Stellar evolution and nucleosynthesis in helium-enriched stars

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Introduction

• HST has revealed sub-populations within galactic globular clusters (e.g., ω Centauri, M22, NGC 2808, NGC 1851)
• The cause includes variations in iron (Fe), helium (Y), and C, N, and O elements
• Some clusters show large variations in helium, from the primordial value of $Y \approx 0.24$ to $Y \sim 0.40$ (i.e., $\Delta Y \sim 0.1$ or more; the solar value $\sim 0.28$)
• The origin of the multiple populations within GCs is unknown
• In particular, the origin of the helium is unknown (e.g., massive stars, asymptotic giant branch stars, massive binary stars...)
Omega Centauri

Metallicity distribution from Johnson & Pilachowski (2010)

Colour-magnitude diagram from King et al. (2012, see also Piotto et al. 2005, Norris 2004, Bedin et al. 2004)
Omega Centauri

Omega Cen and M22 show variations in Fe and elements that are produced by the slow neutron capture process (e.g., Norris & Da Costa 1995; Stanford et al. 2007, Da Costa & Marino 2011, Marino et al. 2011, 2012)

The abundances indicate the contribution from low-mass AGB stars ($M \leq 3\text{Msun}$)
But there are some problems:

1. Low-mass stars evolve slowly
2. Isochrone fitting requires a formation timescale of $\leq 1\text{Gyr}$ (D’Antona et al. 2011)
3. How did the plateau originate?

How to resolve these problems?

Figure from Gary Da Costa using data from Norris & Da Costa (1995)
Helium-enriched stellar models

- Few studies evolve the stars beyond core helium burning
- What happens to helium-enriched stars on the AGB?
- Evolve models of $M = 1.7, 2.4 \text{ Msun}$, $[\text{Fe/H}] = -1.4$ with $Y = 0.24, 0.30, 0.35, 0.40$

From Karakas, Marino & Nataf (2014)
Summary of AGB evolution

$^4\text{He}, ^{12}\text{C}, \text{s-process elements: Zr, Ba, ...}$

At the stellar surface: C>O, s-process enhancements

Interpulse phase ($t \sim 10^{4-5}$ years)

See review by Karakas & Lattanzio (2014)
Helium-enriched stellar models

- Helium enrichment shortens the total stellar lifetime according to:

\[ \tau_{\text{stellar}} \propto M^{-2.69} \times \exp[-5.43(Y - 0.24)] \]

- That is, an increase of Y by 0.05 or in mass by 11% will decrease the stellar lifetime by 24%
- Helium-enriched AGB stars not only evolve more quickly than their helium normal counterparts but with bigger cores and hotter burning shells
- Helium-enriched stars of \( \leq 2\text{M}_\odot \) will have time to contribute to the chemical enrichment
- They also mix less processed material to their surface (up to a factor of 6 less, depending on mass and Y)
- Could these explain the plateau and fix the timescale problem?
Chemical yields from helium-enriched models

- We find that the stellar yields of helium enriched models are significantly reduced relative to their primordial helium counterparts.
- An increase of $Y = 0.10$ at a given mass decreases the yields of C by up to ~60%, of F by up to 80%, and decreases the yields of the s-process elements Ba and La by ~45%.

Results shown for the $M = 2.4M_{\odot}$, $Z = 0.0006$ models

But increases in P, Kr, and Rb

From Karakas, Marino & Nataf (2014)
Intermediate-mass AGB stars

Along with thermal pulses and the third dredge-up, these stars also have:

- **Second dredge-up**: Large change in $\Delta Y$ (up to 0.1)
- **Hot bottom burning**: Proton-capture nucleosynthesis at base of envelope (products: N, Na, Al)

Example: 6Msun, $Z = 0.02$

See review by Karakas & Lattanzio (2014)
Off-centre carbon ignition

- $M \geq 8\, M_{\odot}$ (at $Z = Z_{\text{solar}}$) up to $10\, M_{\odot}$
- These stars go through degenerate carbon ignition
- Q: What fraction explode as supernovae or leave massive white dwarfs?
- Nomoto (1984), Poelarends et al. (2008), Doherty et al. (2010)
- The brightest AGB stars in young populations, with $M_{\text{bol}} \sim -7.6$, brighter than the traditional AGB limit ($M_{\text{bol}} \sim -7.1$)

7.5$M_{\odot}$, $Z = 10^{-4}$ model by Siess (2007)
Super-AGB stars

- Stars that proceed through carbon burning and onto the AGB are known as “super-AGB stars”
- Nucleosynthesis similar to their lower mass cousins
- See discussion in Karakas & Lattanzio (2014)

Figure from Carolyn Doherty
He-rich intermediate-mass models

- $M = 3, 6 \text{ M}_{\odot}$, $[\text{Fe/H}] = -1.4$ with $Y = 0.24, 0.30, 0.35, 0.40$
- We see a similar reduction in total and AGB lifetimes, which results in a reduction in total mass dredged up $\rightarrow$ lower the yields

$$\text{Total mass dredged up} = 0.17 \text{M}_{\odot}$$

No SDU or HBB

Has both SDU + HBB!

Dredges up $0.065 \text{M}_{\odot}$

Shingles, L., et al. (2014, in preparation)
He-rich intermediate-mass models

- The most extreme model we have is a 6M_{sun}, Z = 0.0006 with Y = 0.40. This is a super-AGB star.

Shingles, L., et al. (2014, in preparation)
## Helium-rich Ejecta

<table>
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<th>Mass:</th>
<th>Y in Ejecta</th>
<th>1.7</th>
<th>2.36</th>
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</table>

- One barrier to AGB stars producing the multiple-populations in GCs is the helium limit of $Y \leq 0.38$
- Whereas helium enrichments of up to $Y \sim 0.40$ have been inferred for some systems
- We see a small increase in the initial $Y$ of 0.06 leads to a final $Y = 0.41$ in the most massive AGB model

Shingles, L., et al. (2014, in preparation)
Discussion/summary

- We have investigated the effect of helium enrichment on the evolution and nucleosynthesis of AGB stars.
- We find:
  1) AGB models with enhanced helium will evolve more than twice as fast, giving them the chance to contribute sooner to the chemical evolution of the forming globular clusters, and
  2) the stellar yields of low-mass AGB stars are strongly reduced relative to their primordial helium counterparts.
  3) This study is being extended to intermediate-masses, with the nucleosynthesis models currently being calculated.
- Globular clusters are not the only systems that show helium enrichment (e.g., Galactic bulge and early-type elliptical galaxies).
- Helium is an important third parameter for stellar nucleosynthesis and yields.