) supports the identification of the two "intermediate-aged" (Hβ-strong) M31 clusters (V87 and V116) as being somewhat younger than the dominant cluster populations in the two systems (cf. Brodie & Huchra 1990). However, the Hβ-strong, metal-rich Galactic globular clusters are the bulge clusters NGC 6388 and NGC 6441, which have well-populated blue horizontal branches that do not exist in other metal-rich clusters (Rose & Tripicco 1986; Rich et al. 1997). Point (3) disagrees with the conclusions of Burstein et al. (1984), who found that M31 clusters have stronger CN strengths than Galactic globular clusters, solely because the Lick/IDS database does not contain the metal-rich Galactic bulge clusters, which span the high-CN strengths of the metal-rich M31 clusters. As discussed above, "enhanced" CN at fixed Mgb appears to be a result of $[\mathrm{N}/\alpha] = +0.5$ in these clusters.

I note, however, that many of the globular clusters in Figure 1.4 fall below the Hβ strengths of the TMB03 models. As discussed in §1.2.3 above, this is due to a number of factors. TMB03 use the Worthey et al. (1994) fitting functions, taken from the Lick/IDS stellar library of absorption-line strengths, in which the atmospheric parameters are somewhat inhomogeneous, and which are constrained by very few stars at metallicities below $[\mathrm{Fe/H}] < -1.25$; this makes direct comparison with halo globular clusters problematic. Finally, it is possible that the TMB03 models may have problems with the RGB/AGB luminosity functions, although the Maraston (1998) synthesis method on which TMB03 is based uses the fuel-consumption theorem (Renzini & Buzzoni 1986), which should properly populate the luminosity functions.

1.3.2 The Globular Cluster Systems of Dwarf Galaxies in the Local Group

In Figure 1.5 I show the stellar populations for the globular cluster systems of three dwarf galaxies in the Local Group: the Large Magellanic Cloud (Beasley, Hoyle, & Sharples

* Figure 1.4 ignores the inner bulge clusters of M31, for which spectral indices are unavailable. It may be that those clusters have high metallicity (as the Milky Way bulge globulars have higher metallicity than the halo clusters), which would weaken this conclusion.

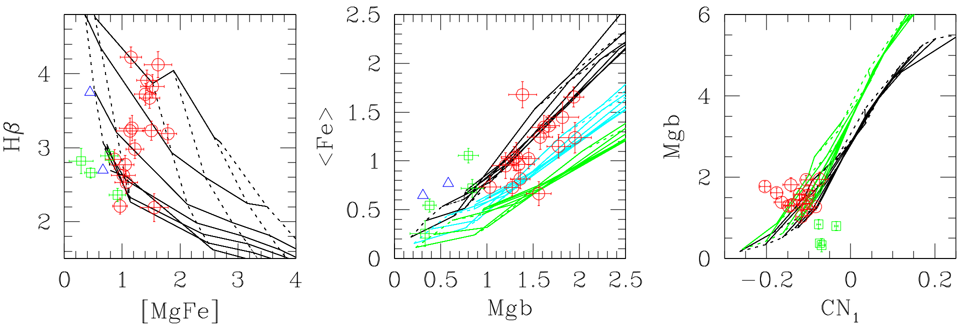

Fig. 1.5. The stellar populations of globular cluster systems of Local Group dwarf galaxies. Circles: LMC clusters from Beasley et al. (2002; for SWB classes IVB–VII only). Squares: Fornax dSph clusters from Strader et al. (2003a). Triangles: NGC 6822 clusters from Cohen & Blakeslee (1998; errors were not published). Panels and models as in Fig. 1.4. Note the CN anomaly in the Fornax dSph globular cluster system.

2002), the Fornax dSph (Strader, Brodie, & Huchra 2003b), and the dIrr NGC 6822 (Cohen & Blakeslee 1998; see also Chandar, Bianchi, & Ford 2000; Strader et al. 2003b). As shown previously by Rabin (1982), Beasley et al. (2002) find that the SWB sequence is indeed an age sequence, with the younger clusters being more metal rich. In fact, the LMC clusters represent the best training set we currently have for calibrating the stellar populations of intermediate-aged populations (Searle 1986), but the multivalued nature of the TMB03 model grids at very low metallicity (because of the blue horizontal branches) makes the old, metal-poor end difficult to calibrate without *a priori* knowledge of the horizontal branch morphology (Beasley et al. 2002). The [α/Fe] ratios of the LMC clusters—which are only slightly supersolar—do not seem to decrease appreciably with decreasing age, so possibly age and [α/Fe] are not tightly coupled (as is also seen for giant ellipticals, Trager et al. 2000b; Fig. 1.3). Moreover, the LMC clusters appear not to have a significant CN anomaly. The reasons for this are unclear, but may be related to the σ–[α/Fe] relation discussed below for early-type galaxies.

The two smaller dwarfs considered in Figure 1.5 have very metal-poor globular cluster populations. The clusters in Fornax are quite old and even show a CN anomaly of the sort present in the Galactic and M31 clusters—that is, the CN strengths are too high at fixed Mg *b* strength. The NGC 6822 clusters have a range of ages, with at least one old cluster (H VII) and a number of younger clusters (Cohen & Blakeslee 1998; Chandar et al. 2000; Strader et al. 2003b). Da Costa & Mould (1988) employed a method similar to Rabin's (1982) study to probe the stellar populations of the globular cluster systems of NGC 147, NGC 185, and NGC 205, comparing the equivalent widths of the Balmer lines with Ca II K. They found that the majority of the clusters were old, although both NGC 205 and NGC 185 have intermediate-aged clusters and NGC 205 has at least two metal-rich clusters similar to those in the Galactic bulge (see their Fig. 3). However, line strengths on the Lick/IDS system do not exist for these clusters, and direct comparison with the stellar populations derived from Figure 1.5 is not possible.

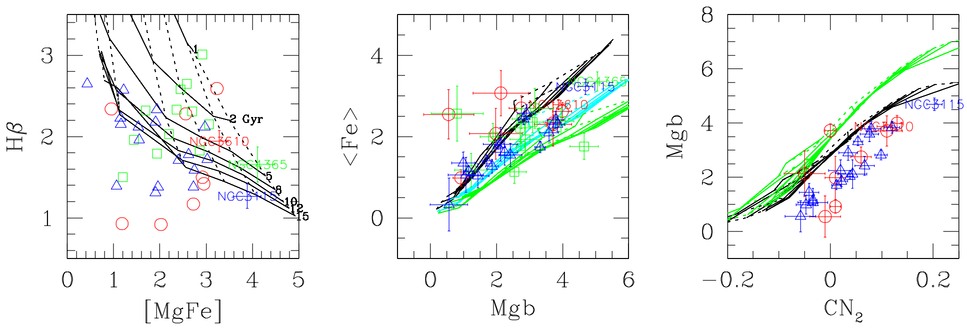

Fig. 1.6. The stellar populations of the globular cluster systems of nearby early-type galaxies. Panels and models as in Fig. 1.4. Triangles: NGC 3115 (Kuntschner et al. 2002). Circles: NGC 3610 (Strader et al. 2003c). Squares: NGC 4365 (Larsen et al. 2003; no CN data available). Host galaxies are labeled with their ID; data taken from Fisher et al. (1996; NGC 3115) or Trager et al. (1998; NGC 3610, NGC 4365). Cluster line-strength errors in the leftmost panel have been removed for clarity; typical errors are $\sigma_{\mathrm{H}\beta} \approx \sigma_{[\mathrm{MgFe}]} \approx 0.5$ Å (slightly smaller for NGC 3115). Note that the cluster systems of NGC 3115 and NGC 3610 apparently have a CN anomaly.

1.3.3 The Globular Cluster Systems of Nearby Early-type Galaxies

Although heroic early efforts were made using 4–5 m class telescopes (Racine, Oke, & Searle 1978; Hanes & Brodie 1986; Mould, Oke, & Nemec 1987; Mould et al. 1990; Brodie & Huchra 1991; Perelmuter, Brodie, & Huchra 1995; Jablonka et al. 1996; Minniti et al. 1996; Bridges et al. 1997), the era of measuring accurate stellar populations of the globular cluster systems of early-type galaxies began in earnest with the availability of multislit spectrographs on 8–10 m class telescopes. Kissler-Patig et al. (1998) and Cohen, Blakeslee, & Rhyzov (1998) studied NGC 1399 and M87, respectively, using the LRIS multislit spectrograph (Oke et al. 1995) on the Keck Telescopes. Cohen et al. (1998) studied the largest sample of extragalactic globular clusters around a single galaxy to date (150). Although the typical signal-to-noise ratio of these spectra is not as good as the most recent studies (e.g., Puzia et al. 2004), given the size of the data set, statistically significant conclusions about the stellar populations of the globular cluster system of an early-type galaxy could be drawn for the first time. In particular, $\sim 95\%$ of the clusters around M87 are old and can be classified into metal-poor ($[\mathrm{Fe/H}] \approx -1.3$) blue clusters and metal-rich ($[\mathrm{Fe/H}] \approx -0.7$) red clusters in a ratio of 2:3, thus resolving most of the debate about the cause of the bimodality in colors of globular cluster systems of early-type galaxies (e.g., Kundu & Whitmore 2001; Larsen et al. 2001). However, a small ($\sim 5\%$) population of intermediate-aged clusters can also be found in M87.

In Figure 1.6 I show recent results for the globular cluster systems of three early-type galaxies: NGC 3115 (Kuntschner et al. 2002), NGC 3610 (Strader et al. 2003c), and NGC 4365 (Larson et al. 2003), together with line strengths of their host galaxies (see figure caption for line-strength references). Although the error bars are large, the basic results of Cohen et al. (1998) are confirmed: there are generally three populations of globular clusters in early-type galaxies: (1) metal-poor, old, blue clusters, (2) metal-rich, old, red clusters, and (3) often small frostings of metal-rich, intermediate-aged, red(der) clusters (see also Puzia et al. 2004). This small frosting of intermediate-aged clusters may be a key to understanding the formation history of their host galaxies. A particularly interesting case is the globular cluster system of NGC 4365, as NGC 4365 has no evidence of having an intermediate-aged stellar population (Davies et al. 2001; Larsen et al. 2003; Fig. 1.6). It may be hoped that the multiple-population degeneracy of the Lick/IDS index system (Trager et al. 2000b) can be broken using globular clusters as tracers of individual star formation events in their host galaxies; such work is in progress (e.g., Larsen et al. 2003). Note also that these globular cluster systems also show a CN anomaly.

1.4 Early-type Galaxies and Bulges

The determination of the abundances and ages of galaxies is far more complex than for globular clusters, which are nearly all SSPs. Galaxies are composite stellar populations, and thus the interpretation of their spectra suffer from (currently) unavoidable difficulties. In particular, the absorption-line strength indices of composite populations are the luminosity-weighted sums of their SSP components. This means that young populations, which have low mass-to-light ratios, unduly bias the analysis of composite populations, if present (see, e.g., Trager et al. 2000b). However, in the absence of other knowledge (like the ages of the globular clusters possessed by the galaxy), line-strength indices only give the *SSP-equivalent* stellar population parameters for any individual galaxy. Therefore, I will proceed with a discussion of the abundances (and ages) obtained from modeling the integrated spectra of early-type galaxies and bulges as SSPs.

In Figure 1.3 I show the stellar populations of the nuclei of early-type galaxies (data from González 1993; Fisher et al. 1996; Kuntschner 2000; Trager et al. 2004) and spiral bulges (S0/a–Sbc; data from Proctor & Sansom 2002). Several results can be read directly from this figure.

(1) The nuclei of early-type galaxies and early-type spiral bulges have metallicities that range from just below solar to nearly 5 times the solar value.
(2) Field ellipticals, S0s in most environments, and early-type spiral bulges span a large range in Hβ over a reasonably small range in [MgFe], and therefore span a large range in SSP-equivalent age.
(3) Cluster *ellipticals* are typically coeval to a factor of ~ 2 in age and vary mostly in metallicity (Bower, Lucey, & Ellis 1992; Kuntschner 2000).
(4) Ellipticals typically have $[\alpha/\mathrm{Fe}] > 0$; $[\alpha/\mathrm{Fe}]$ is proportional to velocity dispersion but apparently not to age (Trager et al. 2000b).
(5) S0s are slightly more "solar" in $[\alpha/\mathrm{Fe}]$ than ellipticals. They also show a variation in $[\alpha/\mathrm{Fe}]$ with velocity dispersion (Fisher et al. 1996), although not as strong as that in ellipticals.
(6) Bulges of early-type spirals (S0/a–Sbc) are similar to field ellipticals in the distribution of their ages, metallicities, and $[\alpha/\mathrm{Fe}]$ ratios.

By analyzing correlations between the derived stellar population parameters, Trager et al. (2000b) found that the nuclei of elliptical galaxies (a) obey a $\log\sigma$–$[\alpha/\mathrm{Fe}]$ relation (point 3 above, and suggested earlier by Worthey et al. 1992) that may (Thomas, Maraston, & Bender 2002) or may not (Trager et al. 2000b) depend on age, and (b) occupy only a thin plane in $\log t$–$[Z/H]$–$\log\sigma$ space (the "Z-plane"), such that age and metallicity are anti-correlated with a slope $\partial\log t/\partial\log Z = -3/2$ at fixed velocity dispersion and metallicity increases with velocity dispersion at fixed age.

The $\log\sigma$–$[\alpha/\mathrm{Fe}]$ relation can be explained (Trager et al. 2000b) as either a varying IMF with galaxy mass—larger galaxies have "flatter" IMFs and therefore more high mass stars and therefore more Type II supernovae and therefore higher $[\alpha/\mathrm{Fe}]$ and, at fixed age, higher $[\mathrm{Z}/\mathrm{H}]$ (Worthey et al. 1992; Matteucci 1994)—or that smaller galaxies have more efficient, metal-enriched winds (Vader 1986, 1987), such that Type II supernovae products are lost more efficiently in these objects and so have lower $[\alpha/\mathrm{Fe}]$ at fixed Type Ia supernova yield, resulting in lower $[\mathrm{Z}/\mathrm{H}]$ at fixed age. In the latter case, a high $[\alpha/\mathrm{Fe}]$ is still required for massive ellipticals, so a very short star formation time scale (< 0.5 Gyr; Matteucci 1994) or a flattened IMF would be required for all elliptical galaxies.

A simple physical explanation for the Z-plane is more difficult to find. Multiple-burst population models seem to fit the data best, with small (1%–10%) bursts of recent (1–3 Gyr) star formation providing the enhanced Hβ strengths and suitably increased metallicities over a dominant (by mass) old population, but the modeling is not unique (Trager et al. 2000b). It is not yet clear if hierarchical merging models can reproduce this plane (Kauffmann & Charlot 1998). This plane has definite observational consequences. Because age and metallicity of elliptical galaxy nuclei are correlated at fixed velocity dispersion with a slope of 3/2, which preserves constant broad-band optical color and metal-line indices (§1.2.1), the Mg–σ relations (e.g., Mg_2–σ) are actually edge-on projections of this plane and therefore are *not* good indicators of a physically significant mass-metallicity relation (Faber 1977; Colless et al. 1999). In fact, *there is no mass-metallicity relation* in the SSP-equivalent populations of *field* elliptical galaxies; however, there *is* such a relation for the roughly coeval and presently old *cluster* elliptical galaxy population.

Although multiple ages in a population are hard to recover, the *light-weighted mean metallicity* is measured quite well from an integrated spectrum. An appendix in Trager et al. (2000b) demonstrates the calculation based on the CMD of the top of the RGB of M32 at $r \approx 1.5r_e$ (Grillmair et al. 1996) and extrapolated absorption-line strengths from $r \approx r_e$ (González 1993). The light-weighted metallicity from the CMD assuming a population between 8 and 15 Gyr old is $[\mathrm{Z}/\mathrm{H}] = [\mathrm{Fe}/\mathrm{H}] = -0.25$ dex; from the line strengths, a Worthey (1994) model (which uses the same isochrones) gives $[\mathrm{Z}/\mathrm{H}] = [\mathrm{Fe}/\mathrm{H}] = -0.32$ dex. A similar (though purely theoretical) calculation for $[\alpha/\mathrm{Fe}]$ suggests that light-weighted abundance ratios are also measured quite reliably from integrated spectra.

Finally, by examining line strengths other than Mg$\,b$ and $\langle\mathrm{Fe}\rangle$, other elemental abundances beside the rather generic $[\alpha/\mathrm{Fe}]$ are coming under scrutiny. Saglia et al. (2002), Cenarro et al. (2003), and Falcón-Barroso et al. (2003) have studied the Ca II triplet at 8600 Å in early-type galaxies and bulges and found that stellar population models (from either TMB03 or Vazdekis et al. 2003) overpredict the strength of the CaT* index by as much as 1.5 Å if $[\alpha/\mathrm{Fe}]$ is set to the level suggested by Hβ, Mg$\,b$, and $\langle\mathrm{Fe}\rangle$, and calcium is included with the α-elements. This suggests that either the IMF is significantly *steeper* than previously, assumed to include more dwarf stars (cf. the discussion about Na D earlier), in conflict with the mass-to-light ratios of the galaxies (Saglia et al. 2002), or that calcium does not act as an α-element in early-type galaxies and bulges (Worthey 1998; Trager et al. 2000a). This latter suggestion has recently been reinforced by Thomas, Maraston, & Bender (2003b), who examined the Ca4227 index (centered on the Ca II λ4227 line) of ellipticals from the Lick/IDS sample (Trager et al. 1998) and found that this index also required Ca to track Fe. More exactly, Thomas et al. required $[\alpha/\mathrm{Ca}] = +0.2$ for giant ellipticals, decreasing as velocity dispersion decreased. Therefore, giant galaxies are Ca underabundant. In fact, the

Ca underabundance is nearly that of the Fe underabundance, $[\mathrm{Fe}/\alpha] = -[\alpha/\mathrm{Fe}] = -0.3$, so $[\mathrm{Ca}/\mathrm{Fe}] < +0.1$ in elliptical galaxies.

1.5 Summary

I conclude this review with an overview of the state of the art in determining the abundances and ages of globular clusters, early-type galaxies, and the bulges of spirals from integrated-light spectra. I then discuss the present difficulties we have with stellar population models and their application. I finish with a hint of what is to come in the immediate future.

1.5.1 The Current State of Play

It is now possible to determine accurately and precisely the age, metallicity, and abundance ratio $[\alpha/\mathrm{Fe}]$ of a simple stellar population—one that has experienced only a single burst of star formation—from its integrated spectrum. We can therefore probe the stellar populations of globular clusters, including those around other, distant galaxies, with confidence. In Local Group galaxies, various researchers have used this technique to determine that the mean metallicity of globular cluster systems correlates with the mass of the host galaxy. The stellar content of many clusters too distant to resolve without adaptive optics or a large space telescope have been probed and the rough chemical compositions characterized. Overly strong CN lines, apparently indicative of N enhancements, have been detected in the Galactic, M31, and Fornax globular cluster systems, but not in the LMC. The stellar populations of the globular cluster systems of early-type galaxies can now be studied in detail, and the bimodality of globular cluster colors is now resolved into *three* populations: blue, old, metal poor and red, old, metal rich, which together dominate the cluster populations, and a frosting of red, intermediate-aged, metal-rich clusters. The CN anomaly is also present in these systems (Fig. 1.6), and so seems an *almost* generic property of globular cluster stellar populations, except in the LMC.

For more complex star formation histories, we can at present only parameterize this history as three (or five) numbers without additional information: the SSP-equivalent age, metallicity, and $[\alpha/\mathrm{Fe}]$ (and now $[\alpha/\mathrm{Ca}]$ and $[\mathrm{N}/\alpha]$; TMB03). However, that parameterization is a useful one, and much progress has been made using this simplistic approach. Field ellipticals, S0s in many environments (except possibly in the richest clusters), and spiral bulges span a large range in SSP-equivalent age. Cluster ellipticals, on the other hand, are typically coeval to within a factor of 2 in age. SSP-equivalent metallicities of the nuclei of early-type galaxies and spiral bulges range from just below solar to nearly 5 times solar. At fixed velocity dispersion (mass), age and metallicity are correlated in such a way as to preserve constant broad-band optical color and metal-line strength; this makes the interpretation of the optical color-magnitude and Mg–σ relations of local early-type galaxies problematic. There *is* a mass-metallicity relation for early-type galaxies *at fixed age*, which manifests itself primarily in cluster galaxies. I note here that line-strength gradients (González 1993; Fisher et al. 1996) suggest that early-type galaxies globally follow the same relations, with lower metallicity and older ages (cf. Trager et al. 2000a). Early-type galaxies and spiral bulges typically have Fe-deficient (“α-enhanced”) stellar populations. The value of this deficiency, $[\alpha/\mathrm{Fe}]$, is well correlated with velocity dispersion. S0 galaxies are slightly more “solar” than giant ellipticals, where $\langle[\alpha/\mathrm{Fe}]\rangle = +0.2$; bulges seem to follow the elliptical track, although the sample of bulges available is still small. Finally, work is progressing on tracking the abundances of other elements, including Ca, which seems to track Fe rather than the α-elements in elliptical galaxies.

1.5.2 Continuing Annoyances

Of course, although we have come a long way toward precision stellar populations, there are several significant issues still outstanding. Here are three.

Oxygen abundance The oxygen abundance controls the temperature of the MSTO (e.g., Salaris & Weiss 1998), but no direct measure of [O/Fe] is available in the optical. Might the OH bands in the near-infrared be exploited for this purpose?

Blue horizontal branches The presence or not of blue horizontal branch stars have been a continuing thorn in the side of those who analyze metal-rich stellar populations (e.g, Trager et al. 2000a). They apparently exist in dense, metal-rich clusters (Rose & Tripicco 1986; Rich et al. 1997), but the evolutionary path by which they appear in those clusters is unknown and therefore cannot yet be included in stellar population models. There is also the question of the importance of very metal-poor populations underlying the metal-rich populations that dominate the light (Rose 1985; Maraston & Thomas 2000). However, Rose (1985) showed that the strong Balmer lines in elliptical galaxies must be dominated by the light from dwarf stars, not giants. This, however, is not true in globular clusters, as seen in Figure 1.4.

Blue straggler stars Given their colors and luminosities, these stars might be another significant worry, confusing age determinations (Rose 1985; Trager et al. 2000a). Again, an evolutionary path for these stars is not yet clear, and therefore they have not appeared in evolutionary syntheses. However, Rose (1985) found little evidence of such stars in his study of the blue line strengths of local elliptical galaxies.

1.5.3 Present and Future Directions

The future for this subject seems bright. Large surveys, such as the Sloan Digital Sky Survey, are beginning to use this method for studying the typical stellar populations of 10^5 galaxies (Bernardi et al. 2003; Eisenstein et al. 2003), although calibrations onto a well-calibrated and well-modeled system are not yet available. Two-dimensional spectroscopy using instruments like SAURON (Davies et al. 2001; de Zeeuw et al. 2002) are now examining the spatial distribution of the stellar populations of early-type galaxies and bulges and combining this information with kinematics. Spectral synthesis of galaxies (beginning with Vazdekis 1999) and principal-component analyses of spectra (e.g., Heavens, Jimenez, & Lahav 2000; Reichardt, Jimenez, & Heavens 2001; Eisenstein et al. 2003) are now coming over the horizon. Finally, several groups are pushing these techniques out to $z \approx 1$ (Kelson et al. 2001; Trager, Dressler, & Faber 2004), which will allow for the direct detection of the evolution of old stellar populations.

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