Age and Metallicity Estimation of Globular Clusters from Strömgren Photometry

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ABSTRACT. We present a new technique for the determination of age and metallicity in composite stellar populations using Strömgren filters. Using principal component (PC) analysis on multicolor models, we isolate the range of values necessary to uniquely determine age and metallicity effects. The technique presented here can only be applied to old (\( \tau \geq 3 \) Gyr) stellar systems composed of simple stellar populations, such as globular clusters and elliptical galaxies. Calibration using new photometry of 40 globular clusters with spectroscopic [Fe/H] values and main-sequence–fitted ages links the PC values to the Strömgren colors, for an accuracy of 0.2 dex in metallicity and 0.5 Gyr in age.

1. INTRODUCTION

The two primary processes that determine the characteristics of a stellar population are its star formation history and its chemical evolution. For an actively star-forming system such as the disk of our Galaxy, these two processes are intertwined and will display a feedback loop as star formation continues. Thus, understanding an active system requires detailed HR diagrams and individual stellar spectroscopy. However, a simple stellar population (SSP), formed in a single event from a single cloud of gas (e.g., a globular cluster), will have a fixed metallicity and age that can be derived from the color-magnitude diagram (CMD). A burst stellar population (i.e., one derived from a extended star formation event) will be composed of a combination of SSPs, and the evolutionary processes are reflected in the population’s age and metallicity by the luminosity-weighted mean of the various SSPs. It is possible to characterize a burst population if the duration of the burst is short and the distribution of metallicities is uniform (Renzini & Buzzoni 1986).

Early studies of composite stellar populations focused on broadband colors of spiral bulges and elliptical galaxies (Sandage & Visvanathan 1978; Tinsley 1980; Frogel 1985), and these data sets supported the (burst) hypothesis that red galaxies are composed primarily of old, metal-rich stellar populations. Unfortunately, it was soon realized that the detailed interpretation of broadband colors with respect to age and metallicity is complicated by several factors. Foremost was the assumption that old stellar systems are composed of a population that is uniform in age and metallicity. It was soon demonstrated by population synthesis techniques (O’Connell 1980) that a young population quickly reddens to integrated colors similar to an old population and that the change in color is abrupt even while the differences in age may be quite large (greater than 5 Gyr). This was also noted by Burstein (1985), who found significant variations in the age and metallicity properties of Galactic globular clusters that was not reflected in their integrated broadband colors. Finally, it was identified through the use of stellar population models, which found that slight changes in age and metallicity operate in the same direction of spectroevolutionary parameter space (Worthey 1994). This coupling of age and metallicity (known as age-metallicity degeneracy; Worthey 1999) is due to competing contributions from main-sequence turnoff stars (sensitive to age) and red giant branch (RGB) stars (sensitive to metallicity) near 5000 Å. Filters that bracket this region of a galaxy’s spectrum will require increasingly accurate values for metallicity to determine a unique age and vice versa.

To avoid the age-metallicity degeneracy problems, a majority of recent stellar population studies have focused on the determination of age and metallicity through the use of various spectral signatures, such as H\( \beta \) for age (Kuntschner 2000; Trager et al. 2000). This approach provides a finer comparison to stellar population models, but requires assumptions about the relationship between metallicity indicators (e.g., Mg) and the [Fe/H] value of the population as reflected in the behavior of the RGB. In other words, spectral lines provide the value of that element’s abundance, but what is really required is the temperature of the RGB, which is a function of the total metallicity, \( Z \). Varying ratios of individual elements to \( Z \) complicate the interpretation of line studies (Ferreras et al. 1999). In addition, these techniques have limitations due to the required high signal-to-noise ratio (S/N) for the data that make them problematic for the study of high-redshift systems.
An alternative approach to spectral-line studies is to examine the shape of specific portions of a spectral energy distribution (SED) using narrowband filters centered on regions sensitive to the mean color of the RGB (metallicity) and the main-sequence turnoff point (mean age) without the overlap that degrades broadband colors. The type of galaxy examined, for example stellar systems with ongoing star formation where a mix of different age populations may be present, will still limit this technique. However, for systems that exhausted their gas supply many Gyr ago (i.e., old and quiescent), it may be possible to resolve the underlying population with some simple assumptions about their star formation history and subsequent chemical evolution. Thus, we have the expectation, guided by the results of evolution models, that objects composed of SSPs or a composite of SSPs (e.g., ellipticals) present special circumstances in which the age-metallicity degeneracy can be resolved and thus allow the study of the evolution of stellar populations.

In a series of earlier papers, we have examined the **uz**, **vz**, **bz**, and **yz** colors of globular clusters and used a combination of their colors and SED models to derive the mean age and metallicity of dwarf, bright, and field ellipticals (Rakos et al. 2001; Odell et al. 2002; Rakos & Schombert 2004). While spectroscopic data are superior for age and metallicity estimations in high-S/N data sets, our goal has been to develop a photometric system that can be used for galaxies of low surface brightness and/or high redshift, where spectroscopy is impractical or impossible. Our past technique has been to relate the **vz** - **yz** color index to metallicity, since the **vz** filter is centered on the absorption-line region near 4100 Å, as guided by our multimetallicity SED models. The **bz** - **yz** color index, whose filters are centered on continuum regions of the spectral energy curve, measures the mean stellar age. This method was crude, since changes in metallicity will move the effective temperature of the RGB, and thus the continuum **bz** - **yz** colors. In our more recent work, we have included photometry through the **uz** filter that provides an additional handle on age and metallicity effects in the other two color indices. In addition, we have applied a principal component (PC) analysis to the multicolor data (Steindling et al. 2001) that more fully isolates metallicity from age effects and the changes due to recent star formation.

The success of our narrowband, multicolor technique has motivated us to return to our original calibration objects (i.e., globular clusters) and obtain higher accuracy photometry and investigate their color behavior under PC analysis. In addition, new globular cluster age estimates are available in the literature (see Salaris & Weiss 2002), based on direct determination from the main-sequence turnoff point rather than SED models; and Schulz et al. (2002) have published a set of new SED models for metallicities from −1.7 to +0.4 and ages from 10^6 yr to 16 Gyr, using the most recent isochrones from the Padova group. Our aim for this paper is threefold: (1) to present our new photometry based on the integrated light from 40 Milky Way globular clusters with well-determined ages and metallicities (baseline SSPs), (2) to demonstrate that narrowband filters are effective in discriminating age and metallicity for single-generation objects by comparing data and SED models, and (3) to calibrate our photometric system to globular cluster ages and metallicities and explore its use, and limitations, as an age and metallicity estimator for dwarf and giant ellipticals.

### 2. DATA AND MODELS

Our primary data sample is the photometry of Milky Way globular clusters published in Rakos et al. (2001), with a few corrections, plus new observations obtained during the 2003 Cerro Tololo Inter-American Observatory (CTIO) observing season. There are 40 clusters in the final sample, in which a small number of clusters were observed multiple times. The photometric accuracy is on the order of ±0.02 mag in **bz** − **yz** and **vz** − **yz**, plus ±0.03 mag in **uz** − **vz**. The Strömgren filters have a long history in the literature of being used to determine metallicity, surface gravity, and effective temperature in stars (Bell & Gustafsson 1978), but their use for a composite system, one composed of many stars of different luminosities and temperatures but a single metallicity, is more complicated.

Our first challenge is to demonstrate that age and metallicity in a stellar population can be discriminated solely from its narrowband colors. To this end, we first need to track the behavior of our colors by convolving our filters to a set of SED models with varying ages and metallicities. Our choice of SED models is recent work published by Schulz et al. (2002), who provide **uvby** (rest frame **uz**, **vz**, **bz**, and **yz**) color indices for SSP models using five different metallicities (−1.7, −0.7, −0.4, 0.0, and +0.4) and ages between 0.8 and 14 Gyr. We have applied these published indices to our modified system using the transformations shown in Rakos et al. (1996) and applied the same PC analysis to the resulting colors as outlined in Steindling et al. (2001).

Scientific data in astronomy are usually not both linear and orthogonal at the same time. Often, for small regions of data, linearity and orthogonality can be achieved through the use of PC analysis (Murtagh & Heck 1987). Close inspection of Schulz et al. (2002) theoretical models has shown acceptable linearity for ages larger than 3 Gyr over the full range of model metallicities. In this restricted region, it is possible to apply PC analysis to (1) separate the age and the metallicity of a stellar population, (2) select the most correlated variables, and (3) determine linear combinations of variables for extrapolation. In Table 1 we list the metallicities, ages, and corresponding photometric color indices (**uz** − **vz**, **bz** − **yz**, and **vz** − **yz**) for the range of models considered here. These correlations deliver the principal components PC1, PC2, and PC3 (see Steindling et al. 2001), but only first two components, PC1 and PC2, have
where \( t \) from equations (1) and (2), respectively; the colors are given

| \( t \) | PC1 | PC2 | \( [\text{Fe/H}] \) | \( \mu_z - \nu_z \) | \( b_z - y_z \) | \( v_z - y_z \) |
|-------|-----|-----|-----------------|-----------------|-----------------|-----------------|
| 0.160 | -3.439 | -1.7 | 3.08 | 0.725 | 0.117 | 0.028 |
| 0.345 | -4.357 | -1.7 | 4.06 | 0.691 | 0.137 | 0.066 |
| 0.710 | -6.193 | -1.7 | 6.02 | 0.646 | 0.167 | 0.123 |
| 1.080 | -8.158 | -1.7 | 8.12 | 0.620 | 0.179 | 0.140 |
| 1.428 | -9.992 | -1.7 | 10.08 | 0.599 | 0.190 | 0.159 |
| 1.779 | -11.824 | -1.7 | 12.04 | 0.606 | 0.192 | 0.165 |
| 2.139 | -13.657 | -1.7 | 14.00 | 0.623 | 0.199 | 0.177 |
| 0.820 | -3.094 | -0.7 | 3.08 | 0.719 | 0.212 | 0.309 |
| 0.995 | -4.011 | -0.7 | 4.06 | 0.716 | 0.215 | 0.317 |
| 1.367 | -5.844 | -0.7 | 6.02 | 0.713 | 0.232 | 0.360 |
| 1.792 | -7.807 | -0.7 | 8.12 | 0.727 | 0.258 | 0.432 |
| 2.143 | -9.639 | -0.7 | 10.08 | 0.731 | 0.260 | 0.442 |
| 2.531 | -11.470 | -0.7 | 12.04 | 0.760 | 0.275 | 0.489 |
| 2.867 | -13.303 | -0.7 | 14.00 | 0.759 | 0.272 | 0.479 |
| 1.003 | -2.900 | -0.4 | 3.08 | 0.739 | 0.230 | 0.354 |
| 1.175 | -3.907 | -0.4 | 4.06 | 0.718 | 0.231 | 0.375 |
| 1.572 | -5.739 | -0.4 | 6.02 | 0.731 | 0.256 | 0.443 |
| 2.005 | -7.701 | -0.4 | 8.12 | 0.768 | 0.279 | 0.513 |
| 2.372 | -9.533 | -0.4 | 10.08 | 0.785 | 0.287 | 0.537 |
| 2.726 | -11.364 | -0.4 | 12.04 | 0.801 | 0.288 | 0.543 |
| 3.113 | -13.196 | -0.4 | 14.00 | 0.829 | 0.303 | 0.587 |
| 1.263 | -2.851 | 0.0 | 3.08 | 0.745 | 0.257 | 0.463 |
| 1.539 | -3.765 | 0.0 | 4.06 | 0.805 | 0.293 | 0.576 |
| 1.869 | -5.598 | 0.0 | 6.02 | 0.784 | 0.291 | 0.571 |
| 2.329 | -7.557 | 0.0 | 8.12 | 0.872 | 0.312 | 0.648 |
| 2.693 | -9.389 | 0.0 | 10.08 | 0.886 | 0.320 | 0.669 |
| 3.109 | -11.219 | 0.0 | 12.04 | 0.945 | 0.340 | 0.736 |
| 3.501 | -13.049 | 0.0 | 14.00 | 0.996 | 0.349 | 0.776 |
| 1.597 | -2.707 | 0.4 | 3.08 | 0.865 | 0.289 | 0.604 |
| 1.899 | -3.619 | 0.4 | 4.06 | 0.949 | 0.332 | 0.737 |
| 2.275 | -5.449 | 0.4 | 6.02 | 1.010 | 0.333 | 0.743 |
| 2.726 | -7.409 | 0.4 | 8.12 | 1.062 | 0.356 | 0.836 |
| 3.126 | -9.240 | 0.4 | 10.08 | 1.108 | 0.375 | 0.884 |
| 3.484 | -11.071 | 0.4 | 12.04 | 1.130 | 0.375 | 0.894 |
| 3.907 | -12.900 | 0.4 | 14.00 | 1.212 | 0.392 | 0.955 |

significant content for our purpose. Their values are given by

\[
P_{\text{C1}} = 0.471[\text{Fe/H}] + 0.175\tau + 0.480(\mu_z - \nu_z) \\
+ 0.506(b_z - y_z) + 0.511(\nu_z - y_z),
\]

(1)

\[
P_{\text{C2}} = 0.345[\text{Fe/H}] - 0.935\tau + 0.047(\mu_z - \nu_z) \\
- 0.061(b_z - y_z) + 0.020(\nu_z - y_z),
\]

(2)

where \( \tau \) is the age of the stellar population in Gyr. Metallicity is found to have similar weight in both equations, unlike the age index, which has a small weight in the first equation and a large weight in the second equation. Of course, a knowledge of the values for PC1 and PC2, combined with the photometric indices, would provide simple solutions to the equations for age and metallicity.

For the models used in Table 1, PC1 and PC2 are calculated from equations (1) and (2), respectively; the colors are given

by the models, and of course [Fe/H] and age are the inputs for each model. Figure 1 displays PC1 versus PC2 for a range of models and demonstrates their orthogonality between age and metallicity. We only have PC1 and PC2 model values for a few discrete values of metallicity and age, but a simple linear interpolation between these values produces PCs with significant accuracy over the entire surface in Figure 1. The advantage of the smooth behavior of age and metallicity in the PC plane is that if all three narrowband colors (\( \mu_z - \nu_z \), \( \nu_z - y_z \), and \( b_z - y_z \)) are available, then knowledge of the correct PC1 and PC2 values allows a unique determination of age and metallicity from equations (1) and (2). If the PC values are unknown, then an iterative search scheme could select a range of values for \( \tau \) and [Fe/H], determine PC1 and PC2 from Figure 1, then evaluate how well those values and the observed colors solve equations (1) and (2). We outline this technique in greater detail in § 3.

To compare the models to main-sequence–fitted ages and metallicities of globular clusters, we have used the results from Harris (1996, updated in 2003 February) and Salaris & Weiss (2002). Salaris & Weiss provide two additional estimates for metallicity, using the designation “CG97” (Carretta & Gratton) and “ZW84” (Zinn & West), and two additional estimates for ages, with the same designation. We have used the mean of all three values for the age and metallicity of each cluster (the mean error from Salaris & Weiss is \( \pm 0.1 \) Gyr in age and \( \pm 0.1 \) dex in [Fe/H]) and calculated PC1 and PC2 using the observed narrowband colors and the fitted metallicities and ages. The resulting PC values are shown in Figure 1.
(filled symbols), with an error bar shown in the bottom left-hand corner that represents the mean error of the Salaris & Weiss sample. The globular cluster data occupy the correct portion of the PC1-PC2 diagram and confirm that the SED models do, in fact, describe the observed colors of the globular clusters. This is not an obvious result, since previous SED models failed to match the $u v$ colors of globular clusters by between 0.5 and 0.7 mag (Rakos et al. 2001). It appears that recent changes in overshoot calculations, which are important for determining colors of the blue HB stars, have converged the model colors and the observed $u v$ colors of globular clusters.

### 3. ITERATIVE PC SOLUTIONS

Reproducing PC values for objects with known metallicities and ages only confirms the validity of the Schulz et al. (2002) SED models. A more powerful approach would be to derive metallicity and age values using only the observed narrowband colors and knowledge of the behavior of the PC surface (i.e., guided by the SED models). This process begins with the production of a mesh of PC1 and PC2 values, with the expectation that one pair in the computed mesh represents the true value for an unknown age and metallicity. To identify the true value of PC1-PC2 for an object with observed colors but

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**TABLE 2**

**Globular Cluster Data**

| NGC  | $u v$ - $v z$ | $b v$ - $y z$ | $v z$ - $z$ | $E(B - V)$ | $[Fe/H]^a$ | $t^b$ (Gyr) | $[Fe/H]_{ph}$ | $t_{ph}$ (Gyr) |
|------|--------------|--------------|-------------|------------|------------|-------------|--------------|--------------|
| 104  | 0.65         | 0.29         | 0.52        | 0.04       | -0.75      | 10.7        | -0.73        | 11.1         |
| 288  | 0.51         | 0.31         | 0.31        | 0.03       | -1.26      | 11.6        | -1.29        | 11.1         |
| 362  | 0.54         | 0.27         | 0.35        | 0.05       | -1.19      | 9.1         | -1.22        | 8.7          |
| 1261 | 0.56         | 0.22         | 0.27        | 0.01       | -1.25      | 8.8         | -1.47        | 9.2          |
| 1851 | 0.62         | 0.26         | 0.35        | 0.02       | -1.16      | 9.1         | -1.10        | 9.5          |
| 1904 | 0.60         | 0.20         | 0.22        | 0.01       | -1.54      | 12.1        | -1.57        | 11.9         |
| 2298 | 0.63         | 0.25         | 0.21        | 0.14       | -1.80      | 12.7        | -1.52        | 12.9         |
| 3201 | 0.60         | 0.27         | 0.33        | 0.23       | -1.45      | 11.7        | -1.18        | 11.4         |
| 4147 | 0.58         | 0.16         | 0.13        | 0.02       | -1.83      | ...         | -1.93        | 11.2         |
| 4372 | 0.40         | 0.14         | 0.07        | 0.39       | -2.09      | ...         | -2.22        | 12.7         |
| 4590 | 0.50         | 0.17         | 0.13        | 0.05       | -2.06      | 11.2        | -2.14        | 11.2         |
| 4833 | 0.54         | 0.18         | 0.14        | 0.32       | -1.80      | ...         | -1.93        | 12.0         |
| 5024 | 0.50         | 0.14         | 0.13        | 0.02       | -1.99      | ...         | -2.02        | 13.2         |
| 5139 | 0.53         | 0.22         | 0.20        | 0.12       | -1.62      | ...         | -1.72        | 11.8         |
| 5272 | 0.54         | 0.21         | 0.28        | 0.01       | -1.52      | 11.7        | -1.54        | 11.9         |
| 5286 | 0.56         | 0.20         | 0.19        | 0.24       | -1.67      | ...         | -1.72        | 11.7         |
| 5466 | 0.52         | 0.07         | -0.01       | 0.00       | -2.19      | 12.3        | -2.25        | 12.3         |
| 5634 | 0.49         | 0.13         | 0.19        | 0.05       | -1.88      | ...         | -1.98        | 9.6          |
| 5897 | 0.58         | 0.22         | 0.20        | 0.09       | -1.82      | 12.3        | -1.65        | 12.4         |
| 5904 | 0.65         | 0.18         | 0.26        | 0.03       | -1.26      | 11.3        | -1.39        | 11.0         |
| 5986 | 0.58         | 0.22         | 0.19        | 0.28       | -1.58      | ...         | -1.60        | 9.8          |
| 6101 | 0.57         | 0.23         | 0.17        | 0.05       | -1.80      | 10.8        | -1.65        | 10.9         |
| 6171 | 0.55         | 0.23         | 0.45        | 0.33       | -1.03      | 11.7        | -1.11        | 11.3         |
| 6205 | 0.50         | 0.20         | 0.25        | 0.02       | -1.50      | 12.4        | -1.75        | 13.2         |
| 6218 | 0.44         | 0.17         | 0.28        | 0.19       | ...        | 12.6        | ...          | ...          |
| 6229 | 0.52         | 0.19         | 0.31        | 0.01       | -1.43      | ...         | -1.50        | 10.3         |
| 6352 | 0.67         | 0.30         | 0.53        | 0.21       | -0.63      | 9.8         | -0.59        | 10.1         |
| 6397 | 0.54         | 0.16         | 0.07        | 0.18       | -1.88      | 12.3        | -2.02        | 13.2         |
| 6584 | 0.56         | 0.21         | 0.22        | 0.10       | -1.44      | 11.7        | -1.66        | 12.3         |
| 6652 | 0.66         | 0.29         | 0.50        | 0.09       | -0.89      | 11.4        | -0.76        | 11.3         |
| 6656 | 0.48         | 0.27         | 0.31        | 0.34       | -1.60      | 12.4        | -1.55        | 12.5         |
| 6681 | 0.52         | 0.25         | 0.25        | 0.07       | -1.46      | 11.7        | -1.56        | 11.9         |
| 6715 | 0.50         | 0.25         | 0.33        | 0.15       | -1.58      | ...         | -1.51        | 12.2         |
| 6723 | 0.56         | 0.26         | 0.36        | 0.05       | -1.07      | 11.6        | -1.35        | 12.4         |
| 6752 | 0.55         | 0.20         | 0.18        | 0.04       | -1.45      | 12.4        | -1.78        | 11.9         |
| 6809 | 0.72         | 0.21         | 0.20        | 0.08       | -1.79      | 12.3        | -1.35        | 11.8         |
| 6864 | 0.62         | 0.25         | 0.35        | 0.16       | -1.16      | ...         | -1.09        | 10.4         |
| 6981 | 0.62         | 0.25         | 0.28        | 0.05       | -1.40      | ...         | -1.41        | 12.6         |
| 7078 | 0.50         | 0.22         | 0.15        | 0.10       | -2.14      | ...         | -1.85        | 12.4         |
| 7089 | 0.63         | 0.22         | 0.20        | 0.06       | -1.62      | ...         | -1.59        | 12.8         |

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* Mean value from Harris (1996).
* Mean value from Salaris & Weiss (2002).
unknown age and metallicity, we interpolate a PC1 and PC2 pair from the assumed age and metallicity (see Fig. 1), use equations (1) and (2) to fill in the observed color indices plus the assumed age and metallicity, and compare the calculated pairs to those derived from the colors.

In practice, the search for the correct age and metallicity is evaluated by calculating the differences between the PC values determined from models (i.e., Fig. 1) and those determined from equations (1) and (2), in which the observed colors are the input. The quality of the solution is measured by the root mean difference (rms) between the PC values over two iteration loops; one for age and one for metallicity. This computation consists of starting with a value for age and increasing the value with an index of 0.1 Gyr. Each age iteration has a nested metallicity loop increasing in steps of 0.004 dex. At each step, PC values are interpolated from the Schulz et al. (2002) models for the step values of age and metallicity, then compared to the PC values determined from equations (1) and (2), again using the step values of age and metallicity plus the observed colors.

To limit interpolation errors, the starting and ending values in the first loop are fixed on values for the age of the models given by Schulz et al. (2002), with step values interpolated from Figure 1. Each step of the age loop has a second loop that iterates over the metallicity interval. At each step, metallicity is first evaluated using the age to calculate the metallicity from equation (1), then age is calculated from equation (2), which is then returned to equation (1), inserting the newly calculated value for age and calculating a better value for the metallicity.

Each iteration produces a better approximation of age (using eq. [2]) and is repeated for a total of six values of age and metallicity. In the case that the iterated PC1-PC2 pair represents the true value, we expect it to have the smallest deviation for the calculated set of six ages and six metallicities. Therefore, we determine the quality of the solution by the sum of mean square deviations of ages and metallicities for the selected PC1 and PC2 values. While this technique is not as rigorous as a least-squares minimization between two functions, it has the advantage of being a quantitative measure of the fit, and the rms sum does become smaller and smaller as we approach the proper values of age and metallicity.

Finally, to avoid problems associated with small local minima, we extend the search for four or more values of age in 0.1 Gyr steps that have the smallest sum of mean square deviations (for a very limited range of metallicity), which implies the closest match to the proper age and metallicity of the system. The resulting grid minimum that is searched for should be deepest and widest within the whole range of PC1-PC2 values. Unfortunately, in some cases there is a secondary minimum produced by the errors for the observed color indices, and the best solution may have a broad range of age values with an equal quality of fitness. A detailed example of our procedure is given in the Appendix for globular cluster NGC 6397.

The above technique was applied to all 40 clusters with metallicity information available from spectroscopy and age dating using CMD diagrams. For one cluster, NGC 6218, no acceptable solution was found; the rest are listed in Table 2, where \( \langle \text{Fe/H} \rangle \) and \( \langle \tau \rangle \) are the values from Salaris & Weiss (2002), and \( [\text{Fe/H}]_{\text{ph}} \) and \( \tau_{\text{ph}} \) are the photometric determinations of metallicity and age. Comparisons of these two determinations are shown in Figures 2 and 3, where the dashed lines represent a one-to-one relationship between \( \langle \text{Fe/H} \rangle \) and \( \langle \tau \rangle \), and the photometrically determined \( [\text{Fe/H}]_{\text{ph}} \) and \( \tau_{\text{ph}} \). The solid lines show a least-squares fit to the relationships. Both relationships are well within the internal errors for metallicity and age from main-sequence fitting, as discussed in § 4.

4. UNCERTAINTIES AND ERROR ESTIMATES

The uncertainties in our technique fall into three categories: (1) observational errors of the colors, (2) errors due to the quality of the solutions from the iterative method (i.e., the range of equally likely solutions based on a quality-of-fit criterion), and (3) the ability of the Schulz et al. (2002) models to reproduce the underlying physical reality of the globular cluster colors. While we can directly test the impact of errors for the first two quantities, we cannot address the meaning of the fits in terms of the various inputs to the population models. How-

![Figure 2](image-url)
ever, we can compare the results of our technique with ages and metallicities determined by other means (in this case, by comparing against results from CMD fitting and spectroscopy) as an indication of the merit of the models as applied to our method.

Observational error can arise due to the inaccuracy of the photometry through either simple Poisson noise in the photon counts, internal errors for the standard stars, or uncertain Galactic reddening values. As described above, the data were obtained under the best conditions, and the error is estimated to be 0.02 for $b_z - y_z$ and $v_z - y_z$ and 0.03 for $u_z - v_z$. In order to estimate the effect of this error on the determination of age and metallicity, we have simply iterated the solution technique using a range of colors within the measured errors. Uncorrelated errors (i.e., randomly changing each color by its mean error) produced solutions that varied by $\pm 0.5$ Gyr in age and $\pm 0.05$ dex in [Fe/H]. Correlated errors (for example, moving all the colors to the blue) produced similar errors, since bluer $u - v$ colors increase age and metallicity fits, whereas bluer $v - y$ colors decrease the fits.

Another source of uncertainty concerns the ability to determine a unique solution to the given narrowband colors. This, in effect, asks if the resulting PC pairs can produce a unique set of age and metallicity values within a certain degree of accuracy. One method of estimating the quality of the solutions is to examine the behavior of the fits for a range of age and metallicities near the chosen solution. For our technique, this involves comparing the rms values for each of the nested loops. The loops with the smallest deviations from the mean are the ones closest to the derived solution (see the Appendix for an example of this using cluster NGC 6397).

The goodness-of-fit criterion assumes that age and metallicity are uncorrelated, which we know to be false. However, as an iterative procedure, we can test each age and metallicity loop separately and find a solution that converges in both parameters. An example of the rms space for NGC 1904 is shown in Figure 4. Each contour represents a normalized sum of the rms values for the age and metallicity loops per PC pair (in this example, age was iterated by 0.1 Gyr and [Fe/H] by 0.005 dex). A minimum is found at an accepted solution of 11.9 Gyr and $[\text{Fe/H}] = -1.55$, with a secondary minimum at 11.6 Gyr. No other minimums were found in the parameter space given by the Schulz et al. (2002) models (but note that we only consider models older than 5 Gyr).
is $\delta \log (\text{age})/\delta (Z) = -1$, as predicted by Worthey (1999) for a near-blue filter system. The difference here is that a clear minimum can be determined (and the full range given by the Schulz et al. [2002] models were searched), although any error in either age or metallicity will be reflected in the other with the slope given above (i.e., along the “valley”).

An inspection of the example in the Appendix demonstrates that the rms minimums are shallower for age loops compared to metallicity loops. This confirms that our chosen filter system is more sensitive to metallicity than age, and therefore the uncertainty associated with age will be greater than that of metallicity. An examination of the rms contours of the globular clusters in the sample finds that the formal errors in the solutions are 0.4 Gyr in age and 0.01 dex in [Fe/H], which is less than the error expected from observational uncertainties. Hence, we conclude that the fitting process does not represent the dominant source of uncertainty in our method and that the age-metallicity degeneracy is broken within the accuracy of the data. We note, however, that the range of models we use to construct the PC pairs limits this statement. In particular, we do not examine models with ages less than 3 Gyr, as these represent unrealistic ages when considering old stellar populations. Thus, age-metallicity degeneracy may once again come into play for very young populations or those with supersolar metallicities, and we stress this caveat in any future use of this technique.

To evaluate the accuracy of the entire technique, including the ability of the Schulz et al. (2002) models to reproduce the integrated colors of globular clusters, we return to Figures 2 and 3, the comparison between the PC solutions and the values for age and metallicity as determined by CMD fitting from Salaris & Weiss (2002). Representative error bars are shown in the bottom right-hand portion of each diagram. The error in the y-axis is taken from the mean error in Salaris & Weiss. The error in the x-axis represents the values for the limits of our technique, discussed above. Both age and metallicity are recovered through the narrowband colors, using our PC technique, and the difference from the one-to-one line and a least-squares fit is negligible. Since the formal error for our solutions is less than the error associated with CMD dating, it is tempting to claim that integrated colors are better predictors of age and metallicity. However, it is more likely that the interplay between the data in CMDs for globular clusters and stellar evolutionary models is also present in our technique and the Schulz et al. SSP models. Thus, we adopt the scatter in Figures 2 and 3 as the real uncertainty in our technique. In Figure 2, the scatter around the mean metallicity is approximately 0.2 dex, greater than the internal error of our technique or the calibrating cluster metallicities. In Figure 3, the scatter around the mean age is

Fig. 5.—Globular cluster $v_z - y_z$ and $b_z - y_z$ colors as a function of the calculated [Fe/H]$_{ph}$. The metallicity color $v_z - y_z$ displays better linearity and lower scatter than the continuum color, $b_z - y_z$. An adequate measure of [Fe/H] can be obtained simply from the color if the population is older than 3 Gyr. The solid line is a least-squares fit to the data as noted in the text.

Fig. 6.—Mean metallicity of the globular cluster sample as determined by the iterative technique vs. the multicolor term that incorporates all of the PC terms. This relationship can be compared to Fig. 5 to demonstrate how the use of the full parameter space reduces the scatter in [Fe/H]. Also shown are the iterative results for a sample of dwarf and giant ellipticals in the Coma cluster with full $uvby$ photometry. The relationship becomes less linear for galaxies, because of the fact that they are composed of an integrated population of SSPs. The low scatter indicates that metallicity is the primary driver of galaxy color (see also Smolcic et al. 2005).
5. METALLICITY CALIBRATION

In a previous paper (Rakos et al. 2001), we have demonstrated a very tight correlation between v_z − y_z color and the published metallicities for globular clusters, deriving the relation

$$\frac{[\text{Fe}/\text{H}]}{\text{S}} = (2.57 \pm 0.13)(v_z - y_z) - (2.20 \pm 0.04),$$

(3)

where the scatter of individual values corresponds to the probable errors published in the literature. Examining equation (1) for principal components, we find as expected that the calculated metallicity value will be influenced in a lesser manner by the other two color indices. From an analysis of computed [Fe/H] values ([Fe/H]_ph; see Table 2), we find a very similar equation (see Fig. 5):

$$[\text{Fe}/\text{H}]_{\text{ph}} = (3.034 \pm 0.177)(v_z - y_z) - (2.305 \pm 0.049)$$

(4)

Note that the fairly good correlation between v_z − y_z and metallicity is due to the small value of the age coefficient in equation (1), and also that the globular clusters used here have a small range of ages (8−13 Gyr). Thus, this “fast” calibration from color to [Fe/H] is only relevant for old stellar populations. Also shown in Figure 5 is the relationship for b_z − y_z, which is clearly not linear but does follow the predicted trend of bluer continuum colors for lower metallicity clusters. The calculated [Fe/H]_ph values are related to the real metallicity values (see Fig. 2) by the linear regression

$$\langle \text{[Fe}/\text{H]} \rangle = (0.876 \pm 0.065)[\text{Fe}/\text{H}]_{\text{ph}} - (0.174 \pm 0.104),$$

(5)

where ⟨[Fe/H]⟩ is mean value of [Fe/H] from Salaris & Weiss (2002). Substituting for [Fe/H]_ph gives

$$\langle \text{[Fe}/\text{H]} \rangle = (2.658 \pm 0.089)(v_z - y_z) - (2.193 \pm 0.052),$$

(6)

which is nearly identical to equation (3). We can use this solution as a quick estimation of metallicity, knowing only one color index, v_z − y_z, since v_z − y_z is the most sensitive indicator of metallicity, because of its measurement of an absorption-line-rich region of the spectrum. To achieve a more accurate estimate of metal abundance, we would need the mean effective temperature of the stellar population in order to calculate the abundance directly from the strength of absorption lines. This implies that the relationship between v_z − y_z is only true for the systems composed of stellar populations of identical temperatures. Therefore, in the absence of temperature information, we combine all three colors as given by PC1, resulting in

$$X = 0.480(u_z - v_z) + 0.506(b_z - y_z) + 0.511(v_z - y_z)$$

(7)

and derive the approximation

$$[\text{Fe}/\text{H}] = -4.24 + 6.47X - 2.29X^2,$$

(8)

which is plotted in Figure 6 for visual comparison. This relation delivers the same values for the metallicity as the principal component analysis for globular clusters and SSP models. In addition, we can apply the same PC method outlined above to the multicolor data we have acquired for dwarf and bright ellipticals from our Coma and field samples (Odell et al. 2002). The resulting [Fe/H] values for this sample of galaxies are also shown in Figure 6, with the caveat here being that the galaxies are assumed to be SSPs, such as globular clusters. While galaxies given in Figure 6 follow the same trend as globulars, the relationship is not linear. We interpret this as confirmation that ellipticals are not SSPs, but rather the summation of many SSPs to form a composite stellar population. However, the low-order difference between globulars and ellipticals signals that the SSP assumption is an adequate approximation for many needs and that the total stellar population in ellipticals must be a simple form (such as a Gaussian distribution) to produce the correlation seen in Figure 6 (see also Smolcic et al. 2005). In fact,
Fig. 8.—Calculated cluster age $T_{ph}$ by the iterative technique as a function of the PC2 indices including [Fe/H]. While the correlation is not as clear as the metallicity relationship, the general trend is discernible and will serve as a crude indicator of age for more complex systems.

6. AGE CALIBRATION

Unfortunately, there is no similar simple solution for the estimation of age that there was for metallicity. In general, mean stellar age correlates with metallicity, since an older population was formed from low-metallicity material, but this correlation is rather variable, depending on the effects of the local environment and the local history of star formation. And, of course, this is the parameter we wish to determine in order to understand the galaxy evolution process. In our Galaxy, younger and older clusters are divided by age difference on the order of 10 Gyr, and older clusters are more metal-poor.

The computed ages for measured globular clusters are listed in Table 2. The recent compilation and discussion of globular ages is found in Salaris & Weiss (2002). There are two sets of ages with the designations CG97 and ZW84, and again the mean is compared with our measurements listed as $T_{ph}$ in Figure 3. The correlation is better than expected and is comparable to the correlation between CG97 and ZW84 itself. For comparison, we have at our disposal only 26 values from the paper of Salaris & Weiss, as opposed to our 40 photometric measurements. We can calculate the mean value of square differences between our estimation and the mean age of CG97 and ZW84; these are plotted in Figure 7. The scatter increases toward larger ages or for metallicities below $-1.7$. This implies a higher uncertainty for values extrapolated outside the models we have used. The realistic estimations of stellar population ages are until now very scarce, and outside our Galaxy, practically impossible unless the underlying HR diagram can be resolved (see Grebel 2004).

An alternative approach would be to derive the metallicity of an object as shown in the previous section, then apply a linear combination of [Fe/H] and all three narrowband colors. For the globular cluster sample, this is shown in Figure 8, again using the PC values from equation (2). The resulting correlation is poor, although a least-squares linear fit can be made (shown in Figure 8). Much of the power in the fit is due to that fact that the globular cluster sample has a fair correlation between metallicity and age. However, the relative differences in age can be derived, and the method shows promise as a method to separate old and young galaxies in a relative sense, which can be a key test to hierarchical models of galaxy formation (Rakos & Schombert 2004).

7. SUMMARY

In this paper we have revised the age and metallicity calibration for the Stro¨mgren filter system as applied to globular clusters and elliptical galaxies. We have first investigated the behavior of the color indices, using the most recent SED models (Schulz et al. 2002) and have applied a principal component (PC) analysis to the SED models to determine the PC axis, in addition to the range and limitations of the color system. With this information, we have developed a technique to derive age and metallicity for a simple stellar population by an iterative calculation scheme. To test this method, we have obtained new photometry of 40 globular clusters with well-determined age and metallicity values and demonstrated that we can recover their star formation history values using our iterative scheme. Finally, we have redetermined the age and metallicity calibration for galaxies with new multicolor indices and tested the calibration against a sample of field and cluster ellipticals that contain a variety of spectroscopic and photometrically determined stellar population indicators.

Our next paper will concentrate on the application of our method to dwarf and normal ellipticals in clusters of galaxies. However, we can already deduce from the low scatter in [Fe/H] curves that the observed colors in ellipticals are primarily driven by the effects of metallicity, and not age. While absolute age determination is problematic, relative age measurements on the level of 1 Gyr can be extracted with sufficiently accurate photometry (errors <0.02 mag).

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APPENDIX

TABLE 3
NGC 6397 Initial Loop

| Test Number | Age (Gyr) and [Fe/H] |  |
|-------------|----------------------|---|
|             | 12.4, −1.966        | 13.5, −1.978 | 13.9, −2.206 |
| 1           | 12.42, −1.944        | 13.53, −1.935 | 13.88, −2.322 |
| 2           | 12.45, −1.904        | 13.57, −1.861 | 13.84, −2.528 |
| 3           | 12.49, −1.834        | 13.63, −1.733 | 13.75, −2.905 |
| 4           | 12.54, −1.713        | 13.71, −1.713 | 13.57, −3.626 |
| 5           | 12.62, −1.504        | 13.85, −1.683 | 13.19, −5.123 |
| 6           | 12.75, −1.155        | 14.05, −0.601 | 12.31, −8.850 |
| Mean        | 12.54, −1.676        | 13.72, −1.469 | 13.42, −4.226 |
| Sum σ²      | 0.075, 0.4512        | 0.193, 1.2900 | 1.804, 30.799 |

As an example of our technique to derive metallicity and age from the PC components of a SSP, we demonstrate the calculation procedure for the globular cluster NGC 6397. We have selected NGC 6397 as an example, since its [Fe/H] value (−1.88) is lower than the range of model values, and thus we must use an extrapolation that allows the metallicity loop to run over the border given by the lowest model metallicity (−1.7). Equation (6) gives an initial estimate for the metallicity of NGC 6397 of [Fe/H] = −2.01; equation (8) predicts −2.13.

In Table 3, three pairs of age (12.4, 13.5, and 13.9 Gyr) and metallicity (−1.966, −1.978 and −2.206) are selected to cover a broad range of age and metallicity at the boundary of the published models. Six of the iterated test values using equations (1) and (2) are shown below each pair. As each test converges on a unique minimum at age and metallicity, the solid line is a second-order fit to the errors, displaying a clear minimum at age and metallicity pair 13.2 Gyr and [Fe/H] = −2.026.

PC1 and PC2 values, the range in age and metallicity values becomes smaller. This is measured by the mean values of each loop and the sum of the squares of the deviations from the mean. For the initial loop, these deviations are large, as expected. From further iterations, we find the minimum to be between the first two pairs.

FIG. 9.—Visual example of the iterative difference errors for six [Fe/H] values in the globular cluster NGC 6397 data (see Table 4), where the sum of the squares of the deviations from the mean is plotted vs. the iteration pairs of age and metallicity. The solid line is a second-order fit to the errors, displaying a clear minimum at age and metallicity pair 13.2 Gyr and [Fe/H] = −2.026.

TABLE 4
NGC 6397 Age and [Fe/H] Loops

| Loop Number | Selected Age and [Fe/H] |  |
|-------------|-------------------------|---|
|             | 12.9, −2.014            | 13.0, −2.018 | 13.1, −2.022 | 13.2, −2.026 | 13.3, −2.030 | 13.4, −2.034 |
| Age Loop:   | 12.92                   | 13.02 | 13.12 | 13.22 | 13.32 | 13.42 |
| 1           |                         | 12.93 | 13.04 | 13.14 | 13.24 | 13.34 | 13.44 |
| 2           |                         | 12.95 | 13.05 | 13.15 | 13.25 | 13.35 | 13.45 |
| 3           |                         | 12.97 | 13.07 | 13.17 | 13.27 | 13.37 | 13.47 |
| 4           |                         | 12.99 | 13.09 | 13.19 | 13.29 | 13.39 | 13.49 |
| 5           |                         | 13.01 | 13.11 | 13.21 | 13.31 | 13.41 | 13.51 |
| 6           |                         | 12.96 | 13.06 | 13.16 | 13.26 | 13.36 | 13.46 |
| Mean        | 12.96                   | 13.06 | 13.16 | 13.26 | 13.36 | 13.46 |
| Sum σ² (× 10⁻⁴) | 61                      | 55    | 55    | 55    | 55    |
| [Fe/H] Loop:| 1.978                   | 13.9, −2.014 | 13.0, −2.018 | 13.1, −2.022 | 13.2, −2.026 | 13.3, −2.030 | 13.4, −2.034 |
| 1           | −2.014                  | −2.018 | −2.022 | −2.027 | −2.031 | −2.035 |
| 2           | −2.014                  | −2.018 | −2.023 | −2.027 | −2.032 | −2.036 |
| 3           | −2.013                  | −2.018 | −2.023 | −2.028 | −2.033 | −2.038 |
| 4           | −2.010                  | −2.016 | −2.023 | −2.029 | −2.035 | −2.040 |
| 5           | −2.005                  | −2.014 | −2.022 | −2.029 | −2.037 | −2.044 |
| 6           | −1.997                  | −2.008 | −2.019 | −2.030 | −2.040 | −2.050 |
| Mean        | −2.009                  | −2.015 | −2.022 | −2.028 | −2.035 | −2.041 |
| Sum σ² (× 10⁻⁴) | 227                     | 77    | 12    | 7     | 57    | 159   |

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Table 4 displays six more pairs for ages from 12.9 to 13.4 Gyr and metallicities from $-2.014$ to $-2.034$. The top portion of the table displays the age results for six iterative searches (metallicity loops are not shown). There is little variation in age within each loop, represented by a nearly constant value for the sum of the squares of the deviations from mean, indicating a broad range of acceptable solutions for age. Below the age loop values is a single sequence of metallicity loops (age loop number 4 in this case, although the variation from loop to loop was small). In the metallicity loop, there is a detectable trend in the sum of the deviations. We can plot the selected pair values as a function of sum of the squares of the deviations for the metallicity (Fig. 9) to demonstrate the final result: a parabola with a clear minimum that displays probable errors of about ±0.03 dex in metallicity and ±0.2 Gyr in age.

While the solutions are older in age and lower in metallicity than the CMD fits from Salaris & Weiss (2002), this cluster is an extreme example and is outside the models shown in Figure 1, yet it still converges to a solution. In addition, we note that Pasquini et al. (2004) find an age for NGC 6397 that is 0.3 Gyr older than the Galactic disk, based on beryllium measurements. Strömgren photometry of the Galactic disk derives an age estimate of between 13.2 and 13.5 Gyr (Twarog 1980), which would make our age determination of 13.2 Gyr for NGC 6397 exactly in line with the beryllium value.

REFERENCES

Bell, R., & Gustafsson, B. 1978, A&AS, 34, 229
Burstein, D. 1985, PASP, 97, 89
Ferreras, I., Charlot, S., & Silk, J. 1999, ApJ, 521, 81
Frogel, J. 1985, ApJ, 298, 528
Grebel, E. 2004, Carnegie Obs. Astrophys. Ser. 4, Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Cambridge: Cambridge Univ. Press), 237
Harris, W. 1996, AJ, 112, 1487
Kuntschner, H. 2000, MNRAS, 315, 184
Murtagh, F., & Heck, A. 1987, Multivariate Data Analysis (Dordrecht: Reidel)
O’Connell, R. 1980, ApJ, 236, 430
Odell, A., Schomber, J., & Rakos, K. 2002, AJ, 124, 3061
Pasquini, L., Bonifacio, P., Randich, S., Galli, D., & Gratton, R. 2004, A&A, 426, 651
Rakos, K., Maindl, T., & Schomber, J. 1996, ApJ, 466, 122
Rakos, K., & Schomber, J. 2004, AJ, 127, 1502
Rakos, K., Schomber, J., Maitzen, H., Prugovecki, S., & Odell, A. 2001, AJ, 121, 1974
Renzini, A., & Buzzoni, A. 1986, in Spectral Evolution of Galaxies, ed. C. Chiosi & A. Renzini (Dordrecht: Reidel), 195
Salaris, M., & Weiss, A. 2002, A&A, 388, 492
Sandage, A., & Visvanathan, N. 1978, ApJ, 223, 707
Schulz, J., Fritze-v. Alvensleben, U., Möller, C. S., & Fricke, K. J. 2002, A&AS, 392, 1
Smolcic, V., et al. 2005, MNRAS, in press
Steindling, S., Brosch, N., & Rakos, K. 2001, ApJS, 132, 19
Tinsley, B. 1980, Fundamentals of Cosmic Physics, Vol. 5, (New York: Gordon and Breach), 287
Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, AJ, 120, 165
Twarog, B. 1980, ApJ, 242, 242
Worthey, G. 1994, ApJS, 95, 107
———. 1999, in ASP Conf. Proc. 192, Spectrophotometric Dating of Stars and Galaxies, ed. I. Hubeny, S. Heap, & R. Cornett (San Francisco: ASP), 283