THE GRADIENTS IN THE 47 Tuc RED GIANT BRANCH BUMP AND HORIZONTAL BRANCH ARE CONSISTENT WITH A CENTRALLY CONCENTRATED, HELIUM-ENRICHED SECOND STELLAR GENERATION

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ABSTRACT

We combine ground- and space-based photometry of the Galactic globular cluster 47 Tuc to measure four independent lines of evidence for a helium gradient in the cluster, whereby stars in the cluster outskirts would have a lower initial helium abundance than stars in and near the cluster core. For our first and second lines of evidence, we show that the red giant branch bump stars exhibit gradients in their number counts and brightness. With increased separation from the cluster center, they become more numerous relative to the other red giant stars. They also become fainter. For our third and fourth lines of evidence, we show that the horizontal branch of the cluster becomes both fainter and redder for sightlines farther from the cluster center. These four results are respectively detected at the $2.3\sigma$, $3.6\sigma$, $7.7\sigma$, and $4.1\sigma$ levels. Each of these independent lines of evidence is found to be significant in the cluster outskirts; closer in, the data are more compatible with uniform mixing. Our radial profile is qualitatively consistent with but quantitatively tighter than previous results based on CN absorption. These observations are qualitatively consistent with a scenario wherein a second generation of stars with enhanced helium formed deep within the gravitational potential of a cluster of previous generation stars having more canonical abundances.

Key words: globular clusters: individual: NGC 104 (47 Tuc)

1. INTRODUCTION

47 Tuc (NGC 104) is among the most massive globular clusters in the Galaxy and is thus one of the most powerful laboratories to investigate the finer details of globular cluster formation and evolution. As the large stellar population renders any potential statistic more accessible, it is interesting that 47 Tuc is not among those globular clusters with more clearly delineated photometric evidence for multiple populations (Bergbusch & Stetson 2009).

However, it has been known for several decades that the stars in the inner part of the globular cluster have stronger CN absorption (Norris & Freeman 1979; Paltoglou 1990). Recently, di Criscienzo et al. (2010) have argued that this chemical gradient is due to the presence of multiple generations of stars, with later generations being helium and CN enhanced by the ejecta of first-generation asymptotic giant branch (AGB) stars. They found strong evidence of a helium spread in the morphology of the subgiant branch (SGB) and horizontal-branch (HB) stars. They compared synthetic populations to the observed photometric data for the cluster and estimated that $\sim70\%$ belong to the subsequent generations of stars. Their work followed an investigation by Anderson et al. (2009), who used Hubble Space Telescope (HST) data to measured the color widths of the cluster main sequence, which they argued could be explained by a spread of $\Delta Y \sim 0.027$. If the helium enhancement is due to a second generation, and if the second generation is indeed more centrally concentrated, as suggested by the CN band strengths and dynamical arguments (D’Ercole et al. 2008), one should expect a higher helium abundance in the center. It has recently been posited that the presence of multiple generations differing in properties such as initial helium abundance and the relative abundances of sodium and oxygen are in fact a ubiquitous property of globular clusters (Carretta et al. 2010). We also note that the origins of multiple generations are a matter of controversy. There are arguments that this self-enrichment could originate from the fast rotating massive star winds of first-generation stars (Prantzos & Charbonnel 2006; Meynet et al. 2006; Decressin et al. 2007).

In this paper, we test the hypothesis of a helium gradient in 47 Tuc using four methods that are rooted in the properties of two densely populated phases of post-main-sequence stellar evolution, the red giant branch bump (RGBB) and the HB. The RGBB phase occurs during the first ascent of the red giant branch (RGB). As the hydrogen-burning shell expands, it eventually comes into contact with the convective envelope (Cassisi & Salaris 1997). This increase in fuel causes the star to become fainter as the fuel is used up before becoming brighter again, effectively crossing the same luminosity three times, leading to a “bump” in the luminosity function. This bump is most populated and thus more measurable in metal-rich clusters such as 47 Tuc (Zoccali et al. 1999; Bono et al. 2001; Riello et al. 2003; Di Cecco et al. 2010; Cassisi et al. 2011).

Stellar evolution predicts the RGBB lifetime to be significantly shortened for increased initial helium abundance (Bono et al. 2001; Di Cecco et al. 2010; Nataf et al. 2011). If this stellar theory prediction is correct, and the hypothesis of a centrally concentrated, helium-enhanced population in 47 Tuc is correct as well, then RGBB stars should be less prominent relative to the remaining red giant (RG) stars closer to the cluster center. We detect a variation in the equivalent width (EW) of the RGBB at the $\sim2.3\sigma$ level. The EW is a measure of the strength of the RGBB feature first introduced in Nataf et al. (2011) and described in Section 4 of this paper. For our second test, we also show that the RGBB stars are fainter with increasing distance from the cluster center, a detection made at the $\sim3.6\sigma$ level.

We also investigate the cluster HB stars. We show that the HB stars are both brighter ($\sim7.7\sigma$) and bluer ($\sim4.1\sigma$) closer to...
the cluster center, though the gradient levels off in the inner ∼200′. This is the expected trend for increased helium in stellar models, as seen for example in Figure 1 of di Criscienzo et al. (2010), which was produced using the code ATON 2.0 (Ventura et al. 1998; Ventura & D’Antona 2009). Briley (1997) showed with high confidence that the HB stars with strong CN absorption were ∼0.04 mag brighter. They argued that this effect could be explained by either a small difference in the core mass of helium-burning stars or a small difference in the initial helium abundance of those brighter, CN-enhanced HB stars. These results show that the cluster HB is consistent with a concentrated, second stellar generation having enhanced helium and CN.

We have conducted these experiments by combining two independent data sets, a space-based data set toward the cluster center (Sarajedini et al. 2007) and a comprehensive ground-based data set for the remaining sightlines (Stetson 2000). The latter contains ∼60% of the stellar subpopulations studied in this paper. The two data sets respectively include ∼500 and ∼700 HB stars, as well as ∼120 and ∼150 RGBB stars. For all four tests, we find significant detections of the trends expected from a helium gradient in the cluster outskirts, with no discernible trend within the cluster center. This is most consistent with a picture of two stellar generations that are evenly mixed within the cluster center, but with the second generation having a characteristic radius beyond which its numbers fall more rapidly. Our estimated transition radius of a few arcminutes is smaller than that derived from previous investigations of CN absorption among cluster giants. Briley (1997) found that the ratio of CN-strong to CN-weak stars was approximately constant up to ∼10–15 arcmin separations from the cluster center, beyond which the ratio fell rapidly.

The structure of this paper is as follows. We describe our data in Section 2, and the models with which we interpret the data in Section 3. The main RGBB and HB measurements are respectively described in Sections 4 and 5. Evidence of a slight gradient in the color of the RGB is presented in Section 6. We discuss our results in Section 7.

2. DATA

We make use of two different data sets in this study to maximize the available information and constrain the effect of any possible systematics.

For the cluster center, we use photometry obtained with HST’s Advanced Camera for Surveys (ACS; Sarajedini et al. 2007) and extend to separations of ∼140′ from the cluster center. The data were taken as part of an HST treasury program to obtain high signal-to-noise ratio photometry down to the lower main sequence for a large number of Galactic globular clusters. We use $V_{\text{ground}}$ and $I_{\text{ground}}$ (hereafter “$V$” and “$I$”) photometry, which were transformed from the original F606W and F814W photometry. Artificial star tests demonstrate that the photometry is expected to be very precise and complete at the brightness of the RGBB (Anderson et al. 2008).

We also use $U$, $B$, $V$, and $I$ observations that come from a database of original and archival observations (Stetson 2000), which are calibrated on the Landolt (1992) photometric system. These observations and the general properties of the 47 Tuc color–magnitude diagram (CMD) are described in Bergbusch & Stetson (2009). We make use of stars in these observations that are outside of the coordinate range observed by the ACS data set; these extend to separations of ∼1400′ from the cluster center. The 135 point sources that are located within 30′ of ($\alpha, \delta$) = (00:21:30.3, −71:56:03), corresponding to the location of Bologna A (Bellazzini et al. 2005), are not included in our analysis. This does not affect our analysis as the background population is way outside the cluster center and its spatial extent is only 60′. We show the respective fields of view in Figure 1. CMDs for the space-based and ground-based data sets are, respectively, shown in Figures 2 and 3.

3. STELLAR EVOLUTION MODELS

We use the Yale Rotating Evolution Code (Delahaye et al. 2010) to compare our output parameters to theory for the RG and RGBB populations. Theoretical considerations for the HB population are taken from the literature (Renzini 1994; Ventura...
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4. RED GIANT BRANCH BUMP GRADIENTS IN BRIGHTNESS AND NUMBER COUNTS

We show that the RGBB grows both fainter and more numerous relative to the RG stars with increased separation from the cluster center, and that the trends are both statistically significant. None of these trends are detected with significance in the inner \( \sim 100'' \) of the cluster as traced by the space-based data set, consistent with previous work (Briley 1997) and our measurements of the HB (discussed in Section 5) that the two stellar populations are smoothly mixed in and near the cluster center.

4.1. Fitting for the RGBB

In both data sets, we cut out a parallelogram around the RGB that keeps stars no more than 1.0 mag brighter or 1.6 mag fainter than the RGBB in \( V \). The range in magnitude is chosen to be as wide as possible while still excluding the HB and AGB stars. We show our color–magnitude cuts for the space-based and ground-based data in Figures 2 and 3, respectively.

We fit for the RGBB and the RG magnitude distribution using a combination of an exponential for the magnitude distribution of RG stars (equivalent to a power-law distribution in luminosity) and a Gaussian for the RGBB:

\[
N(m) = A \exp \left[ B(V - V_{\text{RGBB}}) \right] + \frac{N}{\sqrt{2\pi}\sigma} \exp \left[ -\frac{(V - V_{\text{RGBB}})^2}{2\sigma^2} \right],
\]

where \( V_{\text{RGBB}} \) is the peak magnitude of the RGBB, \( \sigma \) is the dispersion of the Gaussian used to fit the RGBB brightness distribution, \( N \) is the number of RGBB stars, and \( A \) and \( B \) are the normalization and scale of the exponential, respectively. Following Nataf et al. (2011), we defined the EW of the RGBB, to be the ratio of the number of RGBB stars to the number density of RG stars at the magnitude of the RGBB. In this parameterization \( EW = N/A \). We use Markov Chain Monte Carlo (MCMC) to obtain the maximum likelihood values for the parameters. For each value of the parameters tested by the MCMC, we compute the log-likelihood \( \ell \),

\[
\ell = \sum_i \ln[N(m/a, B, EW, \sigma, V_{\text{RGBB}})],
\]

where \( N_{\text{obs}} \) is the total number of stars, and the parameter \( A \) is selected in each run of the MCMC such that the integral of the function \( N(m) \) over the magnitude range is equal to \( N_{\text{obs}} \). We do not fit an RGBB model to the data by first binning it, but it can be shown that this method is equivalent to binning data in the limit of infinitesimal bin widths.

4.2. Evidence for Decreased Brightness and Increased Equivalent Width for RGBB Stars Farther from the Cluster Core

We fit for gradient in the EW and \( V_{\text{RGBB}} \) with separation from the cluster center using the following extension to our

| Table 1
| Predicted Stellar Properties of the RGBB |
|-----------------|-----------------|-----------------|
| Property         | Model A          | Model B          |
|                  | \( Y \) | \( \text{M/H} \) | \( \text{M}_\odot \) | \( \text{M}_\odot \) |
| Initial mass     | \( 0.90 \) | \( -0.52 \) | \( 0.86 \) | \( -0.50 \) |
| Age at RGBB      | \( 12.8 \text{ Gyr} \) | \( 11.93 \text{ Gyr} \) |
| Median RGBB brightness | \( 0.71 \text{(MBol)} \) | \( 0.63 \text{(MBol)} \) |
| \( T_{\text{eff}} \) at RGBB median brightness | \( 4536 \text{ K} \) | \( 4534 \text{ K} \) |
| RGBB EW          | \( 0.33 \text{ mag} \) | \( 0.28 \text{ mag} \) |
| RGBB lifetime    | \( 16.4 \text{ Myr} \) | \( 12.8 \text{ Myr} \) |
| Luminosity evolution before RGBB | \( 16.71 \text{ mag Gyr}^{-1} \) | \( 17.99 \text{ mag Gyr}^{-1} \) |
| Luminosity evolution after RGBB | \( 23.65 \text{ mag Gyr}^{-1} \) | \( 26.11 \text{ mag Gyr}^{-1} \) |
| \( \delta V_{\text{RGBB}} \) | \( 0.09 \text{ mag} \) | \( 0.06 \text{ mag} \) |

et al. 1998; Girardi & Salaris 2001; Ventura & D’Antona 2009; di Criscienzo et al. 2010).

At the expected metallicity \( \text{[M/H]} \sim -0.50 \) and age \( \sim 12 \text{ Gyr} \) of 47 Tuc (McWilliam & Bernstein 2008; Carretta et al. 2010), we find that every 1% increase in the initial helium abundance by total stellar mass yields a \sim 10% decrease in the lifetime of the RGBB, corresponding to a decrease of \sim 0.02 mag in the EW. Two representative models are shown in Figure 4. Within the models, we compute the EW of the RGBB by multiplying the lifetime of the RGBB by the average of the two slopes of magnitude versus time before and after the RGBB. The predicted stellar properties of the RGBB as a function of initial composition are summarized in Table 1. We note the helium-rich track has a higher initial \( \text{[M/H]} \) only because it has a lower initial hydrogen abundance—the initial metallicity content by mass are the same. We also introduce the notation \( \delta V_{\text{RGBB}} \) to refer to the difference in magnitudes between the brightest and faintest parts of the RGBB phase as predicted by stellar models.
Two representative stellar tracks for a 12 Gyr population with a metallicity \([M/H] \approx -0.50\). Model points with a luminosity corresponding to the RGBB phase are plotted in blue, and the underlying RGB in red. Top panel: primordial helium content \(Y = 0.25\), the EW of the RGBB is 0.33 mag. Bottom panel: primordial helium content \(Y = 0.28\), the EW of the RGBB is 0.28 mag. The EW is computed by multiplying the lifetime of the RGBB phase, shown by the length of the black horizontal line, by the average of the slopes of the luminosity evolution function just outside the RGBB, which are shown in green.

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**Figure 4.** Two representative stellar tracks for a 12 Gyr population with a metallicity \([M/H] \approx -0.50\). Model points with a luminosity corresponding to the RGBB phase are plotted in blue, and the underlying RGB in red. Top panel: primordial helium content \(Y = 0.25\), the EW of the RGBB is 0.33 mag. Bottom panel: primordial helium content \(Y = 0.28\), the EW of the RGBB is 0.28 mag. The EW is computed by multiplying the lifetime of the RGBB phase, shown by the length of the black horizontal line, by the average of the slopes of the luminosity evolution function just outside the RGBB, which are shown in green.

\[
V_{\text{RGBB}} = V_{\text{RGBB},0} + \frac{dV_{\text{RGBB}}}{d \log(r)} \times \left[ \log(r) - \log(r_0) \right],
\]

\[
\text{EW} = \text{EW}_0 + \frac{d\text{EW}}{d \log(r)} \times \left[ \log(r) - \log(r_0) \right],
\]

where \(r = (R_i - R_{\text{CC}})\) is the separation in arcseconds of the location of the \(i\)th star \(R_i\) from the cluster center \(R_{\text{CC}}\), taken here as being \((\alpha, \delta) = (00:24:05.4, -72:04:53)\), and is taken from Vizier (Ochsenbein et al. 2000). The mean of the logarithmic separation for all the RG+RGBB stars used to construct the fit is designated \(\log(r)\). We tested parameterizations of both separation, squared separation and the log of separation, and found that using the logarithmic separation from the cluster center yielded the largest improvement in the fit as measured by \(\Delta \ell\), the change in the log-likelihood defined in Equation (2).

Allowing gradients for both \(V_{\text{RGBB}}\) and EW yields \(dV_{\text{RGBB}}/d \log(r) = (0.083 \pm 0.023)\) mag dex\(^{-1}\), and \(d\text{EW}/d \log(r) = (0.27 \pm 0.12)\) mag dex\(^{-1}\) in the ground-based data set, with no significant gradient measured in the ACS data set. A graphical representation of these gradients is shown in Figure 5.

These two gradients each retain nearly identical values when the other is fixed to being zero and can therefore be considered independent. Both gradients go in the direction expected from stellar theory in the presence of a helium gradient where the stars in the cluster core have higher initial helium abundance. The model predictions shown in Figure 4 predict that for a 12 Gyr population with a metallicity \([M/H] \approx -0.50\), the brightness should increase by \(\sim 0.06\) and the EW should decrease by \(\sim 0.035\) mag as the initial helium abundance is increased from \(Y = 0.25\) to \(Y = 0.28\), the variation in \(\Delta Y\) previously suggested by studies of the cluster main sequence, SGB, and HB (Anderson et al. 2009; di Criscienzo et al. 2010). Since the total span of the ground-based data set in arcseconds is approximately 1 dex, the measured gradients are higher than the theoretical expectations. The brightness variation is \(\sim 1\sigma\) higher than the expected value, and the EW variation is \(\sim 2\sigma\) higher. A larger data set may be required to properly ascertain if the results are conflicting.

### 5. Horizontal Branch Gradients in Color and Brightness

The trends in color and brightness with respect to the distance to the cluster center for HB stars are compatible with a uniform mixing of the two stellar generations in and near the cluster center and with the helium-enhanced second generation decreasing more rapidly at larger radii. We discuss four possible contaminating effects and find that none of them have the same predicted trends as are observed.

As there is no definitive way to cleanly and completely separate HB stars from background contamination stars and AGB stars, we utilize visually satisfactory color–magnitude boxes in the space-based and ground-based data sets, respectively, shown in Figures 2 and 3. In the space-based data, we tabulate 545 stars with \(0.82\) mag < \((V - I)\) < 0.98 mag and 13.8 mag < \(V\) < 14.2 mag, whereas in the ground-based data set we tabulate 771 stars with 0.7 mag < \((B - V)\) < 0.9 mag and 13.8 mag < \(V\) < 14.2 mag. For both data sets, we compute
We refer the reader to Figure 1 of di Criscienzo et al. (2010). The HB stars in the space-based data set, toward the cluster center, have a slight trend of getting redder with increased separation from the cluster center. The correlation between brightness and the log of the separation from the cluster center.

In the ground-based data, the HB stars become fainter and redder with increased separation from the cluster center. The brightness gradient is $(0.072 \pm 0.009) \text{ mag dex}^{-1}$ in $V$, and the color gradient is $(0.021 \pm 0.005) \text{ mag dex}^{-1}$ in $(B-V)$. Using only those sources that have at least five measurements in each filter, we also obtain color gradients of $(0.064 \pm 0.009) \text{ mag dex}^{-1}$ in $(B-I)$ and $(0.078 \pm 0.013) \text{ mag dex}^{-1}$ in $(U-V)$. The gradients go in the same direction as expected if a helium-enriched, second-generation globular cluster exists in 47 Tuc with a more central concentration (di Criscienzo et al. 2010). The HB stars in the space-based data set, toward the cluster center, have a slight trend of getting redder with increased separation from the cluster center, but it is a very weak trend, $1.3 \sigma$, and is without a corresponding trend in brightness.

We show the colors and brightness for HB stars as a function of separation from the cluster center in Figure 6. The profile is one of even mixing between the two populations within the inner $\sim 200''$, with the brighter HB stars falling off in relative numbers between $\sim 200$ and $\sim 400''$. That the color and brightness profiles show the same structure with respect to separation from the cluster center is evidence that the trends are genuine attributes of the cluster stars rather than statistical fluctuations.

The potential contamination effects in this comparison would not go in the same direction as the measured gradient. First, both signals go in the opposite direction to the weak signal expected from the CNO variation in the cluster. As stars in the cluster center have higher CNO, they ought to be slightly ($\sim 0.01$ mag) redder and fainter with decreased distance to the cluster center. We refer the reader to Figure 1 of di Criscienzo et al. (2010).

We find evidence for a small color gradient in the cluster RG stars that is not a predicted outcome of the models in the presence of a helium gradient. We compute the least-squares relation between the measured colors of all the RG+RGBB stars and their separation from the center, $(\log(r) - \log(r_c))$, using those stars that have at least five measurements in each filter and that have a brightness within 0.5 mag of $V_{\text{RGBB}}$. The measured slope in $(B-V)$ color is a very small $(0.008 \pm 0.002) \text{ mag dex}^{-1}$—effectively zero since the total extent of the ground-based data set is $\sim 1.1$ dex. However, the gradient measured in $(B-I)$ color is $(0.030 \pm 0.004) \text{ mag dex}^{-1}$, and is $(0.038 \pm 0.007) \text{ mag dex}^{-1}$.
in \((U - V)\) color. Both these gradients is significantly smaller than that for the HB stars, discussed in Section 5, evidence that they are due to evolutionary processes rather than systematic effects such as blending.

Our model results, shown in Table 1, predict that there should be no measurable color gradient due to temperature in the cluster at the level of the RGBB if we are only dealing with two equal-age, equal-metallicity populations differing only in their initial helium abundance by a small amount \((\Delta Y \sim 0.03)\). The presence of these small gradients indicates there may be an additional factor at play, or that helium-enhanced RGs at the luminosity level of the RGBB might be made slightly bluer than predicted by models. The color variation would be consistent with the stars nearer the center either having a lower metallicity, \(\delta[Fe/H] \approx 0.05\) dex, or a temperature colder by \(\delta T \approx 17\) K (Alonso et al. 1999).

There are theoretical predictions of a bluer RGB for stellar populations with higher initial helium abundance. Catelan et al. (2010), in their Figure 1, show that for fixed age and metallicity, a helium-enhanced population is expected to be slightly bluer at the faint end of the RGB, with the difference in temperature narrowing for brighter stars. We do get a larger color gradients for stars that have a brightness \(V_{\text{RGBB}} + 1 \geq V \geq V_{\text{RGBB}}\)—but barely so. The measured gradients are \((0.045 \pm 0.007)\) mag dex\(^{-1}\) in \((U - V)\), \((0.035 \pm 0.004)\) mag dex\(^{-1}\) in \((B - I)\), and \((0.011 \pm 0.002)\) mag dex\(^{-1}\) in \((B - V)\).

7. DISCUSSION

We have found \(\sim 3.6\sigma\) and \(\sim 2.3\sigma\) detections that the cluster RGBB stars become fainter and more numerous with increasing distance from the cluster center, and that the HB becomes fainter and redder at the \(\sim 7.7\sigma\) and \(\sim 4.1\sigma\) levels, respectively. These four independent effects are predicted by stellar theory if there is a second generation of stars in 47 Tuc that is helium enhanced, and more centrally concentrated. Briley (1997), in his analysis of CN-band indices in 283 cluster giants, found a similar radial profile for 47 Tuc. The ratio of CN-strong to CN-weak cluster stars was approximately equal \((\sim 1.8)\) interior to 10', and then dropped steeply for sources separated from the cluster center by 10'–20'. If this is due to dynamical segregation between the two generations, then the thickness of the main-sequence observed by Anderson et al. (2009) in the cluster core should not be observable in the cluster outskirts. This will prove a difficult measurement to make since the surface density of stars on the sky drops steeply at these distances. Additional ground-based data could also prove useful. We estimate that there are \(\sim 30\) cluster RGBB stars outside the range of our observations, and these should be slightly fainter and with a higher EW than those measured thus far. The remaining \(\sim 100\) HB stars should also be fainter and redder than those within 200' of the cluster center.

In spite of the evidence for an overall gradient, it is interesting that we do not find evidence of a gradient within the cluster center as traced by the \(HST\) data set. We discuss three possible explanations. One way to explain this effect is to have the two stellar populations evenly mixed within some radius; this would lead to a flattening of all of the indicators we tested, as observed. Unfortunately, only \(\sim 20\%\) of the RGBB and HB stars in the space-based data set are contained within the King radius of the cluster, estimated to be 20.84' (McLaughlin et al. 2006). No significant trend is detected with the stars outside that radius and within the space-based data set, indicating they may initially fall off in number density at similar rates for \(r \geq r_{\text{King}}\). A second way would be if 47 Tuc indeed has a third stellar generation, as suggested by di Criscienzo et al. (2010). These stars, comprising \(\sim 10\%\) of the cluster population, would be formed from helium-enriched ejecta of previously formed stars that was 50% diluted by pristine material, and can thus be expected to have a different helium abundance itself. A third range of initial helium abundances in stars with a different range of central concentrations could camouflage the population tracers within the cluster core. A third possibility is the role of binary interactions. In their dynamical model of the cluster, Giersz & Heggie (2010) predicted that the binary fraction should be steeply varying for stars with projected separations of \(10''–100''\) from the cluster center, leveling off for larger separations. That range of separations is precisely that traced by the \(HST\) data set, and if the dynamical predictions are correct the role of binary evolution may be “blurring” the signals in our color–magnitude tracers for the HB. However, since the RGBB takes place very early in the ascent of an RGB, we do not expect the RGBB to be affected by binary evolution, thereby limiting the explanatory power of this third hypothetical effect.

Systematic errors in either or both of the two data sets are a concern, and it would be preferable to have a deep, high-precision uniform-photometry data set over the entire cluster, but such ideal data are currently unavailable so we have combined the best photometry available. Within the ground-based data set, it is very difficult to conceive of the broad range of systematics necessary to produce our signals. The decreasing brightness trend for the HB, \((0.072 \pm 0.009)\) mag dex\(^{-1}\), is comparable to that of the RGBB, \((0.083 \pm 0.023)\) mag dex\(^{-1}\). The similarity may be suggestive of a systematic; however, we also detect a significant color trend with the HB of \((0.021 \pm 0.005)\) mag dex\(^{-1}\) with no analog for the RGBB. The RGBB shows no color gradient in the ground-based data set regardless of whether or not we allow for gradients in \(V_{\text{RGBB}}\) and EW. As a further constraint on any potential systematic, the parameter we used to model the RGBB, EW, is independent of any continuous photometric completeness function since the RGBB stars will necessarily have the same probability of detection as the other RG stars of the same brightness, which makes this parameterization very robust.

This is, as far as we know, the first empirical support for the stellar theory prediction that the RGBB lifetime should shorten as initial helium abundance is enhanced (Bono et al. 2001; Di Cecco et al. 2010; Nataf et al. 2011). This opens the prospect that the RGBB can now provide a diagnostic to measure the helium abundance in populations such as dwarf galaxies and galactic bulges. This diagnostic should be more effective in metal-rich populations \(([M/H] \gtrsim -0.5)\) because there are more RGBB stars at higher metallicity (for fixed age and helium enrichment) rendering any given fluctuation more statistically significant. However, recent research has demonstrated that theory may inaccurately overestimate the RGBB luminosity by \(\sim 0.2\) mag (Cassisi et al. 2011), which was estimated by comparing the difference in brightness between the RGBB and the main-sequence turnoff for a sample of 15 Galactic globular clusters, and that predicted given the estimated ages and measured metallicities of the cluster. If there are small systematic errors in the theoretical predictions for RGBB luminosity, there may also be errors in the predictions for the RGBB lifetime. On that note, our brightness gradients for the HB, \((0.072 \pm 0.009)\) mag dex\(^{-1}\), and for the RGBB, \((0.083 \pm 0.023)\) mag dex\(^{-1}\), yield a ratio of \(dV_{\text{RGBB}}/dV_{\text{HB}} = (1.15 \pm 0.35)\). This is unfortunately insufficiently precise to test a stellar theory prediction of Cassisi...
& Salaris (1997). Their models predicted that the RGBB luminosity should respond more steeply to varying initial helium abundance than the zero-age horizontal branch luminosity, and as such the difference in their V-band brightness should decrease by $\sim 0.011$ mag for every increase of 0.01 in $Y$, suggesting a ratio $dV_{\text{RGBB}}/dV_{\text{HB}} \sim 2$. A more precise comparison is within reach if uniform photometry is obtained over the entirety of the cluster.

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