Red giant depletion in globular cluster cores

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ABSTRACT

We investigate the observed depletion of red giants in the cores of post-core-collapse globular clusters. In particular, the evolutionary scenario we consider is a binary consisting of two low-mass stars which undergoes two common envelope phases. The first common envelope phase occurs when the primary is a red giant resulting in a helium white dwarf and main sequence star in a detached binary. The second common envelope phase occurs shortly after the secondary becomes a red giant. During the second common envelope phase the degenerate helium cores merge resulting in a core mass greater than the helium burning limit and the formation of a horizontal branch star. We show that this evolutionary route is enhanced in post-core-collapse clusters by stellar encounters. These encounters increase the population of binary secondaries which would have evolved onto the red giant branch in the recent past.

Key words: binaries: close – stars: evolution – stars: general – globular clusters: general.

1 INTRODUCTION

Observations by Djorgovski et al. (1991) have shown that clusters with central cusps (presumably collapsed cores) have colour and population gradients. Their observations show that a number of post-core-collapse (PCC) clusters become bluer toward their centres, which is an effect of the demise of the red giant and/or sub-giant populations, and possibly an increase in the number of faint, blue objects. The effect is a few per cent of the visible light.

The cores of PCC clusters have been imaged using the high spatial resolution of the Hubble Space Telescope (Bailyn 1994; Shara et al. 1998). The observations show a depletion of the red giant branch stars relative to the horizontal branch. In addition a population of supra-horizontal-branch stars (SHBs) have been observed. These are stars which lie in the Hertzsprung-Russell diagram as a distinct population brighter than normal horizontal branch stars. Bailyn (1994) found SHBs in the core of 47 Tuc which were about one magnitude brighter, while Shara et al. (1998), in images of NGC 6522, found SHBs which were one and a half magnitudes brighter in the $B$ band. The formation of these objects is not well understood.

In PCC clusters more stellar encounters are expected to occur than for the non-PCC clusters. These encounters could deplete the red giant population through two methods. Firstly, collisions between red giants and binaries could either eject the red giant core from the surrounding envelope or result in a common envelope phase (Adams, Sills & Davies 2003). This effect could at most deplete a few per cent of the red giant population. Secondly stellar encounters would modify the binary population through hardening (encounters making the binary tighter) and exchanges (the third star is exchanged with the lower mass binary component if it is more massive). This would result in a different binary population to the non-PCC clusters. This modified population evolves such that the red giants, which would be observed today, undergo mergers with their binary companions.

As red giants evolve into horizontal branch stars any evolutionary model which is considered needs to explain why the horizontal branch is not depleted in the same manner as the red giants. We investigate whether such an evolutionary scenario is possible. Such a scenario would require binary interactions to turn/accelerate the evolution of the red giants into becoming horizontal branch stars (see Djorgovski et al. 1991). In this paper we discuss an evolutionary scenario which naturally explains both the observed depletion of red giants and the non-depletion of horizontal branch/faint, blue stars in PCC clusters. In this scenario, the binary consists of two low-mass (below helium-flash limit) stars and evolves through two common envelope phases. In the first common envelope phase the primary is a red giant and loses its envelope to leave a helium white dwarf–main sequence binary. During the second common envelope phase, in which the secondary has evolved into a red giant, the two degenerate helium cores coalesce resulting in a helium burning core and the remainder of the common envelope forming an envelope around the merged object.

We examine the required parameter space (initial
masses and separation) to explain why the depletion is more likely to occur in PCC clusters. Stellar encounters are expected to play a significant role in PCC clusters. After a number of encounters the original binary will have had its separation ground down and its components will have higher masses due to exchanges (see Davies 1995). The initial mass range which would produce red giants today is between 0.75 \( M_\odot \) and 0.95 \( M_\odot \) depending on the age of the cluster and hence the turn-off mass. We show that without encounters this mass range is more likely to be found in single stars and the higher mass binary components (the primaries). After a number of encounters more are found in binaries and in particular as the secondaries of binaries. It is these secondaries which lose their envelopes in the second common envelope phase explaining why red giant depletion is only observed in PCC clusters.

Our evolutionary scenario is discussed in section 2. In section 4 we investigate the effects stellar encounters have in modifying the binary population of PCC clusters. Section 5 contains a discussion of our results, in particular the observational consequences and the other products of our evolutionary scenario. We give our conclusions in section 5.

2 EVOLUTIONARY SCENARIO

The evolutionary scenario for depleting the red giant branch is shown in Fig. 1. We consider the evolution of binary stars where convective mass transfer occurs when the primary evolves off the main sequence and fills its Roche lobe. A common envelope phase follows. The secondary and the degenerate helium core spiral together as the envelope is ejected. The secondary then evolves to fill its Roche lobe and convective mass transfer again occurs forming a second common envelope phase. During this common envelope phase the degenerate helium cores spiral together.

If the cores coalesce during the second common envelope phase then the combined core masses may be enough to ignite helium and the remainder of the common envelope is left around the merged helium burning core and resembles a horizontal branch star. If the hydrogen envelope mass is small then the product may resemble an sdB star. Alternatively, after the second common envelope phase a tight double degenerate helium white dwarf system could be formed. This system could be close enough that inspiral due to gravitational radiation brings them into contact.

To model the binary evolution we use the binary evolution code of Hurley, Tout & Pols (2002). This code uses analytical formulae for stellar evolution (Hurley, Pols & Tout 2000) and includes the effects of tides, gravitational radiation, mass transfer and mass loss due to winds. For the common envelope the code assumes the inspiral is given by an energy balance between the envelope binding energy and the difference in orbital energy of the inspiraling components. The envelope binding energy is given by

\[
E_{\text{bind}} = -\frac{GM_{c1}M_{\text{env1}}}{\lambda R_1},
\]

where \( M_{c1} \) and \( M_{\text{env1}} \) are the core and envelope mass of the red giant respectively, \( R_1 \) is its radius and \( \lambda \) is a constant.

The change in orbital binding energy is given by

\[ E_{\text{bind}} = \frac{GM_{c1}M_{\text{env1}}}{\lambda R_1}, \]
\[ \delta E_{\text{orb}} = -\frac{1}{2} \left( \frac{GM_1 M_2}{a_1 f} - \frac{GM_1 M_2}{a_1 i} \right) , \]

where \( a_1 \) and \( a_1 f \) are the initial and final separations respectively and \( M_2 \) is the mass of the secondary. The energy balance is then given by

\[ E_{\text{bind}} = \alpha_{\text{CE}} \delta E_{\text{orb}} , \]

where \( \alpha_{\text{CE}} \) is the common envelope efficiency. The ratio of initial to final separation only depends on the product \( \alpha_{\text{CE}} \lambda \) and not on their separate values. We take the value of \( \alpha_{\text{CE}} \lambda = 1 \) in our calculations.

### 2.1 Constraints on initial masses

In order for the observed red giant population to be depleted the secondaries in the binaries require masses near the turn-off mass for the cluster. Fig. 2 shows the age of a star at the end of the red giant branch as function of initial mass and for metallicities \( z = 0.0001, 0.001, 0.002 \). From Fig. 2 it is clear that a large range of cluster ages of 10 – 20 Gyr can be represented if we consider a mass range for the secondary of 0.75 – 0.95 \( M_\odot \). This represents the range of masses of secondaries which would be observed as red giants in globular clusters today.

### 2.2 Constraints on initial separations

The initial separation needs to be such that both binary components overflow their Roche lobes as red giants. If the separation is too small then the secondary will overflow its Roche lobe before it reaches the red giant branch. This will deplete both the red giant and horizontal branch. Alternatively if the separation is too large then the binary will not come into contact for a second time. In this case no depletion of either the red giant or the horizontal branch occurs.

Fig. 3 is a plot of initial primary masses and separations and shows the constraints for the formation of a horizontal branch star via the coalescence of two degenerate helium cores during the second common envelope phase. We assume a metallicity of 0.001 and a secondary mass of 0.8 \( M_\odot \). The solid line shows the separation above which coalescence occurs in the second common envelope. Below this separation the secondary fills its Roche lobe before it has reached the red giant branch. The short-dashed line represents the separation at which a double degenerate helium white dwarf system is formed as opposed to coalescence occurring during the common envelope. The long-dashed line represents the separation at which a helium white dwarf and carbon-oxygen white dwarf is formed due to the primary not filling its Roche lobe until the asymptotic giant branch. The dot-dashed line represents the separation above which the secondary does not fill its Roche lobe.

Fig. 4 is a plot of initial secondary masses and separations and shows the constraints for the formation of a horizontal branch star via the coalescence of two degenerate helium cores during the second common envelope phase. For the evolutionary calculation we assumed a metallicity \( z = 0.001 \) and a primary mass of 1 \( M_\odot \). The lines are the same as in Fig. 3. Fig. 4 shows that the constraints for formation of the merged object are only weakly dependent on the secondary mass.

In all of our calculations in which two degenerate helium cores merge during the second common envelope we find that the combined core mass is sufficient to ignite helium. In all the cases which form a horizontal branch star, the primary overflows its Roche lobe near the end of the giant branch. The core mass of the primary in this case is around...
0.4 \, M_\odot.\) For the second common envelope phase we require the secondary to be a red giant and consequently its core mass is at least 0.2 \, M_\odot.\) Consequently the combined core masses are always sufficiently large enough to ignite helium (which requires \(M_c > 0.48 \, M_\odot\)).

We have run the evolution code with different values for the common envelope efficiency and neglecting the mass loss due to the wind. Neglecting the wind did not significantly change the evolutionary outcome of the systems and the range of parameter space was found to be similar for each model. The common envelope efficiency, however, determines the separations at which coalescence during the second common envelope phase will occur. The dot-dashed line above which the primary overflows its Roche lobe on the asymptotic giant branch is unaffected but the separation after the first common envelope phase is. This in turn affects whether a merger will occur in the second common envelope phase as this will depend on both the common envelope efficiency and the initial separation. It was found that decreasing the efficiency by a factor two shifted the envelope phase as this will depend on both the common envelope efficiency and the initial separation. It was found that decreasing the efficiency by a factor two shifted the

\[ \frac{M}{M_\odot} = \frac{0.19x}{(1 - x)^{0.75} + 0.082(1 - x)^{0.25}} \]

where \(x\) is a random number between 0 and 1. This appears as a power-law for masses greater than \(1 \, M_\odot\) and with a turnover at low masses (with a peak at \(M \sim 0.18 \, M_\odot\)). Of our initial population of stars, we assumed 10% of them were in binaries. To mimic encounters we assumed that a binary has encounters with a star randomly drawn from the single star population. During an encounter if the third star is more massive than one of the binary components they will be exchanged (see Davies 1995) i.e., the remaining binary always consists of the two most massive stars. We simulated a number of encounters for each binary to build up an image of how the population changes with the number of encounters. The mass range which would have evolved onto the red giant branch in the recent past is \(0.8 \sim 0.81 \, M_\odot\). Fig.\[ shows the fraction of stars with this mass range which are the primary and secondary components of binary systems as a function of the number of encounters the binary population has experienced. The results did not significantly change if a different range of masses was chosen. Table\[ shows how the proportions of primary and secondary components after 0, 20 and 40 encounters per binary. In addition the table shows the proportion of stars which may form red giant or horizontal branch stars. We assume only the single stars are likely to form red giants while horizontal branch stars are likely to form red giants or horizontal branch stars. We assume only the single stars are likely to form red giants while horizontal branch stars are likely to form red giants or horizontal branch stars.

\[ \tau_{\text{enc}} = 7 \times 10^4 \frac{n}{10^2/\text{pc}^3} \left( \frac{M_1}{M_1 + M_2} \right) \frac{R_\odot}{b_{\text{min}}} \frac{v_\infty}{10 \, \text{km s}^{-1}} \text{Myr} \]

where \(n\) is the number density of stars, \(b_{\text{min}}\) is the distance of closest approach and \(v_\infty\) is the stellar velocity. For typical parameters in the core of a PCC cluster, \(\tau_{\text{enc}}\) is approximately 400 Myr. This implies that during the main sequence lifetime of a 0.8 \, M_\odot\) star we can expect 20–40 encounters. To determine how encounters change the population of binary components we calculated the effect of a number of stellar encounters on a binary population. We assumed an initial population of stars with a random mass function between 0.5 and 20 \, M_\odot\). For the second common envelope phase we require the secondary to be a red giant and consequently its core mass is at least 0.2 \, M_\odot.\) Consequently the combined core masses are always sufficiently large enough to ignite helium (which requires \(M_c > 0.48 \, M_\odot\)).

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![Figure 4. Plot of initial separation \(a_i\), for \(M_1 = 1 \, M_\odot\), as a function of secondary mass \(M_2\) showing constraints for the formation of a binary as described in section 3.](image-url)
Red giant depletion in globular cluster cores

| \( N_{\text{enc}} \) | Proportion of stars which are | Proportion which can form |
|-----------------|--------------------------|---------------------------|
|                 | Single | Primary | Secondary | Red Giants | Horizontal Branch |
| 0               | 90.0 % | 7.9 %   | 2.1 %     | 90.0 %     | 92.1 %           |
| 20              | 79.5 % | 4.8 %   | 15.7 %    | 79.5 %     | 95.2 %           |
| 40              | 91.5 % | 1.4 %   | 7.1 %     | 91.5 %     | 98.6 %           |

Table 1. A table showing the proportion of stars, in the mass range 0.8 – 0.81 \( M_\odot \) which are single or the components of a binary after 0, 20 and 40 encounters per binary system. During the lifetime of a 0.8 \( M_\odot \) star 20–40 encounters per binary are expected to occur in the core of a PCC cluster. Also shown is the proportion of these stars which will form the red giant and horizontal branch population.

This naturally explains why the depletion of red giants is only observed in PCC clusters. In non-PCC clusters there is not a significant number of binaries which have secondaries of the cluster turn-off mass. After a number of encounters, however, the situation is reversed and a number of turn-off mass stars are the secondaries in binaries. These binaries may undergo two common envelope phases with coalescence in the second common envelope. These mergers form horizontal branch stars and deplete the red giant population.

4 DISCUSSION

We have shown that if a binary system undergoes two common envelope phases it is possible for a merger of the two cores to occur. We have assumed that this results in a horizontal branch star. The masses of the cores will add up to greater than the mass required for helium ignition. If all the helium ignited simultaneously then the nuclear energy generated would be greater than the binding energy of the star. However, as in the case of degenerate helium ignition at the end of the red giant branch, the burning timescale is large enough (~100 Myr) that this does not occur and the envelope remains bound.

If the cores merge near the end of the common envelope phase then the final star will have ejected a large portion of the hydrogen envelope and so the merged object may resemble an sdB star. Han et al. (2002) have investigated the formation channels for sdB stars and although one of the routes considered is dynamical mass transfer followed by a common envelope phase, two common envelope phases are not discussed (although the merger of two white dwarfs is one of the formation channels considered). Whether or not this is a main evolution channel is unknown as it may depend strongly on the initial separation.

The merged objects in our calculations will have a higher core mass and a lower envelope mass than normal horizontal branch stars. The higher core mass will result in a larger luminosity and so the SHBs observed by Bailyn (1994) and Shara et al. (1998) (or a subset of them) may be the merged objects which would form after coalescence during the second common envelope phase.

We have shown that in the cores of PCC clusters the conditions are such that depletion of the red giant population is possible. We have not, however, performed detailed binary population synthesis of the cluster as a whole. This is complicated due to the necessity of including stellar encounters, stellar evolution and binary interactions. The solution to this may be the use of N-body modelling codes. However
all we are showing here is that this evolutionary route is both possible and likely in PCC cluster cores. In this paper we do not attempt the determination of the depletion due to common envelope mergers including the effects of encounters, exchanges and binary evolution simultaneously.

In addition to the horizontal branch stars formed through mergers our calculations predict the existence of a substantial double degenerate population. The double degenerate population we find in our calculations have two main components. The first is where both are helium white dwarfs. In this case the primary will have overflowed its Roche lobe near the end of the red giant branch while the secondary will typically overflow near the start of the red giant branch. This is a consequence of the inspiral during the common envelope phase resulting in the radii of the two stars at Roche lobe overflow being significantly different. The mass ratio in this case is typically between 1.5 and 2 and the final orbital period is a few hours.

The second component to the double degenerate population comes from carbon-oxygen and helium white dwarf binaries. These are formed when the primary overflows its Roche lobe on the asymptotic giant branch resulting in both the carbon-oxygen white dwarf-helium white dwarf binary and a larger separation. The mass ratio in these cases are between 1 and 1.5 with larger periods of a couple of days upwards. Comparing to the observed population of Maxted, Marsh & Moran (2002) we find that these most closely resemble their population in which the mass ratios are around one and the periods are from a few hours to slightly greater than a day. However, there is a significant difference in the ages determined from cooling models. In their models the white dwarfs are within a few 100 Myr of each other while in our models the more massive primary overflows its Roche lobe typically a few Gyr before the secondary. A possible remedy to this scenario may be binaries which are closer in mass to each other or which initially were much more massive. In both these cases they would become giants in similar time-scales allowing the white dwarfs to be formed closer in age to each other. The other populations of double degenerates, however, should still be present and it may be that there are selection effects which determine which binaries are observed or that the double degenerate population in the absence of a number of encounters is different.

Han (1998) has modelled the formation of double degenerates including two common envelope phases. This evolutionary route was found to produce a significant portion of the total double degenerate population. Nelemans et al. (2001) have also modelled the population of double degenerates although they use different assumptions concerning the inspiral during the first common envelope phase and the mass loss due to a wind.

Of the double degenerates which do form a number of them are close enough that they inspiral and mass transfer occurs. In the case of helium-helium white dwarfs the mass ratio is such that the mass transfer is always stable. In this case as mass is transferred the binary becomes wider again. The final binary in this case has a very low mass secondary and a $\sim 0.6 \, M_\odot$ helium white dwarf primary which could undergo ignition to form a carbon oxygen white dwarf.

5 CONCLUSIONS

We have described an evolutionary scenario in which the red giants are depleted in the cores of PCC clusters. The binary undergoes two common envelope phases during the second of which coalescence of two degenerate helium cores occurs. The combined mass of these cores is sufficient for helium burning to commence resulting in the formation of horizontal branch stars. The binary separations required for this to occur are around 100 $R_\odot$ for a primary of mass 1 $M_\odot$ and a range of secondary masses.

We have shown that this evolutionary scenario will be favoured in the cores of PCC due to the effects of stellar encounters. These encounters both harden the binary towards the required orbital separation and increase the population of secondaries which have the cluster turn-off mass.

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