1. INTRODUCTION

One of the biggest problems with any attempt to determine the chemical makeup of amenable stellar systems like quiescent elliptical galaxies is trying to disentangle the effects of C, N, and O in any given spectrum. This is due to the fact that in cool stars and elliptical galaxies, C, N, and O show themselves in any spectrum almost exclusively through molecular species such as NH, CN, C2, CH, and CO rather than atomic species. The intertwining of these three elements starts with CO. The fact that CO has the highest dissociation energy of these molecules means that CO will form the most prolifically if given enough O and C. Since O is typically the most abundant of these three elements, C becomes incorporated into CO instead of the other molecular species. The rest of these molecules are connected through the balancing of molecular equilibria. These interactions give a net effect of O acting like anti-CN since adding any O will decrease the amount of C available for the formation of other molecules (Serven et al. 2005).

To begin disentangling these three elements, it should be possible to start with pseudo-equivalent width indices that are sensitive to these elements such as C24668 (Worthey et al. 1994), which is sensitive to C, and the indices CO5161 and CO4685 (Serven et al. 2005), which are insensitive to N but react to C and O. After figuring out the C and O abundances, one can use the CN band to determine the N abundance. Unfortunately, disentangling C, N, and O in this way turns out to be difficult (Burstein 2003). To low precision, most previous results agree that Mg, C, N, and Na appear to be enhanced in large elliptical galaxies and correlated with velocity dispersion (Worthey 1998a; Sánchez-Blázquez et al. 2003; Kelson et al. 2006; Graves et al. 2007; Worthey et al. 2011).

The existence of a small scatter Mg–σ relation among large elliptical galaxies implies increasingly effective Mg enrichment from Type II supernovae with increasing galaxy size (Worthey 1998b). The similarity of the N–σ and Na–σ relations to that of the Mg–σ relation implies that the same mechanism (that of Type II supernovae) is responsible for the observed trends, and that contributions from manufacturing on the asymptotic giant branch are not significant. If N was mostly produced in the CNO cycle of main-sequence stars and later ejected, the ejection timescale would be more similar to Type Ia supernovae and N could be expected to track the Fe peak better than light elements. The C–σ relation, on the other hand, seems to be intermediate between Mg, N, Na, and Fe-peak elements (from Type Ia supernovae; Trager et al. 1998). This opens a suggestive door to the possibility that the C abundance may come from contributions from both supernovae and the asymptotic giant branch (Henry & Worthey 1999).

What is most often suggested as an alternative for determining the N abundance is the use of the NH feature at 3360 Å since, as has been noted before, it is insensitive to C and O (Sneden 1973; Norris et al. 2002) and is also directly and sensitively measuring N abundances (Bessell & Norris 1982; Tomkin & Lambert 1984).

Below, we will show that this is not the whole story and that there are other contributors to the NH feature. Unfortunately, until recently there had been fewer than 15 early-type galaxies with published NH3360 values due in large part to relative insensitivity of detectors in the near-UV (Toloba et al. 2009), so making use of the NH3360 feature was almost impossible until the introduction of NH3360 values of 35 early-type galaxies from Toloba et al. (2009).

In Toloba et al. (2009), this sample of 35 galaxies was measured using indices NH3360 (Davidge & Clark 1994), CNO3862, CNO4175, CO4685 (Serven et al. 2005), and Mg b (Burstein et al. 1984). Their findings noted that a flat relation exists between the NH3360 index and velocity dispersion. This seems to indicate that a velocity dispersion relation does not exist for nitrogen, contrary to the results of previous work. For example, since the CN relation is stronger and tighter than the C24668 relation, it seems that there should be a
positive [N/Fe] trend with velocity dispersion (Trager et al. 1998).

The rest of this paper is aimed at attempting to explain this disparity. In the first section, the response of the NH3360 feature to various elements is calculated as in Serven et al. (2005) using greatly improved versions of those models. Then, after seeing Mg contamination in the index, two new indices are defined, one for the contaminant Mg and the other for N. The responses for these new indices are then calculated. In Section 3, the NH3360 index along with the NH3375, Mg3334, CN1, and Mg b indices are plotted and compared to models to determine if the effects of an old metal-poor stellar population can explain the observed index trends. Finally, the results and conclusions are discussed in Section 4.

2. ANALYSIS

The method for determining the response of NH3360 as well as the two new indices was similar to that used in Serven et al. (2005). In Serven et al. (2005) simple models of a galaxy spectrum were constructed, using a G dwarf and a K giant. These models varied in that there was one base model of solar metallicity and then 23 variations, each one with a particular elemental abundance doubled. Then the ratios of these spectra were taken to find spectral influence due to any particular element.

The difference for this work is that the numbers tabulated here come from measuring these indices in fully developed single stellar population models. These models are a version of the Worthey (1994) and Trager et al. (1998) models that use a grid of synthetic spectra (as described in Section 2.1 of Lee et al. 2009) and were generated using spectral synthesis codes FANTOM, SSG, and SYNTHE in cool, medium, and hot regimes, respectively. The spectra were generated at high resolution and then rebinned for this analysis to bins 0.5 Å in width. The stellar evolutionary isochrones that predict the numbers, luminosities, and temperatures of the stars are more complete than described in Lee et al. (2009) and, furthermore, are modular, with several choices for isochrone source. A power-law initial mass function with slope −2.35 was used to predict the numbers of stars along the isochrones.

Age, overall metallicity Z, and 23 individual elemental abundances can be varied independently in the models, and spectra for single-burst (simple) stellar populations can be produced that are sensitive to all of those variables. The underlying stellar evolution does not vary as a function of detailed mixture. For N this is definitely not a problem, as the isochrones are nearly invariant even when N abundance is tweaked (Dotter et al. 2007). For this work, the synthetic spectra alone are used without the intermediate step of fitting empirical index fitting functions as was done in Poole et al. (2010). We plot results based on Worthey (1994) isochrones but confirm all results with Padova (Bertelli et al. 1994) and Teramo (Percival et al. 2009) evolution. For this paper, all spectra, synthetic or observed, are smoothed to a common velocity dispersion of 300 km s\(^{-1}\).

The responses of NH3360, NH3375, Mg3334, Fe4383, Mg b, and H\(\beta\) can be found in Table 5. What can be seen is that the NH3360 index, while indeed insensitive to C and O, is sensitive to Mg and, to a lesser degree, Fe and Ni. The anti-correlation with Mg is due to a small Mg absorption feature located in the blue continuum passband (Figure 1). In order to remove this Mg dependence, a new index was defined—the NH3375 index—with an altered blue pseudocontinuum definition that avoids this feature. The new NH3375 index response, which is also found in Table 5, shows a smaller dependence on Mg with some small dependence on Ti and Ni. Unfortunately, the sensitivity of NH3375 to Ti and Ni comes from features of these two elements that overlap the NH feature itself. This limits the degree to which these sensitivities can be removed from any index definition.

For the sake of agreement, a new index was defined for the small Mg feature as well: the Mg3334 index. The response of this index to Mg abundance is surprisingly clean, showing only a small sensitivity to O (see Table 5). This is most likely due to the effects of molecular equilibrium involving molecular species formed for C, N, and O. The definitions of these new indices, as well as NH3360, can be found in Table 1. The index sensitivities to N and Mg are modeled in Figure 2.

A Z-versus-age sensitivity parameter (Zsp) was calculated for NH3360, NH3375, Mg3334, and Mg b as it was in Worthey (1994). The Zsp is the ratio of the percentage change in age to the percentage change in Z (\(Z \approx 0.01689 \times 10^{[\text{Fe}/\text{H}]}\)) of the index measured as shown below:

\[
Zsp = \frac{\delta I_n/\delta \log(Z)}{\delta I_n/\delta \log(\text{age})}. \tag{1}
\]
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5

−0.3−0.2−0.1  0  0.1  0.2  0.3  0.4  0.5

Figure 2. In the first panel, NH3360 (red), NH3375 (green), and Mg3334 (blue) are plotted against [N/Fe]. In the second panel, NH3360 (red), NH3375 (green), and Mg3334 (blue) are plotted against [Mg/Fe]. This figure illustrates the sensitivity of these indices to changes in the N and Mg abundance at fixed [Z/H] = [Fe/H] = 0.0 and age = 8 Gyr, with [Mg/Fe] = 0.0 for the first panel and [N/Fe] = 0.0 for the second.

1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5

−0.3−0.2−0.1  0  0.1  0.2  0.3  0.4  0.5

Figure 3. NH3360, NH3375, Mg3334, and Mg\(b\) are plotted against age for various metallicities. The NH3360 index (top left), the NH3375 index (bottom left), the Mg3334 index (top right), and the Mg\(b\) index (bottom right) are plotted for metallicities (from top to bottom) 0.5, 0.25, 0, −0.225 (ages 1.5, 2, 3, 5), −0.25 (ages 8, 12, 17), −0.5, −1, −1.5, −2, and ages 1.5, 2, 3, 5, 8, 12, and 17 Gyr.

Table 2

| Index     | Zsp |
|-----------|-----|
| NH3360    | 0.2 |
| NH3375    | 0.6 |
| Mg3334    | 1.1 |
| Mg\(b\)   | 1.7 |

Notes. Zsp gauges how changes in metallicity and age affect the various indices. A large Zsp indicates a larger dependence on the overall metallicity than on age, with 1.0 indicating that age and metallicity affect the index equally.

Here, \(\delta I_\alpha /\delta \log(Z)\) is the partial derivative of the index with respect to metallicity at age = 12 Gyr. Similarly, \(\delta I_\alpha /\delta \log(\text{age})\) is the partial derivative of the index with respect to age at solar metallicity. These sensitivities are shown in Table 2. Note that the models indicate that both NH3360 and NH3375 are far more sensitive to age than they are to metallicity, especially NH3360, which has almost no metallicity sensitivity in the metal-rich regime, while the Mg indices are more sensitive to metallicity.

A plot illustrating the sensitivity of these indices to metallicity and age can be found in Figure 3. Note that the NH3360 index, although age sensitive, behaves much the same for metallicities larger than \(Z = −1\). The other indices exhibit a behavior of increasing and plateauing out over time.

3. OBSERVATIONS AND RESULTS

The Toloba et al. (2009) sample consists of long-slit spectra for 35 elliptical galaxies collected with the 4.2 m William Herschel Telescope at Roque de los Muchachos Observatory, using the ISIS spectrograph. The spectra were extracted within a central equivalent aperture of 4″. The wavelength coverage is from 3140 to 4040 Å with a resolution of 2.3 Å (FWHM) and a typical signal-to-noise ratio of \(S/N = 40 \text{ Å}^{-1}\). These spectra were chosen as a subset of those presented in Sánchez-Blázquez...
et al. (2006a) so that these near-UV data could be supplemented with optical data in the wavelength range 3500–5250 Å. The galaxies in this set were also chosen to include field, Virgo, and Coma cluster ellipticals, which cover a range of velocity dispersions (130 km s$^{-1}$ and Coma cluster ellipticals, which cover a range of velocity dispersions (130 km s$^{-1}$ and 330 km s$^{-1}$). The measurements in both the x and y coordinates.

From this sample, the NH3360, NH3375, Mg3334, CN$_1$, Mg$_b$, and H$\beta$ indices were measured at a velocity dispersion of 200 km s$^{-1}$ and corrected for the effects of velocity dispersion of the galaxy using synthetic spectra if the galaxies were bigger than that. The measurements for NH3360, NH3375, and Mg3334 were taken from the Toloba et al. (2009) spectra, while the measurements for CN$_1$, Mg$_b$, and H$\beta$ were taken from the Sánchez-Blázquez et al. (2006a) optical spectra. These measurements were then plotted against the Fe4383 index to compare the trends of these near-UV indices, which are sensitive to N and Mg, with the slightly redder CN$_1$ and Mg$_b$, which are also sensitive to N and Mg (Figure 4). For comparison, Mg3334 versus Mg$_b$ and H$\beta$ versus Fe4383 are also plotted. The trend lines shown in Figure 4 are best-fit lines (Table 3) calculated using fitexy.f (Press et al. 1992), a program for finding the best-fit line for data with errors in both the x and y coordinates.

It minimizes the distance of each point from the line while taking into account weighting by the precision of the individual measurements in both the x and y coordinates.

The index plotted in the first panel of Figure 4 is NH3360, the index in the second panel is NH3375, and the one in the third panel is Mg3334, all of which are plotted against the Fe4383 index. The index plotted in the fourth panel of Figure 4 is CN$_1$, the one in the fifth panel is Mg$_b$, both of which are plotted against the Fe4383 index. The sixth panel of Figure 4 is a plot of Mg3334 versus Mg$_b$, and the seventh panel is a plot of H$\beta$ versus Fe4383. In each panel three lines are plotted along with the index. These lines represent the respective indices measured from a 12 Gyr galaxy model of metallicity [Fe/H] = 0.0 to metallicity [Fe/H] = 0.25. The red line is a model of solar metallicity with no subpopulation. The green line is a model of solar metallicity, but with 5% of the galaxy mass consisting of a 12 Gyr, metal-poor ([Fe/H] = −1.5) subpopulation. The blue line is the same model except that the subpopulation is now 10% of the total mass and the black lines are fits to the data. In the NH3360 and NH3375 plot, a pink line is plotted indicating the shift in the index plot for a change of N abundance from −0.3 dex (bottom) to +0.3 dex (top). The data sources are Toloba et al. (2009) and Sánchez-Blázquez et al. (2006a).

![Figure 4](image-url)
The metal-poor subpopulation has a blue horizontal branch morphology. What can be seen in Figure 4 is that for the two NH indices, the index trends tend to decrease, and Mg3334 looks flat in contrast to panels 4 and 5, of which show a definite trend increasing metallicity. What can also be seen is that for the galactic models, as the percent mass of the subpopulation is increasing metallicity, the model index trends twist to come into fairly good agreement with the observed index trends within a metal-poor subpopulation fraction somewhere around 5% by mass. The redder indices of CN1, Mg b, and Hβ show that the subpopulation has little to no effect on these index trends except lowering the average metallicity. It is clear that the slope of the index trends is in better agreement with observed trends for all three near-UV indices when a subpopulation is included.

Further evidence for the existence of an old metal-poor population can be seen in panel 6 of Figure 3. What can be seen here is that Mg3334 and Mg b, which are fairly clean indicators of Mg (Serven et al. 2005; this work), do not appear to be measuring the same abundance trend. This is an indication that the near-UV indices do indeed suffer from line strength dilution due to an underlying bright and weak-lined near-UV population. The data fit slopes and model slopes are listed in Table 3; while the slope errors are relatively large, it is evident from the numbers that a composite population with a 5%–10% (or even larger) metal-poor subpopulation fits the observed trends better.

To compare the relative effects of N abundance increase and overall metallicity, Figure 5 shows the NH3360 versus CN1 index measurements that were plotted along with the subpopulation models and a 12 Gyr solar metallicity model of varying N abundance (pink line). Comparing both models with the data we find that neither alone accounts for the observed trend. However, a combination of increasing N abundance and the presence of a metal-poor subpopulation could reproduce the observed trend if, for example, the higher metallicity (larger CN1) models also had a N enhancement relative to the lower metallicity model. Then, for a modest N enhancement of ≈0.04, 0.06, and 0.07 dex for the no subpopulation, 5%, and 10% models, respectively, the model trend would concur with the observed slope. This is not a definitive statement about the relative amounts of these quantities, owing to the fact that there may be interplay between the N content and the presence of a metal-poor population.

To compare the relative effects of a solar metallicity population of varying age on the observed trends, see Figure 6. The red, green, and blue lines are the models that coincide with those from Figure 4. The remaining three models consist of the 12 Gyr model ranging from [Fe/H] = 0.0 to [Fe/H] = 0.25. The yellow line represents these models with a 5% by mass subpopulation of 8 Gyr. The pink line represents these models with a 5% by mass subpopulation of 4 Gyr, and the light blue line represents these models with a 5% by mass of subpopulation 1 Gyr. These young populations were chosen to investigate any observable effect due to the presence of young- or intermediate-age populations as well as blue stragglers whose integrated light mimics that of an intermediate-age population (with turnoff mass about twice that of the old population).

What can be seen in Figure 6 and Table 4 is that the addition of a young subpopulation has little to no effect on the index-versus-index trends, with the exception of the NH3360 index, in which case only the youngest subpopulation (1 Gyr) has an appreciable effect. The effect of this subpopulation is counter to that of the metal-poor subpopulation and does nothing to help explain the observed trend.

Table 3

| Index Slope | Slope Error |
|-------------|-------------|
| NH3360 fit  | -0.59       | 0.46        |
| No subpopulation | -0.07   |             |
| 5%          | -0.22       |             |
| 10%         | -0.35       |             |
| NH3375 fit  | -0.31       | 0.57        |
| No subpopulation | 0.38   |             |
| 5%          | 0.15        |             |
| 10%         | -0.04       |             |
| Mg3334 fit  | -0.01       | 0.44        |
| No subpopulation | 0.29   |             |
| 5%          | 0.22        |             |
| 10%         | 0.16        |             |
| CN1 fit     | 0.15        | 0.03        |
| No subpopulation | 0.03   |             |
| 5%          | 0.03        |             |
| 10%         | 0.03        |             |
| Mg b fit    | 1.69        | 0.39        |
| No subpopulation | 0.51   |             |
| 5%          | 0.50        |             |
| 10%         | 0.49        |             |
| Mg3334 vs. Mg b fit | 0.05   | 0.35        |
| No subpopulation | 0.57   |             |
| 5%          | 0.43        |             |
| 10%         | 0.32        |             |
| Hβ fit      | -0.82       | 0.68        |
| No subpopulation | -0.19  |             |
| 5%          | -0.21       |             |
| 10%         | -0.22       |             |
| NH3360 vs. CN1 fit | 2.01   | 3.61        |
| No subpopulation | -2.37  |             |
| 5%          | -7.36       |             |
| 10%         | -12.34      |             |

Note. Also shown are the slopes for the 5% and 10% by mass metal-poor subpopulation models.

Figure 5. NH3360 and CN1 galaxy indices. Symbols and lines are the same as in Figure 4. The pink line represents the same 12 Gyr model of metallicity [Fe/H]= 0.0, but with increasing N abundance from left to right. The leftmost end is at −0.3 dex, while the rightmost point is at +0.3 dex. The horizontal black line is a fit to the data as in Figure 4.
The Astronomical Journal

The Astronomical Journal

4. DISCUSSION, SUMMARY, AND CONCLUSION

With the use of simple stellar population models we have shown that the NH3360 index, while being C- and O-insensitive, suffers from contamination from other elements, most notably Mg (see Table 5). This dependence of the NH3360 index on Mg suffers from contamination from other elements, most notably shown that the NH3360 index, while being C- and O-insensitive, may be due to some other effect, and the metal-poor subpopulations hypothesis explains the difference nicely. Indeed, the pair of indices taken together can be used to characterize the amount and abundance of spread in the underlying metal-poor fraction of stellar mass, if the abundance distribution is about the same in all galaxies.

The presence of a young blue subpopulation has very little effect on the observed index-versus-index trends. The lone exception is that of NH3360 versus Fe4383 where the effect of a 1 Gyr subpopulation affects the model trends counter to what is needed to explain the observed trends (Figure 6 and Table 4). The Mg3334 index turns out to be a useful tool as it is a fairly clean index with very little contamination (Table 5), which allows for a direct comparison to Mg b (Figure 4). The remarkable flat behavior of Mg3334 compared with Mg b, therefore, cannot be attributed to Mg abundance, but must be due to some other effect, and the metal-poor subpopulations hypothesis explains the difference nicely. Indeed, the pair of indices taken together can be used to characterize the amount and abundance of spread in the underlying metal-poor fraction of stellar mass, if the abundance distribution is about the same in all galaxies.

If the abundance distribution is somehow strongly different from galaxy to galaxy (Maraston & Thomas 2000), then more observables need to be examined in order to decide on the abundance distribution width for each galaxy, and we would suggest photometric indices in the near-UV for that job, at least in dust-free systems. However, there is little motivation for seeking volatile abundance distributions, since the Milky Way and M31 (Worthey et al. 2005), M32 (Grillmair et al. 1996), and the giant elliptical NGC 5128 (Harris & Harris 2001; Rejkuba et al. 2011) are all observed to have almost the same abundance distribution width, albeit scaled mildly up and down. Worthey et al. (1996) also did not find any individual cases that require more or fewer than a few percent of metal-poor stars, nor is there any identified astrophysical mechanism for readily altering the progress of chemical evolution from galaxy to galaxy, except those that might operate as a function of velocity dispersion (to explain the Mg−σ trend)—but the Maraston & Thomas (2000) galaxies that look young in the Hβ diagrams are not all small. Finally, young subpopulations explain strong Balmer indices quite readily, and gas-rich mergers are expected in almost every modern galaxy formation scenario.

With the inherently composite nature of the near-UV spectra (Burstein et al. 1988) and metal-poor light mingling with metal-rich light, deriving a N abundance from NH3375 or NH3360 looks more difficult than heretofore suspected. It is outside the scope of this paper, but by using Mg3334 it may be possible to uncover N abundance by comparing derived Mg abundances from Mg3334 and Mg b and then calibrating the underlying metal-poor population until the Mg3334 abundance agrees with that of Mg b. This metal-poor calibration could then be applied to NH3375, which in turn could be used to derive an N abundance for comparison with N abundances derived from C, N, and O indices. Hopefully, these measurements will be in agreement with the N enhancements in large elliptical galaxies deduced by other authors (i.e., Graves et al. 2007; Kelson et al. 2006; Worthey 1998a).
Table 5  
Response of the NH3360, NH3375, Mg3334, and Fe4383 Index Definitions to Various Elements

| Index  | $\lambda_0$ (Å) | $\sigma$ (Å) | C    | N    | O    | Na   | Mg   | Al   | Si   | S    | K    | Ca   | Sc   | Ti   | V    | Cr   | Mn   | Fe   | Co   | Ni   | Cu   | Zn   | Sr   | Ba   | Eu   | upX2 |
|--------|-----------------|--------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| NH3360 | 3.221           | 0.285        | −0.05| 5.18 | −0.52| −0.03| −3.43| −0.04| −0.30| −0.05| 0.00 | −0.20| 0.13 | 0.04 | −0.18| −0.12| −1.70| −0.41| 1.36 | −0.04| −0.37| 0.01 | 0.00 | 0.00 | 0.00 | −3.82|
| NH3375 | 4.688           | 0.322        | −0.20| 4.51 | −0.87| −0.03| −0.71| −0.04| −0.04| −0.05| 0.00 | −0.50| −0.02| 0.25 | −0.08| −0.25| −0.78| −0.27| 1.82 | 0.00 | −0.57| 0.00 | 0.00 | 0.01 | 3.97 |
| Mg3334 | 1.542           | 0.105        | −0.43| −0.22| −1.14| −0.04| 5.91 | −0.05| 0.14 | −0.04| 0.00 | −0.35| −0.24| −0.26| −0.52| 0.18 | −0.65| −0.29| 0.03 | −0.92| 0.06 | −0.26| −0.01| 0.00 | 0.00 | 3.10 |
| Fe4383 | 7.526           | 0.222        | 0.23 | −0.38| −3.09| −0.10| −1.18| −0.35| −0.80| −0.18| −0.02| −1.11| 0.13 | 0.40 | 0.76 | 0.17 | 0.57 | 6.97 | −0.01| 0.15 | 0.00 | 0.00 | 0.02 | 0.00 | −6.73|
| H\(\beta\) | 1.153 | 0.135        | −0.04| 0.13 | 1.55 | 0.24 | −1.88| 0.09 | −0.68| 0.10 | 0.01 | 0.03 | 0.07 | 0.33 | −0.06| −0.45| −0.10| −0.62| −0.13| 0.87 | 0.00 | 0.00 | −0.02| 0.00 | 0.00 | 0.40 |
| Mg \(b\) | 4.882 | 0.149        | −1.10| −0.33| −2.03| −0.35| 10.00| −0.21| −0.15| −0.14| −0.01| 0.02 | −0.01| 0.32 | −0.06| −2.20| −0.18| −1.55| −0.07| −0.02| −0.07| 0.00 | 0.00 | 0.00 | 0.00 | 6.25 |

Note. The first column is the name of the index, the second column gives the index measurements in Å of equivalent width, and the third column gives the error associated with S/N = 100 at 5000 Å. The remainder of the columns are the changes (enhanced minus unenhanced) in the index brought on by an element enhancement of 0.3 dex (or 0.15 dex for C) in units of the error of the third column.
Figure 6. In the first, second, and third panels, respectively, NH3360, NH3375, and Mg3334 indices are plotted vs. Fe4383. In the fourth and fifth panels, respectively, CN1 and Mg b indices are plotted vs. Fe4383. In the sixth panel Mg3334 is plotted vs. Mg b, and in the seventh panel H β is plotted vs. Fe 4383. In each panel, seven lines are plotted along with the index. The lines in red, green, and blue represent the same models found in Figure 4. The lines in yellow, pink, and light blue represent the indices measured from a 12 Gyr galaxy model of metallicity [Fe/H] = 0.0 to metallicity [Fe/H] = 0.25 with a 5% by mass subpopulation of 8, 4, and 1 Gyr, respectively. The black lines are fits to the data.

Major funding for this work was provided by National Science Foundation grants 0307487 and 0346347.

REFERENCES

Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, A&AS, 106, 275
Bessell, M. S., & Norris, J. 1982, ApJ, 263, L29
Burstein, D. 2003, in ASP Conf. Ser. 297, Star Formation Through Time, ed. E. Perez, R. M. Gonzalez Delgado, & G. Tenorio-Tagle (San Francisco, CA: ASP), 253
Burstein, D., Bertola, F., Buson, L. M., Faber, S. M., & Lauer, T. R. 1988, ApJ, 328, 440
Burstein, D., Faber, S. M., Gaskell, C. M., & Krumm, N. 1984, ApJ, 287, 586
Davidge, T. J., & Clark, C. C. 1994, AJ, 107, 946
Dotter, A., Chaboyer, B., Ferguson, J. W., Lee, H.-c., Worthey, G., Jevremović, D., & Baron, E. 2007, ApJ, 666, 403
Graves, G. J., Faber, S. M., Schiavon, R. P., & Yan, R. 2007, ApJ, 671, 243
Grillmair, C. J., et al. 1996, AJ, 112, 1975
Harris, W. E., & Harris, G. L. H. 2001, AJ, 122, 3065
Henry, R. B. C., & Worthey, G. 1999, PASP, 111, 919
Kelson, D. D., Illingworth, G. D., Franx, M., & van Dokkum, P. G. 2006, ApJ, 653, 159
Lee, H. c., et al. 2009, ApJ, 694, 902
Maraston, C., & Thomas, D. 2000, ApJ, 541, 126
Norris, J. E., Ryan, S. G., Beers, T. C., Aoki, W., & Ando, H. 2002, ApJ, 569, L107
Percival, S. M., Salaris, M., Cassisi, S., & Pietrinferni, A. 2009, ApJ, 690, 427
Poole, V., Worthey, G., Lee, H.-c., & Serven, J. 2010, AJ, 139, 809
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes in FORTRAN (2nd ed.; Cambridge: Cambridge: Univ. Press)
Rejkuba, M., Harris, W. E., Greggio, L., & Harris, G. L. H. 2011, A&A, 526, A123
Sánchez-Blázquez, P., Gorgas, J., Cardiel, N., Cenarro, J., & González, J. J. 2003, ApJ, 590, L91
Sánchez-Blázquez, P., Gorgas, J., Cardiel, N., & González, J. J. 2006a, A&A, 457, 787
Serven, J., Worthey, G., & Briley, M. M. 2005, ApJ, 627, 754
Sneden, C. 1973, ApJ, 184, 839
Toloba, E., Sánchez-Blázquez, P., Gorgas, J., & Gibson, B. K. 2009, ApJ, 691, L95
Tomkin, J., & Lambert, D. L. 1984, ApJ, 279, 220
Trager, S. C., Worthey, G., Faber, S. M., Burstein, D., & Gonzalez, J. J. 1998, ApJS, 116, 1
Worthey, G. 1994, ApJS, 95, 107
Worthey, G. 1998a, PASP, 110, 888
Worthey, G. 1998b, in ASP Conf. Ser. 147, Abundance Profiles: Diagnostic Tools for Galaxy History, ed. D. Friedli et al. (San Francisco, CA: ASP), 13
Worthey, G., Dorman, B., & Jones, L. A. 1996, AJ, 112, 948
Worthey, G., Espahah, A., MacArthur, L. A., & Courteau, S. 2005, ApJ, 631, 820
Worthey, G., Faber, S. M., Gonzalez, J. J., & Burstein, D. 1994, ApJS, 94, 687
Worthey, G., Ingermann, B. A., & Serven, J. 2011, ApJ, 729, 148