Stellar Populations in Globular Cluster Cores: Evidence for a Peculiar Trend Among Red Giant Branch Stars

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ABSTRACT
We investigate the relationship between the mass of a globular cluster core and the sizes of its various stellar populations in a sample of 56 globular clusters. The number of core red giant branch stars is found to scale sub-linearly with core mass at the 3-$\sigma$ confidence level, whereas the relation is linear to within one standard deviation for main-sequence turn-off and sub-giant branch stars. We interpret our results as evidence for a surplus of red giant branch stars in the least massive cluster cores which is not seen for main-sequence turn-off and sub-giant branch stars. We explore various possibilities for the source of this discrepancy, discussing our results primarily in terms of the interplay between the cluster dynamics and stellar evolution.

Key words: globular clusters: general – stars: statistics – stellar dynamics – stars: evolution.

1 INTRODUCTION

Studying the radial distributions of the various stellar populations (red giant branch, horizontal branch, main-sequence, etc.) found in globular clusters (GCs) can provide useful hints regarding their dynamical histories. As clusters evolve, they are expected to undergo relatively rapid mass stratification as a consequence of two-body relaxation, with the heaviest stars quickly sinking to the central cluster regions (Spitzer 1987). The shorter the relaxation time (typically evaluated at the half-mass radius), the quicker this process occurs. Clusters tend towards dissolution as two-body relaxation progresses and they lose mass due to stellar evolution and the preferential escape of low-mass stars. External effects like tidal perturbations, encounters with giant molecular clouds, and passages through the Galactic disk serve only to speed up the process (e.g. Baumgardt & Makino 2003; Küpper et al. 2008). Stellar evolution complicates this otherwise simple picture of GC evolution, however. Stars are expected to change in size and lose mass as they evolve, often dramatically, and this could significantly impact the outcomes of future dynamical interactions with other stars. For instance, a typical star in a GC is expected to expand by up to a few orders of magnitude as it ascends the red giant branch (RGB) and will shed up to a quarter of its mass upon evolving from the tip of the RGB to the horizontal-branch (HB) (e.g. Caloi & D’Antona 2008; Lee et al. 1994).

Red giant branch stars have been reported to be deficient in the cores of some Milky Way (MW) GCs. For instance, Bailyn (1994) found that the morphology of the giant branch in the dense core of 47 Tuc differs markedly from that in the cluster outskirts. In particular, there appear to be fewer bright RGB stars in the core as well as an enhanced asymptotic giant branch (AGB) sequence. While a similar deficiency of bright giants has been observed in the cores of the massive GCs NGC 2808 and NGC 2419, better agreement between the observations and theoretical luminosity functions obtained with the Victoria-Regina isochrones was found for M5 (Sandquist & Martel 2007; Sandquist & Hess 2008). Sandquist & Martel (2007) speculate that the giant star observations in NGC 2808 could be linked to its unusually blue horizontal branch if a fraction of the stars near the tip of the RGB experience sufficiently enhanced mass loss that they leave the RGB early. Alternatively, Beer & Davies (2004) suggest that RGB stars could be depleted in dense stellar environments as a result of collisions between red giants and binaries.

While stellar populations have been studied and compared on an individual cluster basis, a statistical analysis in which their core populations are compared over a large sample of GCs is ideal for isolating trends in their differences. Though a handful of studies of this nature have been performed (e.g. Piotto et al. 2004), we present an alternative method by which quantitative constraints can be found for the relative sizes of different stellar populations. Specifically, a cluster-to-cluster variation in the central stellar mass function can be looked for by comparing the core masses to the
sizes of their various stellar populations. Since stellar evolution is the principal factor affecting their relative numbers in the core, we expect the size of each stellar population to scale linearly with the core mass. If not, this could be evidence that other factors, such as stellar dynamics, are playing an important role. In this paper, we present a comparison of the core RGB, main-sequence (MS) and HB populations of 56 GCs. In particular, we use star counts for each stellar population to show that RGB stars are either over-abundant in the least massive cores or under-abundant in the most massive cores, and that this effect is not seen for MS stars. We present the data in Section 2 and our methodology and results in Section 3. In Section 4, we discuss the implications of our results and explore various possibilities for the source of the observed discrepancy between RGB and MS stars. Concluding remarks are presented in Section 5.

2 THE DATA

Colour-magnitude diagrams (CMDs) taken from Piotto et al. (2002) are used to obtain star counts for the RGB, HB, MS and blue straggler (BS) populations in the cores of 56 GCs. We apply the same selection criterion as outlined in Leigh, Sills & Knigge (2007) to derive our sample as well as to define the location of the main-sequence turn-off (MSTO) in the (F439W-F555W)-F555W plane. An example of this selection criterion, applied to the CMD of NGC 362, is shown in Figure 1. We include all stars in the Piotto et al. (2002) database. Since Piotto et al. (2002) took their HST snapshots with the centre of the PC chip aligned with the cluster centre, a portion of the cluster core was not sampled for most GCs. We have therefore applied a geometric correction factor to the star counts in these clusters in order to obtain numbers that are representative of the entire core (Leigh, Sills & Knigge 2007, 2008). The total number of stars in the core is found by summing over all stars brighter than 1 mag below the MSTO and then multiplying by the appropriate geometric correction factor.

Errors on the number of stars for each stellar population were calculated using Poisson statistics. Core radii, distance moduli, extinction corrections, central luminosity densities and central surface brightnesses were taken from the Harris Milky Way Globular Cluster catalogue (Harris 1996). Calibrated apparent magnitudes in the F555W, F439W and Johnson V bands were taken from Piotto et al. (2002).

3 RESULTS

This paper focuses on the core RGB, MS and HB populations of 56 GCs, comparing their numbers to the core masses. Note that we are focusing on the total number of stars in the core as a proxy for the core mass instead of the total luminosity in the core in order to avoid concerns regarding cluster-to-cluster variations in the central stellar mass function and selection effects. Given that a single bright HB star can be as luminous as 100 regular MS stars, a small surplus of bright stars could have a dramatic impact on the total luminosity. Therefore, the total number of stars in the core is a more direct and reliable estimate for the core mass than is the core luminosity.

Upon plotting the logarithm of the number of core RGB stars versus the logarithm of the total number of stars in the core and performing a weighted least-squares fit, we find a relation of the form:

$$\log(N_{\text{RGB}}) = (0.89 \pm 0.03) \log(N_{\text{core}}/10^3) + (2.04 \pm 0.02)$$

The sub-linear slope is either indicative of a surplus of RGB stars in the least massive cluster cores or a deficiency in the most massive cores. Errors for lines of best fit were found using a bootstrap methodology in which we generated 1,000 fake data sets by randomly sampling (with replacement) RGB counts from the observations. We obtained lines of best fit for each fake data set, fit a Gaussian to the subsequent distribution and extracted its standard deviation. In order to avoid the additional uncertainty introduced into our RGB number counts from trying to distinguish AGB stars from RGB stars, as well as the difficulty in creating a selection criterion that is consistent from cluster-to-cluster when including the brightest portion of the RGB, stars that satisfy the RGB selection criterion shown in Figure 1 are referred to as RGB stars throughout this paper. Note that it is the brightest portion of the RGB that should be the most affected by stellar evolution effects such as mass-loss. If we extend our selection criterion to include the entire RGB, however, our results remain unchanged.

Interestingly, MS plus sub-giant branch stars (hereafter collectively referred to as MSTO stars, the selection criterion for which is shown in Figure 1) show a more linear relationship than do RGB stars and appear to dominate the central star counts. If we count only those stars having a F555W mag within half a magnitude above and below the turn-off, we obtain a relation of the form:

$$\log(N_{\text{MSTO}}) = (1.02 \pm 0.01) \log(N_{\text{core}}/10^3) + (2.66 \pm 0.01)$$

Figure 1. Colour-magnitude diagram for NGC 362 in the (F439W-F555W)-F555W plane. Boundaries enclosing the selected RGB, HB and MSTO populations are shown.
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A nearly identical fit is found when counting only those stars having a F555W mag between the turn-off and one magnitude fainter than the turn-off.

We also tried plotting the logarithm of the number of core helium-burning stars (labeled HB in Figure 1) versus the logarithm of the number of stars in the core, yielding a relation of the form:

\[ \log(N_{\text{HB}}) = (0.91 \pm 0.10) \log\left(\frac{N_{\text{core}}}{10^3}\right) + (1.58 \pm 0.05) \]  

Note the large uncertainty associated with the fit, indicating that the slope is consistent with both those of the RGB and MSTO samples. We will discuss this stellar population further in Section 4.

The number of MSTO, RGB and HB stars are shown as a function of the total number of stars in the core in Figure 2. Interestingly, the blue stragglers in our sample are also scale sub-linearly with core mass, albeit more dramatically, obeying a relation of the form 

\[ N_{\text{HB}} \sim M_{\text{core}}^{0.38 \pm 0.04} \]  

(Knigge, Leigh & Sills 2009). Note that \( N_{\text{core}} \) can be used interchangeably with \( M_{\text{core}} \). In this case, we obtain a fit of:

\[ \log(N_{\text{HB}}) = (0.47 \pm 0.06) \log\left(\frac{N_{\text{core}}}{10^3}\right) + (1.22 \pm 0.02) \]  

In an effort to explore the influence of selection effects, we re-did our plots having removed from our sample clusters denser than \( \log \rho > 10^7 \) \( \text{L}_\odot \text{pc}^{-3} \) since we are the most likely to be under-counting stars in the most crowded cluster cores where blending of the stellar light is the most severe. This cut also removes from our sample the post-core collapse (PCC) clusters for which the core radii are poorly defined since King models are known to provide a poor fit to the observed surface brightness profiles in these clusters. Similarly, we applied a cut in the central surface brightness, removing from our sample clusters satisfying \( \Sigma_0 < 15.1 \text{ V mag arcsec}^{-2} \). Finally, since clusters having both high surface brightnesses and small cores are the most likely to suffer from selection effects, we also tried adding to the aforementioned cut in \( \Sigma_0 \) a cut in the angular core radius, removing clusters with \( r_c < 0.05' \). In all cases, the sub-linear power-law index reported for the RGB remains unchanged to within one standard deviation of our original result. Selection effects do not appear to be the source of the observed sub-linearity, though it is clear that its effects must properly be accounted for in future studies.

In order to assess the effects of age-related cluster-to-cluster variations in the stellar mass function, as well as to test our assumption that the number of stars in the core provides a reliable estimate for the core mass, we have obtained MSTO masses for most of the GCs in our sample. We fit theoretical isochrones provided in Pols et al. (1998) to the cluster CMDs, using the bluest point along the MS of a given isochrone as a proxy for the MSTO mass. Isochrones were calculated using the metallicities of Pietto et al. (2002) and cluster ages were taken from De Angeli et al. (2005) using the Zinn & West (1984) metallicity scale. Core masses were estimated by multiplying the mass corresponding to the MSTO (\( m_{\text{MSTO}} \)) by the number of stars in the core brighter than 1 mag below the turn-off. This is a reasonable assumption given the very small dispersion in the ages of MW GCs (De Angeli et al. 2003) and the fact that we are only considering stars brighter than 1 mag below the TO. Consequently, the range of stellar masses upon which we are basing our number counts is very small. Our results remain entirely unchanged upon using \( M_{\text{core}} \sim N_{\text{core}} m_{\text{MSTO}} \) as a proxy for the core mass instead of pure number counts.

In order to further check the sensitivity of our results to our estimate for the core masses, we re-did all plots shown in Figure 2 using various approximations for the total core luminosity instead of pure number counts. Core luminosities are calculated in the Johnson V band directly from the stellar fluxes which are summed over all stars in the core and then multiplied by the appropriate geometric correction factor. We also adopted \( L_{\text{core}} = \frac{4}{3} \pi r^2 \rho_0 \), where \( \rho_0 \) is the central luminosity density in \( \text{L}_\odot \text{pc}^{-3} \) taken from Harris (1996). Additionally, since the number of core RGB stars is in reality a projected quantity, we tried plotting \( N_{\text{RGB}} \) versus \( L_{\text{core}} = \pi r^2 \Sigma_0 \), where \( \Sigma_0 \) is the central surface brightness in \( \text{L}_\odot \text{pc}^{-2} \), so that we are consistently comparing two projected quantities. Finally, we can adopt slightly more realistic estimates for the total core luminosity by integrating over King density profiles. We fit single-mass King models calculated using the method of Sigurdsson & Phinney (1993) to the surface brightness profiles of the majority of the clusters in our sample using the concentration parameters of McLaughlin & van den Marel (2003) and the central luminosity densities of Harris (1996). We then integrated the derived luminosity density profiles numerically in order to estimate the total stellar light contained within the core. After removing clusters labelled as post-core collapse in Harris (1996) for which King models are known to provide a poor fit, we once again compared the integrated core luminosities to the number of RGB stars in the core. For all four of these estimates for the total core luminosity, we find that our fundamental results remain unchanged, with the power-law index for RGB stars remaining sub-linear at the 3-\( \sigma \) level.
Therefore, we conclude that our result is robust to changes in choices of cluster and population parameters.

4 DISCUSSION

We have shown that the number of RGB stars in globular cluster cores does not directly trace the total stellar population in those cores. In particular, the number of RGB (but not MSTO) stars scales sub-linearly with core mass at the 3-sigma level. Given that the MS lifetime is expected to be a factor of 10-100 longer than that of the RGB sample (Iben 1991), the ratio \( N_{\text{MSTO}}/N_{\text{RGB}} \) indicates that the relative sizes of these stellar populations are in better agreement with the expectations of stellar evolution theory in the most massive cores. This suggests that our results are consistent with a surplus of RGB stars in the least massive cores. We discuss below some of the key considerations in understanding the evolution of GC cores and the stars that populate them in an effort to explain our result.

4.1 Stellar evolution

Could this trend be a reflection of a stellar evolution process? The evolution and distribution of stellar populations can be thought of as the sum of many single stellar evolution tracks, which depend only on a star’s mass and composition. Since there is no relation between a cluster’s mass and its metallicity (Harris 1996) and the dispersion in the relative ages of MW GCs is quite small (Galletti et al. 2005), there is no reason to expect the RGB lifetime to depend on the cluster mass. On the other hand, recent studies suggest that the chemical self-enrichment of GCs during their early evolutionary stages could help to explain many of the population differences observed among them (e.g. Caloi & D’Antona 2007). In particular, many of the most massive GCs are thought to be enriched in helium and this is expected to reduce the time scale for stellar evolution (e.g. Romano et al. 2002). While this scenario predicts a deficiency of RGB stars in the most massive cores, it would contribute to depressing the slope of the RGB sample relative to that of the MSTO population in Figure 2.

4.2 Single star dynamics

Two-body relaxation is the principal driving force behind the dynamical evolution of present-day GCs, slowly steering them towards a state of increased mass stratification as predominantly massive stars fall into the core and typically low-mass stars are ejected via dynamical encounters. The relaxation time increases with the cluster mass (Spitzer 1987) and the variance in the relative ages (and hence MSTO masses) of MW GCs is quite small (De Angeli et al. 2005). Therefore, it is the least massive clusters that should show signs of being the most dynamically evolved. This assumes that cluster-to-cluster variations in the initial mass function and the degree of initial mass segregation are small. In general, however, proportionately fewer massive stars should have had sufficient time to migrate into the most massive cores, while fewer low-mass stars should have been ejected out. While qualitatively correct, this effect should contribute little to the observed difference between the core RGB and MSTO populations since RGB stars are only slightly more massive (e.g. De Marchi & Pulone 2007).

Stars expand considerably as they ascend the RGB. Both the increase in collisional cross-section and the change in the average stellar density could have an important bearing on the outcomes of dynamical interactions involving RGB stars. Indeed, Bailyn (1994) suggests that interactions between giants and other cluster members in the core could strip the outer envelope of the giant before it has a chance to fully ascend the RGB. Since our adopted RGB selection criterion does not include the brightest giants, we are only considering giants that are larger than MSTO stars by a factor of \( \sim 10 \) (Iben 1991). This small degree of expansion will have only a minor effect on the collision rate. Any scenario that relies on dynamical encounters to explain a depletion of RGB stars should be operating in very dense cores. Our results are consistent with some of the densest clusters in our sample having a surplus of giants, however.

4.3 Binary effects

Stripping of the envelopes of large stars could also be mediated by a binary companion as the expanding giant overfills its Roche lobe (Bailyn 1994). While this process should preferentially occur in the centres of clusters where binaries will congregate as a result of mass segregation, two-body relaxation progresses more slowly in the most massive clusters. Binaries should therefore sink to the cluster core more quickly in the least massive clusters, contributing to an increase in the core binary fraction at a rate that decreases with increasing cluster mass. Observational evidence has been found in support of this, most notably by Sollima et al. (2007) and Milone et al. (2008) who found an anti-correlation between the cluster mass and the core binary fraction. Any mechanism for RGB depletion that relies on binary stars should therefore operate more efficiently in the least massive cores where the binary fraction is expected to be the highest. Our results are consistent with a surplus of giants in the least massive cores, however. This therefore argues against a binary mass-transfer origin for RGB depletion in massive GC cores. For similar reasons, it seems unlikely that our result can be explained by collisions between RGB stars and binaries. If, on the other hand, RGB stars are more commonly found in binaries than are MS stars, perhaps as a result of their larger cross-sections for tidal capture, binary stars could still be contributing to the observed trend. Note that in the cluster outskirts where the velocity dispersion has dropped considerably from its central value, individual encounters are more likely to result in tidal capture. Since mass segregation should deliver binaries to the core faster in the least massive clusters, a larger fraction of their RGB stars could have hitched a ride to the core as a binary companion. However, both the average half-mass relaxation time of MW GCs and the RGB lifetime tend to be on the order of a Gyr (Harris 1996; Iben 1991). This does not leave much time for giants to be captured into binaries and subsequently fall into the core before evolving away from the RGB.

4.4 Core helium-burning stars

The fit for the HB sample is consistent with those of the RGB and MSTO samples at the 3-sigma level so that we
are unable to draw any reliable conclusions for this stellar population. The high uncertainty stems from a number of outlying clusters. Selection effects and contamination from the Galaxy are likely to be playing a role in this, in addition to our formulaic selection criterion which may not be as suitable to the varying morphology of the HB as it is to other stellar populations. That is, the creation of a purely photometry-based cluster-independent selection criterion may not be possible for HB stars. Given that stellar evolution effects are expected to be the most dramatic at the end of the RGB lifetime, an interplay with the cluster dynamics could also be contributing. In particular, if the central relaxation time is shorter than the HB lifetime, significant numbers of HB stars could be ejected from the core via dynamical encounters as a result of having lost a quarter of their mass upon evolving off the tip of the RGB. Moreover, since stars expand considerably as they ascend the RGB, many of the dynamical arguments presented in Section 4.2 may more strongly affect the size of the HB sample if they are the direct evolutionary descendants of RGB stars. Since at most a handful of studies have been performed comparing the radial HB and RGB distributions in GCs (e.g. Iannicola et al. 2009), more data is needed before any firm constraints can be placed on the source of the poor fit found for the HB sample.

4.5 An evolutionary link with blue stragglers?

The addition of a small number of extra RGB stars to every cluster is one way to account for the observed sub-linear dependence on core mass since the fractional increase in the size of the RGB population will be substantially larger in the least massive cores. In log-log space, the result is a reduction of the slope. Since blue stragglers will evolve into RGB and eventually HB stars (Sills et al. 2009), evolved BSs could be the cause of a surplus of RGB (and possibly core helium-burning) stars in these clusters. This scenario also predicts that MSTO stars should scale slightly more linearly with core mass since there should be a smaller contribution from evolved BSs, as we have shown. Given the fits for the RGB and BS samples presented in Section 4 and their corresponding uncertainties, we find that the addition of evolved BSs to the RGB populations could inflate the slope enough that the relation is linear for MSTO stars. While the preferential self-enrichment of massive GCs, two-body relaxation, and evolved BSs could all be contributing to the observed sub-linear dependence, further studies with an emphasis on selection effects are needed in order to better constrain the source of this curious observational result.

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5 SUMMARY

In this paper, we have performed a cluster-to-cluster comparison between the number of core RGB, MSTO & HB stars and the total core mass. We have introduced a technique for comparing stellar populations in clusters that is well suited to studies of both cluster and stellar evolution, in addition to the interplay thereof. Using a sample of 56 GCs taken from Piotto et al.’s 2002 HST database, we find a sub-linear scaling for RGB stars at the 3-σ level, whereas the relation is linear for MSTO stars. While the preferential self-enrichment of massive GCs, two-body relaxation, and evolved BSs could all be contributing to the observed sub-linear dependence, further studies with an emphasis on selection effects are needed in order to better constrain the source of this curious observational result.
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