Abstract

We have measured the extinction of red giant branch (RGB) and asymptotic giant branch (AGB) stars in galaxies, and we have used these measurements to test the predictions of population synthesis models. We find that the models predict the colors of the RGB and AGB stars, but that the observed colors are systematically redder. This suggests that the models may be missing some important component of the stellar population. We have also measured the extinction of the nearby galaxy NGC 613, and we find that the extinction is consistent with the predicted values.

Testing population synthesis models with RGB and AGB stars.
used instead). We dereddened the clusters' colors using the values of $E_{B-V}$ given in the catalogs and the Cardelli et al. (1989) extinction curve for $R_V = 3.1$. For M31, we excluded clusters where the color in the spectroscopic metallicity was $\sigma_{[Fe/H]} > 0.5$, and clusters suspected of being young on the basis of strong Balmer absorption or blue $B-V$ colors (see Barnby et al. 2000). For both galaxies, we excluded clusters with $E_{B-V} > 0.5$; there are 103 M31 and 85 Galactic clusters in the final sample. Photometric data is not available in all bandpasses for all clusters: only about two-thirds have measured $R$ and $I$, and less than half have $H$.

We compare the cluster colors to those for simple stellar populations of ages 8, 12, and 16 Gyr from three sets of models: those of Worthey\(^1\), Bruzual and Charlot (hereafter BC) (both the Worthey and BC models are reported in Leitherer et al. 1996), and Kurth et al. (1999) (hereafter KFF). Although model colors are tabulated in smaller age increments (typically 1 Gyr), initially it is more reasonable to use the models as a rough guide to relative ages rather than attempting to derive precise cluster ages from them. The Worthey models are computed at $[Fe/H]$ values of $-2.0, -1.5, -1.0, -0.5$, and $-0.25$ dex, and the BC and KFF models are computed at $[Fe/H]$ values of $-2.33$ (KFF models only), $-1.63$, $-0.63$, and $-0.32$ dex. We compared clusters to both the Salpeter IMF (Worthey’s ‘vanilla’ models) and Scalo (1986) (Miller & Scalo 1979, in the Worthey models) IMF version of the models. Worthey (1994) finds that some of his model colors have defects (e.g., $B-V$ is too red by $0.04-0.06$ mag due to problems in the theoretical stellar atmospheres and the color-temperature calibration), but the sizes of these defects are not well-determined so we do not correct for them. Figure 1 shows data and models in two frequently-used two-color diagrams.

Since the models are computed at discrete values of $[Fe/H]$, we use the spectroscopic metallicities of the clusters to compare only clusters with comparable metallicities ($\pm 0.25$ dex) to each model. The Galactic cluster metallicities given in Harris (1996) are on the Zinn & West (1984) (ZW) metallicity scale, and the M31 cluster metallicities are also tied to this scale through the calibration of Brodie & Huchra (1990). Recent work (Carretta & Gratton 1997; Rutledge et al. 1997) suggests that the ZW scale may be non-linear at both high and low metallicities. We retain the ZW scale in this paper because we found that using the Carretta & Gratton (1997) scale to assign clusters to model comparison bins made little difference in our results. We caution, however, that the effect of changing the metallicity scale is unknown for the $[Fe/H] = -0.25$ model bin. The transformation from the ZW to CG scales is only defined for $[Fe/H]_{ZW} < -0.5$, the lower limit of this metallicity bin.

We calculated the mean offsets between model and cluster colors (referenced to $V$) for each metallicity bin; Figures 2–3 show some representative comparisons. We plot $\Delta (X-V)$ for all bandpasses $X$ to make clear the differences in spectral energy distributions between models and data; we remind the reader that the offsets for bandpasses redward of $V$ thus have the opposite sign from the usual colors. One general characteristic of the models visible in the Figures is that younger-aged models predict bluer colors. The exception is the KFF Scalo model for $[Fe/H] = -1.63$, which predicts only very small color differences ($\lesssim 0.01$ mag) between ages of 12 and 16 Gyr. The effect of the IMF on the colors appears to depend on both metallicity and age. For the Worthey $[Fe/H] = -1.50$ models, Miller-Scalo IMF colors are redder than Salpeter model colors at all ages, but for the $[Fe/H] = -0.50$ models, the Miller-Scalo IMF colors are bluer for 8 and 12 Gyr and almost identical for 16 Gyr. BC predict almost no color difference between the Salpeter and Scalo IMF models of the same age and metallicity.

A striking feature in Figures 2 and 3 is the range of discrepancies between models and data. For example, the largest difference between the Worthey model with parameters (Salpeter IMF, $[Fe/H] = -1.50$, age 16 Gyr) and the mean colors of clusters with $-1.75 \leq [Fe/H] \leq -1.25$ is 0.04 mag in $U-V$. The same models with $[Fe/H] = -0.50$ are well-represented by the data at all colors except $U-V$; the largest offset is 0.23 mag in $V-K$. To determine the best-fitting models, we quantified the overall goodness-of-fit for each model/cluster

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\(^1\)The version we used updates the Worthey (1994) models by including a more realistic treatment of the horizontal branch for $[Fe/H] < -1.0$.\[1\]
metallicity bin pair as:
\[
F = \frac{\sum_k \Delta(X - V)k / \sigma_k^2}{\sum_k 1 / \sigma_k^2}
\]
(1)
The color differences $\Delta(X - V)k$ are weighted by $1/\sigma_k^2$, where $\sigma_k$ are the standard errors in the mean colors of objects in the bin. Table 1 gives the $\Delta$ and $F$ values for the best fitting models in each metallicity bin.

3. Discussion

Table 1 shows that the best-fitting models fit the data quite well, with typical color offsets of $0.02 - 0.03\arcsec$. The two bandpasses with the most significant offsets are $U$ and $B$: the models are too blue in $U - V$ and too red in $B - V$. Neither offset shows a clear trend with metallicity. The offsets are likely not due to systematics in the photometric system or in the extinction curve. While problems with the photometric systems might be expected in the $R$ and $I$ bands (due to conversion between the Johnson and Cousins $RI$ systems), both data and models use the well-defined Johnson $UBV$ system. Problems in the reddening curve also seem unlikely for the same reasons. We suspect that the offsets are more likely due to systematic errors in the models. The $B - V$ offset in particular is likely due to the flux libraries used. Both Worthey (1994) and Lejeune (1997) found their model $B - V$ colors to be $0.04 - 0.06\arcsec$ too red compared to empirical solar-metallicity spectra, even after correcting to the empirical color-temperature scale. This suggests a possible problem with the stellar atmosphere models of Kurucz (1995), upon which both libraries are based.

The cause of the offset in $U - V$ is not as clear. This offset is actually worse than it appears: since we compute the $U - V$ colors for the BC and KFF models as $(U - B) + (B - V)$, the red $B - V$ colors compensate for some of the $U - B$ defect, which is actually larger than the defect in $U - V$. Worthey (1994) - whose models give $U - V$ directly - finds that his model $U - V$ is too blue compared to solar neighborhood stars and elliptical galaxies. Worthey cites problems with the $U$ fluxes from the stellar libraries as a possible cause: modeling the many blended atomic and molecular lines bluerward of $B$ is difficult, and many of the necessary opacities are not well determined. This cannot be the only cause of model problems in $U$, since the BC and KFF models, which use the same stellar library, predict different $U - V$ colors. The treatment of the horizontal branch in the models is another possible source of problems in the $U - V$ colors because the HB emits most of the blue light. However, systematic problems with the model HB color (which depends on metallicity), would presumably produce a $U - V$ offset dependent on metallicity, which we do not observe. Observational error is another possible contributor to the $U - V$ offset, as many of the $U - B$ colors of the M31 clusters are poorly determined (see Table 3 of Barnby et al. 2000). Understanding the rest-frame $U$ flux of stellar populations becomes increasingly important when studying high-redshift galaxies and global star formation history, and further investigation of the models in this bandpass is clearly warranted.

A secondary result in Table 1 is that age determines which model best fits the data. Higher-metallicity cluster colors are best fit by 8 Gyr models, regardless of IMF. Lower-metallicity cluster colors ([Fe/H]$_{\text{bin}} \leq -1.00$) are best fit by 12 or 16 Gyr models. The best-fit age depends on the IMF for several of the models, but not in any systematic fashion. This result is consistent with the determinations of relative ages for Galactic clusters by Rosenberg et al. (1999). These authors determined relative ages of 35 Galactic globular clusters from a homogeneous set of $V$, $V - I$ color-magnitude diagrams. They compared theoretical isochrones with the observational CMDs to determine ages using two independent methods. They found that the clusters with [Fe/H]$_{\text{GC}} > -0.9$ were ~17\% younger than clusters with [Fe/H]$_{\text{GC}} < -1.2$, with the intermediate-metallicity clusters showing a ~25\% age dispersion. These results are model-dependent, as are ours, but the results’ similarity implies that either there is a real difference between metal-rich and metal-poor clusters or there is a systematic problem in the models in one of the metallicity regimes.

What possible systematic errors in our input data or comparison procedure could produce the result that the metal-rich clusters are younger? We reid the comparison procedure considering the clusters of each galaxy separately, and still found younger ages for the most metal-rich clus-
ters. Although M31 has a greater proportion of the metal-rich clusters, younger ages are found for both M31 and Galactic metal-rich clusters. Cohen & Matthews (1994) suggest that the spectroscopic metallicities of the most metal-rich M31 clusters measured by Huchra et al. (1991) are systematically too high. If this is true, the clusters would appear too blue compared to old, high-metallicity models and the best-fit model would be younger. We compared the metal-rich M31 clusters to the Worthey [Fe/H] = −1.0 models, and the best-fitting model had age 16 Gyr. However, the goodness-of-fit was better for the young, metal-rich models than for the older, more metal-poor model, so we conclude that younger ages are still favored for these clusters. Overestimating the reddening of the metal-rich clusters would make the derived intrinsic colors too blue and yield younger ages. This seems unlikely, given that the color-metallicity relations for Galactic and M31 clusters match well throughout their metallicity range (see Barnby et al. 2000), and the methods of reddening determination for M31 and Galactic clusters are different.

If the detection of younger ages for metal-rich globular clusters is real, it has implications for galaxy formation. A range of GC ages implies that GC formation took place over an extended period of time. Conditions for GC formation were not particular to the early universe, an assertion supported by observations of ‘proto-globular’ clusters in present-day merging galaxies (e.g., Zepf et al. 1999). More precise knowledge of the distribution of cluster ages in each galaxy would be extremely useful in understanding cluster system formation. If the age distribution is continuous, the relation between age and metallicity might hold clues as to what factors controlled the cluster formation rate. If the age distribution is bimodal – with most clusters old and coeval and the remainder younger and coeval – then some event must have triggered the second episode of GC formation. Perhaps the younger clusters were stripped from or accreted along with satellite galaxies of M31 and the Galaxy.

4. Conclusions

Comparison of three sets of population synthesis models with integrated colors of M31 and Galactic globular clusters shows that the models reproduce the redder average cluster colors to within the observational uncertainties. The poorer agreement in $U-V$ and $B-V$ is likely due to systematic errors in the models. Younger-age models are required to best match the colors of the metal-rich clusters, consistent with the findings of Rosenberg et al. (1999) that the most metal-rich Galactic clusters are younger than the bulk of the globular cluster population. A range of ages for globular clusters implies that conditions for cluster formation were not restricted to the early universe. The cluster age distribution has important implications for galaxy and globular cluster system formation, and attempts to determine it more precisely are needed.

REFERENCES

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Fig. 1.— $(B-V)_0$ vs. $(U-V)_0$ and $(V-K)_0$ for M31 globular clusters (triangles) and Galactic GCs (squares). Lines are population synthesis models of ages 8 Gyr (bluer colors) and 16 Gyr (redder colors): Worthey (solid), BC (dashed), KFF (dotted).
Fig. 2.— Color offsets $\Delta(X - V)\ (\text{data-models})$ for Salpeter IMF. ($\Delta V = 0$ is plotted to emphasize that the models are normalized to the data at $V$.) Solid lines: 16 Gyr models, dotted lines: 12 Gyr models, dashed lines: 8 Gyr models. The $-1.5$ and $-0.5$ bins in [Fe/H] are Worthey models; the $-1.63$ and $-0.63$ [Fe/H] bins are BC models. Error bars (plotted only on the 8 Gyr models for clarity) are the standard errors of the mean cluster colors and do not include observational uncertainties.
Fig. 3.— Color offsets $\Delta(X - V)$ or $\Delta(V - X)$ (data–models) for Scalo or Miller-Scalo IMF. Symbols same as Figure 2. The $-1.5$ and $-0.5$ bins in [Fe/H] are Worthey models; the $-1.63$ and $-0.63$ [Fe/H] bins are KFF models (which have no $\Delta(J - V)$, $\Delta(H - V)$ since they do not predict these colors).
\begin{table}
\centering
\caption{Color offsets for best-fitting models}
\begin{tabular}{cccccccccc}
\hline
\[\text{[Fe/H]}\] & \text{model} & \(F\) & \(N_{\nu}\) & \(\Delta(U-V)\) & \(\Delta(B-V)\) & \(\Delta(V-R)\) & \(\Delta(V-I)\) & \(\Delta(V-J)\) & \(\Delta(V-H)\) & \(\Delta(V-K)\) \\
\hline
-0.25 & W8sc & 0.023 & 15 & 23.4 ± 2.4 & -0.4 ± 0.9 & -3.0 ± 1.1 & -0.3 ± 1.0 & 3.2 ± 1.6 & -1.4 ± 6.0 & -6.0 ± 4.9 \\
-0.32 & K8sc & 0.022 & 17 & 11.5 ± 2.2 & -2.5 ± 0.8 & -2.1 ± 1.0 & 0.2 ± 0.9 & \cdots & \cdots & -3.9 ± 4.6 \\
-0.50 & W8sc & 0.013 & 30 & 21.8 ± 3.1 & -0.3 ± 0.8 & -1.0 ± 0.7 & 1.2 ± 1.3 & 4.6 ± 4.6 & 2.8 ± 5.2 & -3.3 ± 7.2 \\
-0.63 & K8sp & 0.012 & 35 & 12.2 ± 3.2 & -1.0 ± 0.9 & -0.6 ± 0.6 & 2.4 ± 1.2 & \cdots & \cdots & 2.1 ± 5.9 \\
-1.00 & W1sc & 0.014 & 48 & 13.7 ± 2.2 & -2.3 ± 1.0 & 0.0 ± 0.5 & -1.1 ± 1.2 & 3.2 ± 1.8 & 6.9 ± 2.5 & 4.3 ± 2.1 \\
-1.30 & W16sp & 0.016 & 75 & 4.1 ± 1.4 & -3.0 ± 0.6 & -0.3 ± 0.5 & -1.0 ± 0.8 & 2.0 ± 1.7 & -0.7 ± 3.3 & 2.0 ± 2.3 \\
-1.63 & K16sp & 0.019 & 77 & 5.1 ± 1.2 & -0.7 ± 0.5 & 1.7 ± 0.4 & 2.8 ± 0.7 & \cdots & \cdots & 10.8 ± 3.1 \\
-2.00 & K16sp & 0.027 & 37 & 8.2 ± 1.2 & -2.6 ± 0.6 & -0.3 ± 0.8 & -1.6 ± 1.2 & -6.7 ± 2.6 & -5.2 ± 3.7 & -5.8 ± 3.5 \\
-2.23 & K16sp & 0.027 & 12 & 4.1 ± 2.3 & 1.8 ± 1.3 & 2.3 ± 2.1 & 3.4 ± 2.0 & \cdots & \cdots & -7.1 ± 6.2 \\
\hline
\end{tabular}
\end{table}

\textbf{Note.}—Units are hundredths of a magnitude. The capital letter in the model column indicates the best-fitting model (Worthey, BC or KFF), the number is the model age in Gyr, and 'sp' or 'sc' indicate Salpeter or Scalo IMF, respectively.