Mem. S.A.It. Vol. 88, 244

Memorie della

The effect of enhanced helium abundances on the AGB-supernove mass transition

Amanda I. Karakas[1] and Luke J. Shingles[2]

[1] Monash Centre for Astrophysics, School of Physics & Astronomy, Monash University, VIC 3800, Australia, e-mail: amanda.karakas@monash.edu
[2] Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, Northern Ireland, UK

Abstract. Globular clusters are now known to harbour helium-rich stellar populations. While the stars we see today are all of low mass, there were once stars of all mass ranges with helium mass fractions up to $Y \approx 0.40$. It has also been suggested that the younger stellar component of the Galactic bulge is both metal-rich and helium rich, with Y up to 0.40. In this study we investigate the effect of helium enrichment on the stellar evolution of stars near the AGB-supernova mass transition, which is 8 Msun for solar metallicity. In particular we show that the AGB-supernova mass transition decreases in mass with increasing helium abundance, for both metal-poor and metal-rich models. This will have an impact on the stellar yields and on the chemical evolution of helium rich stellar populations.

Key words. Galaxy: Abundances, Nucleosynthesis, Abundances – Stars: Abundances, Stars: AGB and Post-AGB — ISM: abundances

1. Introduction

Variations in the helium abundance have now been established for a number of Galactic globular clusters (GCs) including ω Centauri, NGC 2808, NGC 2419, and M22 (see review by Gratton et al. 2012). While the first studies relied on indirect detections of helium, there are now direct detections of helium enrichment in stars in a number of GCs. For example, Marino et al. (2014) find $Y = 0.34$ in a sample of horizontal branch stars in NGC 2808, whereas Dupree & Avrett (2013) inferred helium abundances from measurements of the He I line in red giant stars in ω Cen (Pasquini et al. 2011).

The origin of the helium enrichments and light-element abundance correlations observed in ω Cen and other Galactic globular clusters has been the subject of much debate. Both result from hot hydrogen burning (e.g., Prantzos et al. 2007), which produces helium via the CNO cycles. Two favoured polluters include intermediate-mass asymptotic giant branch (AGB) stars between $\approx 3 - 8 M_{\odot}$ (Ventura & D'Antona 2009) and either single or binary massive stars (Decressin et al. 2007; de Mink et al. 2009). Numerous studies have discussed the merits and problems with each polluter and the various scenarios and we do not repeat that discussion here (e.g., Fenner et al. 2004; Norris 2004; Karakas et al. 2006; Renzini 2008; D'Ercole et al. 2010; D'Antona et al. 2011).

Here we consider the implications of high helium abundances on the stellar evolution of intermediate-mass stars near the AGB-supernova mass transition.

2. The effect of helium on stellar evolution

The effect of the initial helium abundance on stellar evolution has been extensively discussed (Iben & Faulkner 1968; Sweigart & Gross 1978; Salaris & Cassisi 2005; Caloi & D'Antona 2007). This is partly because the primordial helium abundance has only been fairly well established over the last 10 years so it was prudent to make stellar models with a range of initial helium abundances.

Recent studies have focused on helium-enriched stellar models of $M \leq 1M_\odot$. That is because these are the long-lived stars that make up the current stellar content of globular clusters today (Gallart et al. 2005; Valcarce et al. 2012; Joo & Lee 2013; Campbell et al. 2013; Charbonnel et al. 2013). Furthermore, few of these previous studies evolved the stellar models beyond core helium burning (e.g., Chantereau et al. 2015).

Data for massive GCs like ω Cen inform us that there were populations of stars of all masses born with high helium abundances initially. For example, data from King et al. (2012) suggests there was a stellar population born with [Fe/H] = = -1.4 and $Y \approx 0.38$. The question is: What happened to the intermediate-mass stars in that population when they died? How did the initial helium abundance affect the mass range for core carbon burning and core-collapse supernovae?

3. Helium-enriched models of intermediate-mass

Shingles et al. (2015) and Karakas et al. (2014) present the first stellar yields from helium-enriched intermediate-mass stars that have been evolved through all stellar evolutionary phases including the AGB. The models were evolved for a metallicity of $Z = 0.0006$ or [Fe/H] = -1.4 (for primordial hydrogen models) for masses $M = 1.7M_\odot$ to $6M_\odot$; for each mass four models were calculated for the following initial helium abundances: $Y = 0.24, 0.30, 0.35, 0.40$. The stellar evolutionary sequences were used in a post-processing code to determine the nucleosynthesis yields of all stable elements from hydrogen to bismuth.

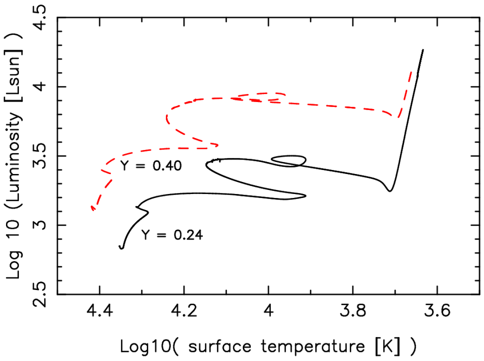

Fig. 1. Evolutionary tracks of the $5M_\odot$ models with $Y = 0.24$ and $Y = 0.40$ from the main sequence through to the start of the thermally-pulsing AGB phase of evolution. Using data from Shingles et al. (2015).

In Fig. 1 we show the HR diagram for the $5M_\odot$ models with $Y = 0.24$ and $Y = 0.40$. The model with increased helium behaves on the HR diagram as if it is initially more massive: it is hotter and brighter on the main sequence, behaviour which is seen to carry through to all evolutionary stages. The final fate of the model with a primordial helium is that of a CO-core white dwarf. In contrast, the model with $Y = 0.40$ goes through off-centre degenerate carbon ignition although the flame does not reach the centre. The white dwarf has a hybrid CO/ONe, with the composition shown in Fig. 2.

For all intermediate-mass models the stellar lifetimes are shorter. For the main sequence this is obvious – more helium means less hydrogen, which results in less fuel to burn and thus a shorter lifetime. But even on the AGB we found that the lifetimes were shorter by factors of 4-10, depending on the initial stellar mass (Shingles et al. 2015). Overall it is the main sequence lifetime that dominates the total stellar lifetime. According to models from Karakas et al. (2014) even low-mass AGB stars of $1.7M_\odot$ with $Y \geq 0.35$ can contribute to chemical evolution in under 1 Gyr.

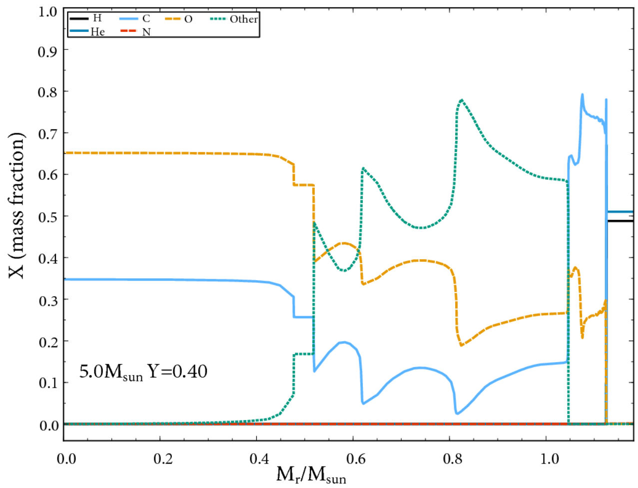

Fig. 2. Core composition of the $5M_{\odot}$, $Y = 0.40$ model at the beginning of the thermally-pulsing AGB. Interior mass is shown on the x-axis and mass fractions of H, He, C, N, O, and elements heavier than O ("Other") on the y-axis. Off-centre degenerate carbon burning converts some of the carbon exterior to $M_r = 0.5$ into Ne, which is seen by the increase in the abundance of elements heavier than O. Credit: Luke Shingles

The third dredge-up efficiency is lower *per pulse* in models with increased helium compared to the primordial helium models. The total amount of He-shell material dredged into the envelope is therefore lower, once integrated over all thermal pulses (Shingles et al. 2015). The main consequence is that the stellar yields of elements dependent on third dredge-up are reduced, which includes C, F and heavy elements produced by the *s*-process.

Owing to the models with increased helium entering the AGB with larger core masses, the minimum mass for hot bottom burning was shifted from $\gtrsim 4M_{\odot}$ to $3M_{\odot}$. Furthermore, we found that the minimum mass for carbon burning was also reduced, as noted above for the $5M_{\odot}$ case.

Using the *Kepler* stellar evolution code (Heger & Woosley 2010) models of intermediate-mass between 4 to $15M_{\odot}$ were calculated by Josh Cameron, an undergraduate student at Monash University. The models were calculated with the same initial composition and set of helium abundances used in Shingles et al. (2015). These models in particular push into the regime of core-collapse supernovae and more closely probe the AGB-supernovae mass transition. We summarize these results below.

4. Discussion and summary

There is evidence of a metal-rich, helium rich component to the Galactic bulge (Nataf & Gould 2012). Karakas (2014) followed up on calculating helium-rich metal-rich AGB models and noted that the reduction in third dredge-up removed carbon stars from a stellar population. For $Z = 0.03$ (twice solar) only a small increase in helium of $\Delta Y = 0.05$ removed all carbon stars, which may explain the paucity of carbon stars in the metal-rich inner ring of M31 (Boyer et al. 2013). We also investigated the AGB-supernovae mass transition for solar metallicities and found that stars of $\gtrsim 6M_{\odot}$ will evolve through off-centre carbon burning when $Y = 0.40$, with the minimum mass for core-collapse supernova similarly decreasing from above $10M_{\odot}$ to $\approx 8M_{\odot}$. The implications of these results still need to be studied but will mean an increased number of ONe white dwarfs, neutron stars and black holes. We summarize our conclusions for the metal-poor helium-rich models:

1. Shorter evolutionary lifetimes in all evolutionary phases, including the AGB phase.
2. Even a small initial increase in helium reduced the third dredge-up efficiency. For most models the total mass of material dredged to the surface is significantly lower.
3. Stellar yields were generally lower for all elements including carbon and typical *s*-process elements such as Ba and La. The exception was for the $3M_\odot$ model, which behaves like an intermediate-mass star for $Y \geq 0.35$.
4. The minimum mass for hot bottom burning is reduced from $4M_\odot$ to $3M_\odot$ with even a small increase in the initial helium.
5. The minimum mass for core carbon burning was reduced from above $6M_\odot$ to between 4 to $5M_\odot$ for $Y \geq 0.35$.
6. Neutron stars can form from models of $\geq 6M_\odot$ and black holes for $\geq 18M_\odot$. In comparison, for the primordial case, neutron stars and black holes form for $\geq 8M_\odot$ and $\geq 23M_\odot$, respectively.

Acknowledgements. AIK thanks the LOC for organizing a fantastic conference!

References

Boyer, M. L., et al. 2013, ApJ, 774, 83
Caloi, V. & D'Antona, F. 2007, A&A, 463, 949
Campbell, S. W., et al. 2013, Nature, 498, 198
Chantereau, W., Charbonnel, C., & Decressin, T. 2015, A&A, 578, A117
Charbonnel, C., et al. 2013, A&A, 577, L17
D'Antona, F., et al. 2011, ApJ, 736, 5
de Mink, S. E., Pols, O. R., Langer, N., & Izzard, R. G. 2009, A&A, 507, L1
Decressin, T., Charbonnel, C., & Meynet, G. 2007, A&A, 475, 859
D'Ercole, A., et al. 2010, MNRAS, 407, 854
Dupree, A. K. & Avrett, E. H. 2013, ApJ, 773, L28
Fenner, Y., et al. 2004, MNRAS, 353, 789
Gallart, C., Zoccali, M., & Aparicio, A. 2005, ARA&A, 43, 387
Gratton, R., Carretta, E., & Bragaglia, A. 2012, A&A Rev., 20, 50
Heger, A. & Woosley, S. E. 2010, ApJ, 724, 341
Iben, I., Jr. & Faulkner, J. 1968, ApJ, 153, 101
Joo, S.-J. & Lee, Y.-W. 2013, ApJ, 762, 36
Karakas, A. I. 2014, MNRAS, 445, 347
Karakas, A. I., et al. 2006, ApJ, 652, 1240
Karakas, A. I., Marino, A. F., & Nataf, D. M. 2014, ApJ, 784, 32
King, I. R., et al. 2012, AJ, 144, 5
Marino, A. F., et al. 2014, MNRAS, 437, 1609
Nataf, D. M. & Gould, A. P. 2012, ApJ, 751, L39
Norris, J. E. 2004, ApJ, 612, L25
Pasquini, L., Mauas, P., Käufl, H. U., & Cacciari, C. 2011, A&A, 531, A35
Prantzos, N., Charbonnel, C., & Iliadis, C. 2007, A&A, 470, 179
Renzini, A. 2008, MNRAS, 391, 354
Salaris, M. & Cassisi, S. 2005, Evolution of Stars and Stellar Populations (Wiley, Chichester, UK)
Shingles, L. J., et al. 2015, MNRAS, 452, 2804
Sweigart, A. V. & Gross, P. G. 1978, ApJS, 36, 405
Valcarce, A. A. R., Catelan, M., & Sweigart, A. V. 2012, A&A, 547, A5
Ventura, P. & D'Antona, F. 2009, A&A, 499, 835