TESTS OF CHEMICAL ENRICHMENT SCENARIOS IN ELLIPTICALS USING CONTINUUM COLORS AND SPECTROSCOPY

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Received 2008 July 21; accepted 2008 October 21; published 2008 December 19

ABSTRACT

We combine spectroscopic metallicity values with integrated narrowband continuum colors to explore the internal metallicity distribution in early-type galaxies. The different techniques for determining metallicity (indices versus colors) allow for an estimate of the contribution from metal-poor stars in a predominantly metal-rich population, which, in turn, places constraints on the shape and width of a galaxy’s metallicity distribution function. The color-spectroscopic data are compared with the closed box, infall, and inhomogeneous chemical evolution models. The G-dwarf problem, a deficiency in metal-poor stars as compared with closed-box models, is evident in the data set and indicates that this deficiency is common to all early-type galaxies. However, even simple infall models predict galaxy colors that are too blue compared with the observations. A simple analytical model is proposed that matches the elliptical data and recent Hubble Space Telescope observations of M31 and NGC 5128 by reducing the number of metal-poor stars in a systematic fashion. Without physical justification, the shape of these models is similar to predictions of inhomogeneous enrichment scenarios.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: stellar content

1. INTRODUCTION

The chemical history of galaxies has been a key astrophysics issue since the discovery that our own Galaxy is separated into kinematically distinct regions by metallicity (Baade 1944; Gilmore et al. 1989). Due to the process of enrichment by supernova (SN) and asymptotic giant branch (AGB) mass loss, plus a star formation rate that is extended in time, the metallicity distribution function (MDF) in a galaxy evolves with time such that the canonical view of galaxy evolution is that the enrichment process continues to increasingly higher yields until the onset of a galactic wind (powered by SN input) halts the star formation (Matteucci 2007). Thus, the MDF of stars becomes a map of past galaxy evolutionary mechanisms.

For nearby galaxies, a direct examination of the color–magnitude diagram (CMD) provides the clearest view of chemical evolution (Dolphin 2002; Skillman et al. 2003; Harris & Zaritsky 2004; Grebel 2004). Fortunately, the section of the CMD most sensitive to metallicity effects is the red giant branch (RGB), which is the brightest part of a galaxy’s CMD and visible to the largest distances. This situation differs from methods to determine a galaxy’s age, which are dependent on measurements of the fainter turnoff portion of the CMD.

For more distant galaxies, we are forced to deduce the metallicity of the underlying stellar population by comparison of colors or spectral indices interpreted by spectroscopic evolutionary distribution (SED) models. Unfortunately, this type of analysis produces only a luminosity-weighted, mean metallicity, although there can be some spatial information (i.e., color gradients). Color information does not resolve the shape of the metallicity distribution, which is a critical piece of information in order to test the type of chemical evolution that a galaxy has undergone.

In the last decade, a series of new techniques to investigate the metallicity of stellar populations in galaxies allowed for the possibility of extracting some limited information on the shape of the MDF in ellipticals. It has been noted by several studies that the colors of ellipticals are extremely uniform (Smolčić et al. 2006) yet cannot be matched with a SED model that is composed of a single metallicity stellar population (Rakos et al. 2008). In addition, their colors, as compared with SED models, indicate a contribution from a bluer (i.e., possibly metal-poor) component (Worthey et al. 1996; Rakos et al. 2008), in line with expectations from the MDF of stars in nearby galaxies.

To resolve the effect of a metal-poor population on galaxy colors requires a model of the MDF plus SED spectra of each metallicity bin to sum into an integrated color. In addition, an independent measure of metallicity is required to distinguish the observed value of the colors from the colors presented by a population of singular metallicity. Fortunately, just such a measurement of $\langle \text{Fe/H} \rangle$ exists from spectroscopic studies, the ($\text{Fe}$) index. This index has the advantage of skipping the need for SED models (although an MDF will produce a luminosity-averaged value of $\langle \text{Fe} \rangle$) and directly measures the abundance of Fe. Since Fe is the primary contributor to line blanketing on the RGB, it is also the primary link to color changes in galaxies from metallicity effects.

The goal of this project is to take advantage of the different manners in which metallicity is determined in galaxies (i.e., colors versus spectroscopy) to deduce the basic shape of the MDF in early-type galaxies. To achieve this goal, we will require a series of predicted MDFs, given by various chemical evolutionary scenarios, combined with SED models to calculate the expected galaxy colors. Thus, we will first examine the quality of the current generation of SED models with respect to globular cluster colors and metallicity for a set of special narrowband and near-IR (NIR) filters (a modified Strömgren system; Rakos & Schombert 1995). Second, we will present a subset of galaxies from spectroscopic studies where we have matching narrowband colors, and explore the behavior of color versus (Fe) for this sample. Lastly, we will compare the resulting [M/H] versus color plane with respect to the predictions of various chemical evolution scenarios (such as closed box, infall, inhomogeneous) in order to determine which scenario most closely matches the data.
2. ANALYSIS OF SED MODELS

In order to interpret the global colors or line indices in galaxies, one needs (1) a star formation history model, which includes not only a star formation rate but a chemical enrichment model so that a present-day galaxy is characterized by the sum of light from stars with a range of age and metallicity plus (2) accurate SEDs for each stellar population of a particular age and metallicity. Clearly, we wish to deduce the star formation history of a galaxy by first determining the present-day mixture of internal stellar populations parameterized by their mean age and metallicity. These stellar populations have unique luminosities by mass, which can be summed to determine the total color (or luminosity-weighted line index) for the galaxy.

The first step in unraveling the underlying populations in galaxies is to test the predictions of the various SED models in the literature against systems where we have detailed knowledge of the age and metallicity of the stars (i.e., stellar clusters). The SED models take on the simplest assumptions, a single burst resulting in a population with a single value for their age and metallicity ([M/H]), a so-called single stellar population (SSP). Their direct comparison with galaxy colors is problematic as resulting in a population with a single value for their age and metallicities. These stellar populations have unique luminosities by mass, which can be summed to determine the total color (or luminosity-weighted line index) for the galaxy.

There have been numerous SED models published in the literature since the earliest attempts to model galaxies (Faber 1972; O'Connell 1976; Pickles 1985). Our own narrowband photometry work (Rakos et al. 2008) has focused on the Bruzual & Charlot (2003; hereafter BC03) models and the models from the Gottingen group (Schulz et al. 2002). The choice of these two groups was for convenience as we used the original Bruzual & Charlot models for our study of distant clusters (Rakos & Schombert 1995), and we later switched to the Gottingen models since they published Strömgren colors (uvwby) that were easy to transform into our modified Strömgren system (uz, vz, bz, yz).

The adoption of the latest stellar tracks from the Padova group (Girardi et al. 2000) by both BC03 and Schulz et al. has rendered their models to be nearly identical with only minor differences in resulting colors and line indices. Thus, for the remainder of this paper, we will use the model tracks from BC03 for our analysis and only note the differences between the BC03 and Schulz et al. models where relevant.

For this work, we have selected a fairly standard range of models with an age of 12 Gyr and [Fe/H] from −2.3 to +0.4, all using the Chabrier (2003) IMF (mass cutoff at 0.1 and 100 M⊙) and Padova 2000 isochrones. Each SSP is interpolated at the 0.1 dex level in metallicity and convolved to our narrowband filters to produce a full grid of colors. These SSPs are then convolved into our various metallicity distribution models as will be discussed in a latter section.

2.1. Comparison of SSP Models with Globular Clusters

There do exist stellar systems that closely resemble the narrow conditions of an SSP, the globular clusters of our own Galaxy (hereafter GCs). Their limited range of internal metallicity and age, as determined from detailed studies of their CMD, indicates a constant metallicity to within Δ[Fe/H] < 0.2 and spread in an internal age of less than 1 Gyr (Bruzual 2002).

A first test to the accuracy of an SED model is to match to the isochrones of globular clusters, for which the modern formulations in the literature are all adequate (see the analysis in Schiavon 2007). The second is to match the integrated colors of SSPs to colors of globular clusters. With respect to the BC03 models, there is an excellent discussion of the model fits, as compared with broadband colors, in Bruzual (2002).

As our work deals with integrated narrowband colors, we have collected a sample of 32 GCs with high-quality narrowband colors (uz, vz, bz, yz; Rakos & Schomber 2005) and combined this sample with a subset of GCs with NIR colors from Cohen et al. (2008). The resulting six color–color diagrams are shown in Figure 1 along with the SSP models of BC03 for an age of 12 Gyr. The change in color is solely due to the changes in metallicity ([Fe/H]) as the range of age for GCs is less than 2 Gyr (Salaris & Weiss 1998), and there is a negligible change in the SSP models for this age range. Note that uz, vz, bz, and yz differ from the normal Strömgren (uvby) system in the sense that the filters are slightly narrower (by 20 Å) and the uz filter is shifted 30 Å to the red in its central wavelength as compared with the original system. The uz, vz, bz, and yz system covers three regions in the near-UV and blue portion of the spectrum. The first region is longward of 4600 Å, which under the influence of absorption lines is small. This is characteristic of the bz and yz filters (λ_eff = 4675 Å and 5500 Å). The second region is a band shortward of 4600 Å, but above the Balmer discontinuity. This region is strongly influenced by metal absorption lines (i.e., Fe, CN) particularly for spectral classes F to M, which dominate the contribution of light in old stellar populations. This region is exploited by the vz filter (λ_eff = 4100 Å). The third region is a band shortward of the Balmer discontinuity or below the effective limit of crowding of the Balmer absorption lines. This region is explored by the uz filter (λ_eff = 3500 Å).

The scatter in optical and NIR colors is relatively large considering the photometric accuracy of the observations. However, this is not a statement concerning the quality of the models but rather an observation effect due to the stochastic aspect of stellar light from GCs. While a GC may be composed of over 10^5 stars, the stars at the tip of the AGB and horizontal branch (HB) dominate the integrated light and, therefore, small variations in the number of these stars can dramatically alter the measured colors (see an excellent discussion of this effect in BC03). Given this stochastic scatter, the models display a good match with the GC colors. The only serious discrepancy is found in the J − K color, for reasons that are not immediately apparent. The clearest correlation in color is found between our two optical colors (vz − yz, bz − yz) and the NIR V − K color. These are the three colors most sensitive to metallicity changes and it is not surprising to find them strongly correlated.

The correlations between color and metallicity are shown in Figure 2, plots of color versus [Fe/H]. For consistency, we have adopted a calibration from the total metallicity ([M/H]) from [Fe/H] based on the Padova 2000 tracks (Girardi et al. 2000; discussed in BC03). From these plots, it is clear that colors in the near-UV region of the spectrum are degenerate with respect to metallicity. NIR colors are well fitted by the models, but have shallow slopes at low metallicities making their use problematic. The steepest slopes are seen in vz − yz and bz − yz, with the tightest correlation found for vz − yz. This confirms what we have learned in our earlier studies on the uniformity in color for ellipticals and the correlations with galaxy mass (i.e., the color–magnitude relation; Odell et al. 2002). As our previous work on the age and metallicity of ellipticals has demonstrated (Rakos et al. 2008), the range of age in ellipticals is very limited and the majority have mean ages greater than 10 Gyr. For these ages, vz − yz is strictly a measure of metallicity and, thus, becomes our
primary tool for determining metallicity in SSP systems (such as GCs) and composite systems (such as S0s and ellipticals). This will be discussed further in Section 3.

### 2.2. Composite Stellar Populations

Galaxies are known to be composed of more than a single stellar population (i.e., single age and metallicity). This is clearly the case for the Milky Way, based on studies of nearby stars (Twarog 1980). And metallicity gradients in ellipticals demonstrate that they too are composed of stars with a range of metallicities (Sánchez-Blázquez et al. 2006). With respect to integrated optical and NIR colors, ellipticals have colors that are clear extrapolations from SSP colors, such as galactic globulars, but have significant differences that demonstrate that they are composed of stars with a range of metallicities. For example, the mid-ultraviolet region of an elliptical’s spectra is best modeled by an old, metal-rich plus smaller, old, metal-poor population (Bressan et al. 1994; Rose & Deng 1999; Lotz et al. 2000).

This composite color effect is best seen in Figure 3, a plot of our optical $v_z - y_z$ and $b_z - y_z$ colors and the NIR color $V - K$. The globular cluster data from Figure 2 are replotted along with BC03 12 Gyr SSP models, a good match to the GC data. Also shown are the colors of 50 bright ellipticals in the core of the Coma cluster. The optical colors for the Coma sample are derived from Odell et al. (2002) and the NIR colors for the same galaxies are taken from Eisenhardt et al. (2007). While the SSP models are a good fit to the GC data, they do not fit the elliptical colors. The deviations from an SSP model are such that ellipticals have $v_z - y_z$ colors that are slightly bluer than single metallicity models (Rakos et al. 2008). This is exactly what one would expect by ignoring the contribution of low-metallicity stars, and a simple model that considers a range of metallicities is shown as a dashed line in Figure 3. A slightly younger SSP (7 Gyrs in Figure 3) would match the optical colors, but would fail to match the NIR colors. While this simple composite model will be discussed in greater detail below, it demonstrates that elliptical colors are best explained by a composite of underlying metallicities, an obvious conclusion based on population studies of our own Galaxy.

Decoding the color of galaxies requires a map of the ages of the stellar populations and their metallicity distribution (as a
function of age). For the purposes of this initial examination of a galaxy’s underlying metallicity distribution, we will assume that all the color change in their integrated luminosity is solely due to metallicity effects. There are many reasons to believe that a majority of the stars in ellipticals are old (τ > 10 Gyr), ranging from the tight correlation of the color–magnitude relation to the red envelope in high-redshift studies of clusters. In a parallel paper (J. Schombert & K. Rakos 2009, in preparation), we present a detailed analysis of spectroscopic determination of galaxy ages as it impacts on the observed color properties of ellipticals, that is, the color–magnitude relation (CMR). Spectroscopic studies find a high fraction of ellipticals with ages less than 7 Gyr (see review by Schiavon 2007); however, these ages are in conflict with the colors of early-type galaxies. Detailed comparison with the CMR demonstrates that early-type galaxies with ages less than 7 Gyr are rare and we have ignored galaxy age from our analysis.

2.3. Chemical Evolution Models

In order to model galaxy-integrated colors, we will need to combine the predicted colors from the SED models with a model of the internal metallicity distribution, the so-called MDF (Pagel 1997). The mean metallicity, Z, of a galaxy will then be a luminosity-weighted sum of the contribution from a continuum of metallicities. And it is expected that the peak Z-value will vary with the position in the galaxy (i.e., gradients) and with the mass of the galaxy, such that higher mass galaxies process more material before the onset of galactic winds overcomes their gravitational potentials to halt star formation and further enrichment.

There are only few galaxies with actual MDFs measured from Hubble Space Telescope (HST) imaging of the tip of the RGB. The most relevant examples of this study are the old populations in M31 (Worthey et al. 2005) and the nearby elliptical NGC 5128 (Harris & Harris 2000). Both studies display MDFs with several features in common: (1) a well-defined Gaussian-like peak, (2) a long tail to low metallicities, and (3) a sharp cut-off on the high-metallicity side. Both galaxies display a lower metallicity peak with increasing radius from the galaxy center (i.e., metallicity gradients). This results in a narrower MDF at lower peak metallicities.

The simplest model of chemical evolution to produce a MDF is, of course, the closed-box enrichment scenario (van den Bergh & Henry 1962). This scenario assumes no infall or outflow of gas, and the metallicity of the stars increases in yield with every epoch of star formation. The solution for this model is analytical and displayed in Figure 4.

A well-known problem for a closed-box model is that it overestimates the number of low-metallicity stars ($Z/Z_\odot < 0.3$), the so-called G-dwarf problem (Gibson & Matteucci 1997). This overestimation occurs not only for stars in the local solar neighborhood (van den Bergh & Henry 1962; Schmidt 1963), but also in the MDFs in nearby galaxies (Sarajedini & Jablonska 2000).
The standard solution is to allow for a nonzero initial abundance for the gas that produces the first generation of stars or a prompt enrichment mechanism. A simple shift of initial abundance has been demonstrated to be a poor fit for M31 and other nearby galaxies (Harris & Harris 2000; Sarajedini & Jablonka 2005); however, an accreting box scenario (a relaxation of the infall constraint; Harris & Harris 2000, dashed line) has been more successful and also lends itself to an analytical solution. For comparison with these models, we have replotted the inner MDF of NGC 5128, a nearby elliptical (Harris & Harris 2000) in Figure 4. Neither of these two models is a particularly good match to the data.

A more recent model is given by an infall scenario (Kodama & Arimoto 1997). This model has the advantage of linking the accretion rate to the star formation rate, a more physically realistic scenario, and yielding a constant gas mass. This model is shown in Figure 4, but also suffers from an overabundance of metal-poor stars as compared with observations. Adjustments to lower the number of metal-poor stars only result in an overproduction of metal-rich stars, although the general shape of the infall MDF follows the trend of the data. This is primarily due to the instantaneous mixing assumption for these models, which smoothes the production of metals overspace and time allowing for more metal-poor stars. In reality, one would expect regions of high metallicity to form, which would produce a fast enrichment sequence.

The G-dwarf problem led us to consider a modification to the infall or accreting models in a completely artificial fashion to match the MDF in NGC 5128. This modification, which we call the “push” model, is a simple reduction of the low-metallicity end of the infall model. To perform this reduction, we adopt an infall model’s shape, a peak metallicity with a high-metallicity cutoff, and a long low-metallicity tail. This metallicity distribution’s peak [Fe/H] is adjusted to alter the total mean metallicity. Our push model artificially reduces the low-metallicity end of this distribution, simply by a linear reduction while keeping the total normalization constant (i.e., we push down the number of low Z stars per mass bin).

For our experiments herein, adequate fits to the data were obtained with less than a 30% reduction of the low-metallicity side.

There is no direct theoretical or model support for our push model (although it forces a relaxation of the instantaneous mixing assumption); it is simply done to explore the effect of fewer low-metallicity stars on the integrated colors. However, we note that the shape of the push model reproduces the MDFs produced by inhomogeneous enrichment models (Malinie et al. 1993; Oey 2000), where star formation occurs in discrete patches throughout a galaxy and is only allowed to mix between star-formation episodes. This increases the amount of mixing and results in fewer metal-poor stars. As we can see in Figure 4, this type of model (with a 30% reduction of metal-poor stars) produces the best “French curve” through the NGC 5128 data. Although our push model lacks a physical foundation, we note that the inhomogeneous models also lack any simple parameterization that relates to known galaxy properties and has a large number of unconstrained variables.

3. [Fe/H] DETERMINATION FROM THE (Fe) INDEX

As stated in Section 1, the power-to-line index measurements (e.g., the Lick/IDS system) are direct determinations of an element’s abundance. One of the clearest measures of global metallicity, as outlined in Trager et al. (2000), is the ⟨Fe⟩ index, the numerical average of the Fe 5270 and Fe 5335 lines. This feature measures Fe, C, Mg, Ti, and Si and, thus, will be mildly sensitive to changes in the ratio of α elements to Fe. However, for the samples we have chosen (see below), the variation in α/Fe is small and will be ignored.

The ⟨Fe⟩ index has been used by numerous studies of metallicity and age in galaxies, but we have selected our sample, for comparison with our narrowband colors, from three studies of early-type galaxies: Trager et al. (2000), Poggianti et al. (2001), and Thomas et al. (2005). Our choice of these data sets is for a number of practical reasons. One of them is that the Trager et al. work was a clear and strong step forward in the use of the Lick/IDS system for galaxy work and sets the standard for age and metallicity determination in that spectral system. The Poggianti et al. study was on Coma cluster galaxies where we have matching narrowband and NIR colors (Rakos et al. 2008). The Thomas et al. study is one of the most recent, and largest, works with published ⟨Fe⟩ values. The total sample contains 185 galaxies of which we have matching color data for 119 galaxies. For the remaining 72 galaxies, we have estimated their vz − yz colors using their absolute M5500 luminosity and the CMR (Odell et al. 2002), although their exclusion from the analysis does not change our results.

The resulting plot of log ⟨Fe⟩ versus metallicity color (yz − yz) is shown in Figure 5. Also plotted are the BC03 SSP models for ages of 4 and 12 Gyr. What is immediately obvious from this plot is that a majority of the metallicity data lies above and/or to the left of the SSP models. As the SSP models accurately match the globular cluster color and metallicities, we might at first interpret the difference in Figure 5 as due to the composite nature of elliptical stellar populations. However, this diagram only implies, logically, that ellipticals are either (1) bluer in vz − yz color per metallicity value or (2) more metal-rich per integrated color bin. And these regions of the color–metallicity diagram could be occupied for various star-formation reasons.

For the first option, a bluer vz − yz color can be derived at a constant metallicity by a younger mean population, that is, less than 4 Gyr in age. We discuss the impact of younger stars in a latter paper (J. Schombert & K. Rakos 2009, in preparation); however, to summarize that work, in order to match the color values in Figure 5, the mean age of the entire underlying stellar population in a majority of ellipticals would be required to be less than 2 Gyr. This is extremely young for a total stellar population (although there may be small numbers of young stars in ellipticals; see Trager et al. 2000) and is not apparent in any other color system or spectral indicator. In addition, it would imply that a majority of ellipticals in intermediate redshift clusters (0.3 < z < 0.7) have star-forming colors, which is clearly not seen (Rakos & Schombert 1995).

The other logical option is that the metallicity indicator ⟨Fe⟩ simply measures a different quantity in galaxies than the integrated color vz − yz, in this case a higher metallicity than indicated by the integrated color. This might be true due to the geometry of the data sampling, as spectral values are based on core luminosities whereas the metallicity color, vz − yz, is based on the total galaxy light. Strong metallicity gradients would result in a noticeable difference for metallicity values determined by core light versus halo light. In addition, composite populations of varying metallicities may sum up in differing ways for ⟨Fe⟩ versus color (i.e., in particular, the contribution from hot BHB stars or a metal-poor MS turnoff
A key difference between line index studies and color work is observational in that line indices, using the Lick/IDS system, are determined by the smaller angular-sized slit or fiber spectroscopy. The typical slit sizes are such that a line index measurement of a particular galaxy is going to be confined to the central regions. Thus, due to the geometry of the observational technique and the fact that spectroscopic data are surface brightness weighted, the galaxy light obtained by line index studies will be heavily weighted toward the core regions. Since early-type galaxies have clear color gradients (Sánchez-Blázquez et al. 2006), which are known to be primarily due to metallicity gradients, this leads to the possibility that line index values are biased toward higher metallicity values. Thus, the comparison of line index values with global colors, those determined by the average metallicity as given by the entire luminosity of the galaxy, may be invalid.

While it seems obvious that some bias toward higher metallicity values exists in line index studies, the amount of bias is unknown and may be negligible. Certainly, as color gradients are known to be small in early-type galaxies (Sandage & Visvanathan 1978; Peletier et al. 1990; Schombert et al. 1993), there is an expectation that with sufficient areal coverage (e.g., over 1/3 an effective radius), the difference between a global metallicity value and that determined from spectroscopy will be small.

In order to estimate the metallicity bias for spectroscopic work due to an aperture correction, we consider the Coma observations of Poggianti et al. (2001) described in Mobasher et al. (2001). These data were taken with a fiber spectrograph with 2.7 arcsec slits (for comparison, Sloan Digital Sky Survey (SDSS) uses 3 arcsec fiber diameters). At the redshift of Coma, this corresponds to a diameter of 1.2 kpc. For an L* galaxy, the light measured through this aperture corresponds to approximately one-third the total light of the galaxy. This will be less for brighter galaxies (larger effective radii) and more for lower luminosity galaxies resulting in a variation of about 20% for the luminosity range given by the Poggianti et al. sample.

With the existence of color gradients, this smaller fraction of total light measured by fiber slits will also contain a redder (more metal-rich) stellar population. Using the color gradients for our narrowband color, \( v_z - y_z \) (Schombert et al. 1993), we find that gradients take on a range of values. Galaxies with strong gradients (e.g., NGC 4374) have values of \( \Delta (v_z - y_z)/\Delta \log r = -0.15 \). Galaxies with weak gradients (e.g., NGC 7562) have values near \(-0.05\). This results in differences for mean color between the core luminosity seen by slits and total color as \(+0.09\) for strong gradients to \(+0.03\) for weak gradients. Converting this color difference into [Fe/H] (using BC03 12 Gyr SSPs) leads to [Fe/H] values being 0.25–0.09 dex higher for spectroscopic measurements compared with values deduced from a galaxy’s total light. Thus, on average, the Lick/IDS values need to be lowered by approximately 0.15 dex to represent the mean [Fe/H] of a galaxy as a whole, which corresponds to a change of 0.04 in the \( \log (Fe) \) index.

**5. MULTIMETALLICITY POPULATION CORRECTION TO [Fe/H]**

A second correction to consider is that the value measured by colors is, of course, a luminosity-weighted integrated value. Comparison with models has always assumed that the underlying stellar population is simple (i.e., SSP). There is every expectation that this is false based on any chemical enrichment models, which predict a spread in the metallicity. In addition, HST imaging has demonstrated broad MDFs in nearby galaxies (Worthey et al. 2005).

Again, using the SED models from BC03 combined with an infall scenario of chemical enrichment (Kodama as described in Yi et al. 1998), we can estimate the difference between the numerical-averaged [Fe/H] (actual sum of the metallicities of the stars) versus the luminosity-weighted value, \( [Fe/H] \). A series of simulations were run using this formula where the only variable in this simulation is the peak \( [Fe/H] \), which is allowed to vary from \(-2.5\) to \(+0.5\). The shape of the MDF is fixed, starting at \([Fe/H] = -2.5\) and linearly adjusted to the peak \([Fe/H] \). This MDF is then convolved with the SED models to produce colors for a composite stellar population (CSP). The output values from the CSP model are the luminosity weighted \( [Fe/H] \), what one would measure from the integrated light and the actual numerical average metallicity, \( [Fe/H] \), from the sum of the stars by mass. For an SSP, or stellar population with a very narrow range of metallicities, these values would be equivalent. But for a stellar population with a wide range of metallicities (in particular, a long low-metallicity tail), each metallicity bin contributes a slightly different luminosity per mass (higher for lower \([Fe/H] \) values) and, thus, the resulting observed \([Fe/H] \) value does not match the actual underlying metallicity of...
the population by mass. Since a metal-poor population is more luminous than the metal-rich population by mass, a luminosity-weighted value of \([\text{Fe}/\text{H}]\) will underestimate the true value (Arimoto & Yoshii 1987).

A series of conclusions were reached by comparing the values of a luminosity-weighted metallicity with those of the actual metallicity by a stellar number. First, the exact shape of the MDF has little effect on the correlation between average \([\text{Fe}/\text{H}]\) and the luminosity-weighted \((\text{Fe}/\text{H})\) as long as there is a low-metallicity component to the model. Second, a metal-poor tail is a requirement to the model as any distribution without a metal-poor component failed to match the galaxy colors (e.g., the CMR). Third, the relationship between the actual mean \([\text{Fe}/\text{H}]\) and the luminosity-weighted (i.e., observed) metallicity is linear and easy to calculate. A correction can be defined between an observed \([\text{Fe}/\text{H}]\) value \((\text{Fe}/\text{H})\) and the true value, which is expressed as

\[
[\text{Fe}/\text{H}] = 1.063(\text{Fe}/\text{H}) + 0.099.
\]

Not too surprisingly, the inclusion of a metal-poor tail to a metallicity distribution causes the observed colors converted into a \([\text{Fe}/\text{H}]\) value (usually calculated from SSP models) to underestimate the real numerical-averaged \([\text{Fe}/\text{H}]\). Thus, for solar metallicities, the observed \([\text{Fe}/\text{H}]\) must be adjusted upward by approximately 0.1 dex. Interestingly, this upward correction to \([\text{Fe}/\text{H}]\) is almost exactly balanced by a downward correction needed for aperture corrections to line index work (see the previous section), which would explain the high consistency among various studies.

Lastly, we can ask of the simulations the typical difference a metal-poor component makes on the observed values of the \((\text{Fe})\) index versus colors. In the above examples, the typical change in color was on the order of 25% for a CSP model versus a SSP. On the other hand, the corresponding change in \((\text{Fe})\) was only 10%. What this implies is that observed colors are more strongly influenced by the hot component of a metal-poor population (BHB stars), whereas the \((\text{Fe})\) index derives most of its luminosity from the RGB stars.

To summarize, the metallicity line index, \((\text{Fe})\), will suffer from both an aperture effect, due to galaxy metallicity gradients, and an overestimate of mean metallicity due to the use of SSP models with only a single metallicity. However, these two effects balance one another such that the \((\text{Fe})\) index is a good measure of the mean \([\text{Fe}/\text{H}]\) of a galaxy’s stellar population. Colors, however, being a total measure of the integrated light of a galaxy, require a correction to estimate the mean \([\text{Fe}/\text{H}]\) since they will display the overall color of the CSP. The correction is simple, only weakly dependent on the assumed chemical enrichment model. These effects also allow for an opportunity to measure the effect of a composite population by comparing \((\text{Fe})\) values with a galaxies-integrated color.

6. CHEMICAL ENRICHMENT INTERPRETATION OF COLOR VERSUS \([\text{Fe}/\text{H}]\)

Metallicity determination by colors requires an intermediary step, either calibration by comparison with SED models or comparison with a standard system such as galactic globulars. For our continuum color system, the \(v_z - y_z\) color is the metallicity indicator of choice since it has a linear relationship with \([\text{Fe}/\text{H}]\) that varies only slightly with age, as long as the stellar population is older than 5 Gyr (Rakos et al. 2008). For some subset of all three \((\text{Fe})\) samples, we have matching narrowband photometry of the same galaxies for direct comparison. These objects are shown as data points in Figures 5 and 6, where the Thomas et al. (2005) sample is shown as blue points, Trager et al. (2000) as red, and Poggianti et al. (2001) as green.

In order to test a CSP model of chemical enrichment, we have collected, as discussed in Section 3, a direct measure of \([\text{M}/\text{H}]\) of the underlying stellar population through the \((\text{Fe})\) index and color for the underlying stellar population as produced, primarily, by the mean \([\text{M}/\text{H}]\) in our \(v_z - y_z\) narrowband photometry. As discussed in Sections 4 and 5, there are corrections to be made to spectroscopic values to account for aperture effects and a metal-poor component. However, since the aperture corrections were matched by opposing luminosity corrections (see Section 5), no change was made to \((\text{Fe})\) data, and \((\text{Fe})\) was converted to \([\text{M}/\text{H}]\) using the prescriptions outlined in Trager et al. (2000). We will adopt these values as the mean metallicity of the entire galaxy, a numerical average. The model tracks for the various chemical enrichment scenarios will use a mean metallicity versus a luminosity-weighted color, as the integrated colors reflect the entire underlying stellar population.

The resulting plot of metallicity \((\text{M}/\text{H})\) versus galaxy color \((v_z - y_z)\) is shown in Figure 6. The color–metallicity relation (i.e., mass–metallicity relation) is evident even though the mass range of the sample is limited. Also plotted are the data for Galactic globular clusters (Rakos & Schomert 2005). The SSP models for a 12 Gyr population of various metallicities are shown as a dashed line. While these models are excellent fits to the GC data, they fail to describe the galaxy data. A vast majority of the galaxy data lie to the blue side of the SSP models indicating, again, that galaxies must be composed of a significant, at least in luminosity, population of metal-poor stars.

The first chemical enrichment model to test is the closed-box model as outlined in Sarajedini & Jablonka (2005) and shown as the red track in Figure 6. Of course, the immediate result of an enrichment model is the addition of low-metallicity stars to the integrated stellar population. Using our CSP technique of summing a mixed stellar population, we find, not surprisingly, that the integrated \(v_z - y_z\) colors are bluer for a closed-box scenario than for a single metallicity SSP. However, the closed-box track in Figure 6 is clearly too blue compared with the data on ellipticals. This is the famous G-dwarf problem (Pagel 1975), the known deficiency of low-metallicity stars in the solar neighborhood. This deficiency has also been noted in Milky Way halo populations (Tantalo et al. 1996), populations in M31 (Worthey, et al. 2005), and NGC 5128 (Harris & Harris 2000).

The usual resolution is to modify the closed-box assumption with a model that has an initial enrichment component and an inflow of metal-poor gas, an infall model.

The infall model assumes that gas flows into a system while the epoch of star formation is still ongoing. Thus, the gas is replenished at the same rate as star formation consumes it (Gibson & Matteucci 1997). For our purposes, we adopted the Kodama infall model outlined in Yi et al. (1998). We parameterized the models over galaxy mass by sliding the metallicity distribution shape over the metallicity range \([\text{M}/\text{H}]\) = 1 to 2, as described in Rakos et al. (2001). The resulting CSP models using an infall scenario of varying total masses is shown as the blue line in Figure 6. While the infall model reduces the number of metal-poor stars, thereby reddening the predicted \(v_z - y_z\) colors, this effect does not match the elliptical data.
The failure of the infall model, in that it still appears to produce too many metal-poor stars per gas mass, motivated us to produce a model that suppresses the low-metallicity tail. We refer to this model as the “push” model as it pushes down the low end of the metallicity curve (see Section 2.3). However, this is a completely artificial change to the infall model, and has no physical basis other than it results in the color changes needed to match the data. Our push model, shown in Figure 6 and the resulting color–metallicity track shown in green in Figure 6, is a good match for the data with a 30% reduction to the metal-poor component. This also confirms that the G-dwarf problem is even more severe in ellipticals than spirals such as the Milky Way and M31 (Worthey et al. 1996).

A sharp reduction of the low-metallicity end of a galaxy’s MDF is a feature of inhomogeneous enrichment models. These models relax the chemical homogeneity assumption by adopting a fixed dispersion in metal production. Following the paradigm of Oey (2000), these models are parameterized by two variables: (1) the number of generations of star formation and (2) the filling factor in the interstellar medium (ISM) that each generation occupies. As noted in the Oey study, an old, metal-rich population is achieved by a high filling factor. To reproduce our push model values would require a low number of star formation generations, that is, a rapid and short initial star formation epoch for ellipticals in agreement with the conclusions based on α/Fe ratios and galaxy mean ages (Rakos et al. 2008).

7. CONCLUSIONS

Combining information from spectroscopic measurements of galaxy cores with narrowband colors allows for a test of two, relatively independent, estimators of mean metallicity. For example, spectroscopic lines measure key metallicity lines (e.g., Fe) directly, whereas colors measure the effect of changing metallicity on the temperature of the stellar population’s atmospheres (primarily the position of the RGB in a Hertzsprung–Russell diagram (H–R) diagram). This different sensitivity to metallicity can be exploited to test predictions from chemical enrichment models on the shape of the MDF.

We summarize our results as follows.

1. We have examined the accuracy of SED models on predicting narrowband and NIR colors in globular clusters, simple stellar populations of singular age and metallicity. We find that our optical colors and V–K are well matched by SED models; however, NIR colors (i.e., J–K) do not follow SSP tracks.

2. The most accurate measure of metallicity (e.g., [Fe/H]) is our narrowband vz–yz color. Based on arguments in J. Schombert & K. Rakos (2009, in preparation), the range of galaxy ages from 8 to 13 Gyr has a negligible effect on the [Fe/H] versus vz–yz correlation. In addition, J. Schombert & K. Rakos (2009, in preparation) reject the proposal that a majority of galaxy ages in clusters are of less than 8 Gyr. Thus, for this limited set of galaxy morphology (early-type), we can use the vz–yz color as a sole measure of integrated [Fe/H] in a CSP.

3. Comparison of optical and NIR elliptical colors demonstrates that early-type galaxies are best explained by a CSP. As we reject extremely young mean galaxy ages, then, in order to match the colors of ellipticals, the underlying stellar population must be singular in age but with a range of internal metallicities.

4. There is a well-defined continuum between vz–yz color and metallicity ([M/H]) where the colors of ellipticals are bluer than those predicted by SSP models. The inclusion of a metal-poor stellar population is an obvious solution, where the fraction of metal-poor stars can be estimated from a chemical evolution scenario.
5. The simplest chemical evolutionary scenarios, the closed-box model, and the initial enrichment model can be rejected as solutions to the MDF in ellipticals due to their overproduction of metal-poor stars (and resulting blue integrated colors). This results in the infamous G-dwarf problem (Pagel 1975), a well-known problem for the local stellar neighborhood and stellar populations in nearby galaxies. Our data indicate that the G-dwarf problem is universal (Worthey et al. 1996).

6. Infall models, while a better match to the data, also overproduce metal-poor stars and lie on the blue side of the data. Our analytical “push” model is an artificially constructed curve that suppresses the number of metal-poor stars to the typical infall model. This MDF shape, narrower at its peak, reduced on the metal-poor end and sharper on the metal-rich end, matches the elliptical galaxy data. These types of curves are also predicted by inhomogeneous models of chemical evolution (Tinsley 1975; Malinie et al. 1993; Oey 2000) with high filling factors and rapid initial epochs of star formation.

A missing key piece of the chemical evolution puzzle in ellipticals is the age–metallicity relationship (AMR). The AMR would provide a detailed breakdown of the evolution of the MDF; however, this information will be difficult to extract from composite systems such as distant ellipticals. Another avenue for exploration is the presence of metallicity gradients. With guidance from a galaxy formation scenario (matching our chemical enrichment scenarios), one could, ideally, match the metallicity distribution as a function of radius mapped onto time. Future work with our narrowband system will concentrate on spatial analysis of nearby ellipticals to this very end.

Financial support from Austrian Fonds zur Foerderung der Wissenschaftlichen Forschung and NSF grant AST-0307508 is gratefully acknowledged. We thank all the various observatories, which have supported our effort: KPNO, CTIO, and ESO. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA and has made use of data obtained from or software provided by the US National Virtual Observatory, which is sponsored by the National Science Foundation.

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