Empirical determination of the integrated red giant and horizontal branch stellar mass-loss in ω Centauri

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ABSTRACT

We herein determine the average integrated mass-loss from stars belonging to the dominant metal-poor population ([Fe/H] ~ −1.7) of the Galactic globular cluster ω Centauri (NGC 5139) during their red giant and horizontal branch (HB) evolution. Masses are empirically calculated from spectroscopic measurements of surface gravity and photometric measurements of temperature and luminosity. Systematic uncertainties prevent an absolute measurement of masses at a phase of evolution. However, the relative masses of early asymptotic giant branch (AGB) stars and central red giant branch (RGB) stars can be measured, and used to derive the mass-loss between these two phases. This can then be used as a physical check of models of HB stars. For ω Centauri, the average difference is found to be 26 ± 4 per cent. Assuming initial and final masses of 0.83 and 0.53 M⊙, we determine that 0.21 ± 0.03 M⊙ is lost on the RGB and 0.09 ± 0.05 M⊙ is lost on the AGB. The implied HB stellar mass of 0.62 ± 0.04 M⊙ is commensurate with literature determinations of the masses of the cluster’s HB stars. The accuracy of this measurement can be improved through better selection of stars and spectral coverage, and applied to other clusters where HB models do not currently agree.

Key words: stars: AGB and post-AGB – circumstellar matter – stars: mass-loss – stars: winds, outflows – globular clusters: individual: ω Cen – infrared: stars.

1 INTRODUCTION

Though all stars lose mass, the vast majority experience their most significant mass-loss on the red and asymptotic giant branches (hereinafter RGBs and AGBs, respectively). The amount of mass-loss determines both the mass and the type of the stellar remnant. It can profoundly alter not only the post-RGB track of a star’s evolution in a Hertzsprung–Russell diagram (HRD), but also the mass, chemical state, composition and mineralogy of the material returned to the interstellar medium. The processes that govern this mass-loss are relatively well understood (e.g. see review by Willson 2000) and can be broadly divided into two categories. Mass-loss from a star’s hot (∼10 000 K) chromosphere ejects mostly atomic gas at low mass-loss rates (<10−7 M⊙ yr−1; Dupree, Smith & Strader 2009) over most of the star’s life. On the other hand, pulsation-enhanced mass loss, driven by a cool (∼2000 K), dusty wind, can reach rates of >10−5 M⊙ yr−1 (van Loon et al. 1999), but for a much shorter period of time. Instantaneous mass-loss rates have been derived for a large number of stars, but they are difficult to measure with any absolute accuracy and can vary substantially on evolutionarily-short time-scales. Determination of the integrated mass-loss rate (i.e. the difference in mass) between two evolutionary phases is necessary if one is to probe how a star with a given set of parameters will evolve.

Stellar clusters provide excellent testbeds in which to probe stellar evolution, containing one (or sometimes a few) distinct population at a known age, distance and metallicity, which have giant stars at the same initial mass. Increasingly-precise stellar evolution models (e.g. Dotter et al. 2008; Marigo et al. 2008) and white dwarf observations (e.g. Moehler et al. 2004) can determine the initial and final masses of present giants to within a few per cent. In intermediate stages, however, there are considerable systematic differences in the modelled stellar masses.

This is perhaps most notable for horizontal branch (HB) stars. In clusters with blue HBs, stellar masses are relatively easy to determine via HB modelling and RR Lyrae pulsations. If the masses of HB stars are ≳0.65 M⊙ (depending on the HB model and the cluster metallicity), they will be too cool to become RR Lyrae stars and modelling becomes less precise due to the weaker dependence of the predicted Teff of red HB stars on their mass. In some cases, different models can disagree on HB masses by as much as ~25 per cent, depending on the model chosen (Carraro et al. 1996; Catelan 2009b;...
McDonald et al. 2011b). This causes severe problems when one tries to determine the total mass-loss on the RGB, whether RGB or AGB mass-loss is dominant and the detailed evolutionary stages where mass-loss is important.

In this Letter, we use a simple method to directly determine the fractional mass difference between RGB and early-AGB stars, which by definition gives the time-integrated mass-loss between these two phases. We apply this method to the metal-poor ([Fe/H] ≈ −1.7) population of ω Centauri (NGC 5139): a well-studied globular cluster with a blue HB and well-determined HB star masses. This allows us to empirically confirm the accuracy of the HB models and investigate the precision with which we can determine the time-integrated mass-loss.

2 METHOD

If one knows the distance and reddening to a star, one can determine its mass simply from three observable parameters: the gravity, log g, determined from high-resolution spectroscopy; the bolometric luminosity, L, derived from the integrated spectral energy distribution (SED) and cluster distance; and the effective surface temperature, T _eff_, derived from spectroscopy, photometric colours or SEDs. Using these, the stellar radius can be simply derived using the Stefan–Boltzmann Law and Newtonian gravity as follows:

\[ R^2 = \frac{L}{4\pi\sigma T_{\text{eff}}^4} = \frac{GM}{g}; \]

hence,

\[ M = \frac{gL}{4\pi\sigma T_{\text{eff}}^4 G}. \] (1)

Given the difficulty in determining these parameters accurately (particularly \( \log g \)), it is not normally possible to usefully constrain the masses of individual stars. Systematic errors mean that absolute masses for groups of stars are also usually too imprecise to be useful. By applying a statistical approach to a large number of systematically surveyed stars, however, one can gain a useful measure of the difference in mass between two populations of stars within the same cluster that is theoretically model-independent. In practice, one must accept some dependency on the stellar atmosphere of the difference in mass between two populations of stars within the same cluster that is theoretically model-independent. In practice, one must accept some dependency on the stellar atmosphere models used to derive the observables (L, T _eff _ and \( \log g \)), but these can mostly be circumvented by choosing stars with a similar temperature range where systematic effects are small.

In recent years, large-scale studies of stars in globular clusters have meant many stars have had their fundamental parameters accurately determined. The cluster ω Centauri has had photometric temperatures and luminosities, and spectroscopic metallicities determined for a large number of its stars (McDonald et al. 2009, hereinafter M+09, and Johnson & Pilachowski 2010, hereinafter JP10, respectively; see also van Loon et al. 2007; Marino et al. 2011). We present here the spectroscopic gravity determinations from the original spectra of JP10 and use these to measure the relative masses of RGB and AGB stars.

3 SAMPLE SECTION AND DATA REDUCTION

An essential requirement is to accurately differentiate RGB from AGB stars. The most reliable way to do so is photometrically, on the early-AGB (eAGB), where the two branches separate on HRDs and colour–magnitude diagrams (CMDs). Our selection is based on cuts applied to the HRD of M+09 and the CMD of Bellini et al. (2009): stars common to M+09 and JP10 are selected if they fall into the designated regions on both the HRD and the CMD (Fig. 1).

A well-known spread exists in the elemental abundances and metallicity of ω Centauri’s stars (e.g. JP10). To minimize the effects of this spread, and due to the difficulty in identifying AGB stars in the metal-rich populations in the cluster, we further restrict our sample to stars with a metallicity range of −1.9 ≤ [Fe/H] ≤ −1.5. This is centred on the cluster’s bulk population, at [Fe/H] = −1.7. This also helps prevent any metallicity-related bias and leaves a total sample of 161 RGB and 38 eAGB stars.

Changing the metallicity limits we choose (−1.9 ≤ [Fe/H] ≤ −1.5) by ±0.1 dex does not change our results by more than the random error. We also probed for variations in the mass differential within the sample, but could find no significant variation with metallicity or with any other elemental abundance (as listed in JP10). Seven of the stars in our final sample (LEIDs 23033, 24027, 38226, 42174, 43104, 43108 and 47151, where LEIDs stands for Leiden Identifiers) have positive [Na/O] abundances, suggesting they may belong to a second-generation, helium-rich population. These are all RGB stars and excluding them makes no significant difference to the final result.

A systematic temperature difference of ~130 K exists between the reddening-corrected photometric temperatures of M+09 and the \((V − K)\)-based temperatures of JP10. This was traced to inaccuracies in the filter transmissions and zero-point fluxes used for the optical photometry in M+09. The M+09 data were re-reduced, adopting a reddening value of \(E(B − V) = 0.12\) mag (Harris 1996) and a...
Figure 2. Example spectra of an RGB and AGB star with a typical temperature and metallicity (LEID 56118: \( T_{\text{eff}} = 4620 \) K, \([\text{Fe/H}] = -1.64\); and LEID 34056: \( T_{\text{eff}} = 4875 \) K, \([\text{Fe/H}] = -1.63\)). Synthetic spectral models of the 6149 and 6247 Fe II lines are overplotted with a fixed [Fe/H] II abundance. The open circles indicate the observed spectrum, the solid black line shows the best-fitting log g synthesis (derived from the equivalent-width analysis) and the dashed lines indicate changes in log g of +0.1/−0.1 dex (blue/red lines).

The log g values published in JP10 are based on photometric colours, which assume a priori a mass of \( 0.8 M_\odot \). As we measure mass, we require spectroscopic values of log g, which are free from such assumptions. These were determined by comparing the [Fe/H] I and [Fe/H] II abundances\(^1\) derived from the equivalent widths provided in JP10 (their table 3). Model atmosphere grids were constructed for each star with log g covering ±0.5 dex (in 0.01 dex increments) from the photometrically derived value provided in JP10 (their table 2). Although the \( T_{\text{eff}} \) and microturbulence values were held fixed at the values given in JP10, we iteratively adjusted the model metallicity to equal the average value of the [Fe/H] I and [Fe/H] II ratios for a given log g grid point. The final spectroscopic gravity was then selected as the log g value that satisfied [Fe/H] I = [Fe/H] II. The need for accurate log g values meant that spectra were discarded where one or both of the Fe II lines could not be reliably measured and/or the two lines did not provide reasonable agreement on the ‘best-fitting’ log g value. The comparative weakness of the Fe II lines (Fig. 2) means that this represents a substantial reduction in our sample size. A further four RGB and two AGB stars were removed because they no longer fell into their respective regions in the HRD created using the Bellini et al. data. The final sample of high-quality targets comprises 66 RGB and 21 eAGB stars. This subset of targets has negligible difference in their average metallicity, temperature and luminosity compared to our original selection. The new photometric and spectroscopic parameters for these objects are listed in Table 1, where stars are listed by their LEIDs. These parameters were then used to measure a mass for each star, using equation (1).

\[^1\] [Fe/H] abundances derived from Fe I and Fe II lines, respectively.

Table 1. Spectroscopic and photometric parameters for our target stars. The complete table is available online (see Supporting Information).

| LEID  | \( T_{\text{phot}} \) (K) | \( L_{\text{phot}} \) (\( L_\odot \)) | [Fe/H] (dex) | log g (cm s\(^{-2} \)) |
|-------|--------------------------|-----------------------------|-------------|----------------------|
| RGB   |                          |                             |             |                      |
| 16019 | 4803                     | 206.8                       | −1.74       | 1.64                 |
| 16027 | 4850                     | 166.0                       | −1.86       | 1.63                 |
| ...   | ...                      | ...                         | ...         | ...                  |
| AGB   |                          |                             |             |                      |
| 19022 | 4963                     | 232.2                       | −1.80       | 1.51                 |
| 24040 | 4907                     | 221.3                       | −1.75       | 1.47                 |
| ...   | ...                      | ...                         | ...         | ...                  |

4 ERROR BUDGET

The random error associated with individual RGB stellar masses is dominated by errors in log g caused by uncertainties in the stellar metallicity, temperature and luminosity. The metallicity errors (taken from JP10) and a conservative microturbulence error of \( ±0.3 \) km s\(^{-1} \) were propagated through the log g determinations described above. From these, a mass error is derived of \( \delta M/M = ±11^{+14}_{−10} \) per cent. Internal temperature errors of \( ±56 \) K were estimated (being the rms deviation between values in Table 1 and JP10), yielding an error of \( \delta M/M = ±13^{+18}_{−16} \) per cent. Finally, luminosity errors of \( ±5 \) per cent yield a proportional effect on \( \delta M/M \). Taking these errors in quadrature, we derive an rms random error of \( \delta M/M = ±18 \) per cent. Errors on the AGB should be similar, though the log g determination imparts a \( ±16 \) per cent error in these stars, bringing the total error to \( \delta M/M = ±21 \) per cent. This matches well with the rms scatter observed in Fig. 3: the rms scatter is 20 per cent for the RGB stars and 17 per cent for AGB stars. This shows that our random error budget covers the observed errors and suggests that the spread in the masses of stars on the eAGB is unlikely to be more than a few hundreds of a solar mass.

The systematic error budget is dominated by errors in temperature, reddening and distance to \( \omega \) Centauri. Systematic errors in temperature of \( ±50 \) K were estimated, based on the \( 47 \) K systematic difference between the temperatures in Table 1 and those of JP10, providing an error of \( \delta M/M = ±12^{+16}_{−11} \) per cent as above. A
6 DISCUSSION

While the absolute masses we determine for our RGB and eAGB stars are systematically uncertain, the percentage difference between them can be put into context using well-calibrated initial and final stellar masses. This allows the mass of the HB stars to be determined and compared with HB models. The mass predicted by isochrone fitting for a 200-L⊙ RGB star in ω Centauri is between 0.80 and 0.85 M⊙ (Girardi et al. 2002; Dotter et al. 2008; M+09, and references therein), with very little mass-loss occurring before this stage. This mass range agrees with 0.806 ± 0.056 M⊙ determined from the binary OGLEGC 17 (Thompson et al. 2001). The final white dwarf mass in similar globular clusters is found to be 0.53 ± 0.03 M⊙ (also derived using equation 1; Moehler et al. 2004).

Taking these two limits, this yields an eAGB star mass of 0.62 ± 0.04 M⊙ and infers a mass-loss of 0.21 ± 0.03 M⊙ between the central RGB and eAGB (the difference in initial mass between the RGB and AGB stars is only a few ×10−3 M⊙). The eAGB mass is commensurate with both 0.61 and 0.63 M⊙ derived using the Victoria–Regina and Dartmouth HB tracks, respectively (M+09), and within the spread of masses (±0.05 M⊙) which these models predict.

The aforementioned isochrone fits provide the average RGB star we target with another 20 Myr on the RGB. Assuming the mass-loss on the HB itself is negligible, this translates to an average mass-loss rate of 10−8 M⊙ yr−1 over the remainder of the RGB. In concurrence with previous relations (Catelan 2009a, and references therein), this is rather higher than the average Reimers’ mass-loss rate (Reimers 1975) of 1.9 × 10−9 M⊙ yr−1 (assuming Reimers’ η = 0.5). It is towards the higher end of the observed range of mass-loss rates estimated from chromospheric line profiles (e.g. Dupree et al. 2009; Vieytes et al. 2011), suggesting that stronger mass-loss at the RGB tip is important.

One can also use the white dwarf mass to estimate that there is only 0.09 ± 0.05 M⊙ of material for the star to lose during ~9 Myr it spends in its (post-)AGB phases: also yielding an average mass-loss rate of 10−8 M⊙ yr−1. Chromospheric mass-loss appears continuous on the AGB and can reach ~6 × 10−8 M⊙ yr−1 (Dupree et al. 2009), while the cluster also has several dust-producing stars, which typically sustain a mass-loss rate of ~10−6 M⊙ yr−1 for ~103 yr (M+09; McDonald et al. 2011c). The combination of these processes may mean that many stars lose their entire envelope before they reach the post-AGB phase, perhaps even becoming AGB-manqués (‘failed’ AGB stars; e.g. O’Connell 1999). This would explain the surprisingly-low luminosity (L ~ 1500 L⊙) of ω Centauri’s known post-AGB stars: LEID 16018 (Fehrenbach’s star) and 32029 (V1) (McDonald et al. 2011c).

Having measured the differential RGB/eAGB mass in ω Centauri, and confirmed it against existing models, it now becomes possible to repeat the study in other clusters where the models are less certain. In particular, this technique will be useful in those clusters with higher metallicities and higher envelope masses, where the temperature of HB stars is less sensitive to stellar mass. Our current observations do not allow us to relate metallicity, initial mass or initial abundance to RGB mass-loss. For that, we need these observations to be repeated in other clusters. While other clusters are less populous than ω Centauri, we are limited here by the existence of spectra, not by

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5 THE RGB VERSUS eAGB MASS RATIO

The average masses and sample standard deviations found for our sample of RGB and eAGB stars are 0.488 ± 0.117 M⊙ and 0.657 ± 0.090, respectively. We stress that these values do not take into account the systematic errors of δM/δM = ±20 per cent outlined above. The RGB mass is 18 per cent lower than the canonical ±0.8 M⊙ expected from stellar isochrone modelling (Girardi et al. 2002; M+09), which is commensurate with these errors. It would be speculative to suggest why the masses we derive are systematically lower, though we note that the cluster’s distance is (by a small margin) the largest contributor to the systematic error budget.

Taking the ratio of the two masses, which is largely independent of systematic errors, we find that 25.7 ± 4.3 per cent (standard error) of mass is lost between the central RGB and eAGB. The true error may be a little larger (perhaps 1–2 per cent), due to temperature-dependent effects below the level of statistical detectability and the robustness with which we can photometrically differentiate between RGB and AGB stars.

2 These values assume helium of Y ≈ 0.24, [α/Fe] ≈ +0.3 and [Fe/H] ≈ −1.62.
the number of stars. Bespoke targeting of stars (particularly on the eAGB), and the selection of a spectral range with more gravity-sensitive lines, would allow this study to be repeated to higher accuracy, even in much smaller clusters.

7 CONCLUSIONS

We have spectroscopically determined surface gravities for 66 central RGB and 21 eAGB stars in ω Centauri, and combined these with photometric temperature and luminosity measurements to calculate the difference in mass between the two populations. We find that 26 ± 4 per cent of their mass is lost between these evolutionary phases, corresponding to 0.21 ± 0.03 M⊙ for an initial mass of 0.83 M⊙. By implication, this limits the mass-loss on the AGB to some 0.09 ± 0.05 M⊙, which may lead to early termination of the AGB and formation of AGB-manqué stars. Our derived HB masses of 0.62 ± 0.04 M⊙ compare very well with HB models, which predict HB masses of 0.61–0.63 M⊙ for appropriate (Y ≈ 0.24, [α/Fe] ≈ +0.3, [Fe/H] ≈ −1.62) models. This method has the potential to provide physical constraints on currently uncertain regimes in modelling HB stars.

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REFERENCES

Alonso A., Arribas S., Martínez-Roger C., 1999, A&AS, 140, 261
Bellini A. et al., 2009, A&A, 493, 959
Carraro G., Girardi L., Bressan A., Chiosi C., 1996, A&A, 305, 849
Catelan M., 2009a, Ap&SS, 320, 261
Catelan M., 2009b, in Mamajek E. E., Soderblom D. R., Wyse R. F. G., eds, Proc. IAU Symp. 258, The Ages of Stars. Cambridge Univ. Press, Cambridge, p. 209

del Principe M. et al., 2006, Mem. Soc. Astron. Ital., 77, 330
Dotter A. et al., 2008, ApJS, 178, 89
Dupree A. K., Smith G. H., Strader J., 2009, AJ, 138, 1485
Girardi L. et al., 2002, A&A, 391, 195
Harris W. E., 1996, ApJ, 112, 1487
Johnson C. I., Piłachowski C. A., 2010, ApJ, 722, 1373 (JP10)
McDonald L. et al., 2009, MNRAS, 394, 831 (M-09)
McDonald I., Boyer M. L., van Loon J. T., Zijlstra A. A., 2011a, ApJ, 730, 71
McDonald L. et al., 2011b, ApJS, 193, 23
McDonald I. et al., 2011c, MNRAS, in press (arXiv:1104.5155)
Marigo P. et al., 2008, A&A, 482, 883
Marino A. F. et al., 2011, ApJ, 731, 64
Moehler S. et al., 2004, A&A, 420, 515
O’Connell R. W., 1999, ARA&A, 37, 603
Reimers D., 1975, Mem. Soc. R. Sci. Liege, 8, 369
Thompson I. B. et al., 2001, AJ, 121, 3089
van de Ven G., van den Bosch R. C. E., Verolme E. K., de Zeeuw P. T., 2006, A&A, 445, 513
van Leeuwen F. et al., 2000, A&A, 360, 472
van Loon J. T. et al., 1999, A&A, 351, 559
van Loon J. T. et al., 2007, MNRAS, 382, 1353
Vieytes M. et al., 2011, A&A, 526, A4
Willson L. A., 2000, ARA&A, 38, 573

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. Spectroscopic and photometric parameters for our target stars.

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