Nucleosynthesis during the peculiar core helium flash of low-mass primordial stars

Simon W. Campbell
Monash University School of Physics & Astronomy, Australia

Konkoly Observatory, Hungary:
Carolyn Doherty & Maria Lugaro

Monash University, Australia:
Alexander Heger, John Lattanzio, Amanda Karakas & Melanie Hampel (PhD student)
Subtitle: Beating the drum for low-mass stars!
Interestingly, EMP stars are often found to contain high levels of carbon \( \Rightarrow \) “CEMPs”

Campbell 2007 (PhD thesis)
Also, some CEMP(s) are enriched in neutron-capture elements

- **CEMP:**
  \([C/Fe] > 0.7\) dex

- **CEMP-s:**
  \([Ba/Fe] > 0.5\)
  \([Eu/Fe] < 1.0\)

- **CEMP-s/r:**
  \([Ba/Fe] > 0.5\)
  \(\text{and} \ [Eu/Fe] > 1.0\)

What do low-mass stellar models predict?

Case study:
Theoretical evolution of a0.85 M☉ Population III star
Pop III (Z=0) 0.85 $M_\odot$ HRD: MS to RGB Tip

- Typical Halo star mass
- Z=0 star has:
  - Higher luminosity
  - Higher surface temperature.
  - RGB tip luminosity ~ 1 dex lower.
- Major factor altering the evolution is low opacity of the metal-free gas.
- Also, the lack of CNO elements precludes the Z=0 star from burning H via the CNO cycles.

Campbell 2007 (PhD thesis)
Z=0, 0.85 M☉: Internal Structure, MS

PP-chain energy release has a *much* weaker T dependence than CNO cycle → fundamental change in structure.

- Snapshot near end of MS
- At this stage the 'normal' star is switching to CNO H burning
- The Z=0 star cannot do this, so it continues to burn via the pp-chains, which creates a marked difference in structure

Blue = Zero metallicity
Dashed = GC metallicity

- Hotter all round
- Denser core
- Low opacity
- Higher energy production: pp burn

Campbell 2007 (PhD thesis)
Main Event:
The helium core-flash of the $0.85 \, M_\odot$
Population III Star
$Z=0$, $0.85 \, M_\odot$: Core He Flash

- At the top of the RGB He ignition results in a runaway burn (‘flash’) due to partial degeneracy of core material.
- In the $Z=0$ model this happens much further from the centre of the star...
Z=0, 0.85 M☉: This Core Flash is not normal!

Comparison between a Z=0/EMP star and a GC metallicity star

- Grey shading = convection
- Blue line = H burning shell
- Dashed line = He burning shell

Convection breaks out of core!
→ Mixes protons down to region burning helium: VERY HOT for H (~100 MK; normally H burns at ~20 MK)

This is unique to EMP/PopIII stars!
The mixing of protons downwards into high temperature regions has 2 consequences:

1) Massive energy release: H burns very rapidly at such high T → ‘Hydrogen Flash’ → “Dual Core Flash”

2) Interesting nucleosynthesis: H is not often found in such conditions, a range of isotopes can be produced → and mixed to the surface!
It was suggested by Fujimoto et al (1990) that neutron-capture elements may be produced during a DCF, since the protons should be captured by $^{12}\text{C}$ in He burning region, to produce $^{13}\text{C}$, and this can then produce neutrons.

In this model we found that $^{13}\text{C}$ was produced in large amounts, and that the neutron-producing reaction $^{13}\text{C}(a,n)^{16}\text{O}$ was very active.

Interestingly the neutron density in this model is $\sim 10^{13} \text{ cm}^{-3}$.

This is much higher than s-process densities!

But not as high as needed for the r-process.

This simulation had a limited nuclear network (75 isotopes, up to S), so more investigation was required.

Campbell 2007 (PhD thesis)
Ingested protons mixing & burning

\[ ^{12}\text{C}(p,\gamma)^{13}\text{N} \]

\[ ^{13}\text{N}(\beta^+)^{13}\text{C} \quad [t_{1/2} \sim 10 \text{ mins}] \]

\[ ^{13}\text{C}(\alpha,n)^{16}\text{O} \quad [T \sim 2 \times 10^8 \text{ K}] \]

\[ n \rightarrow \text{s/i-process} \]

Protons

Hydrogen-rich, stable

Helium-rich, convective

Helium-rich, stable

\( T_{\text{mix}} \sim 50 \text{ min} \)

So \(^{13}\text{N}\) can travel before decaying to \(^{13}\text{C}\)
Larger network confirmed the high neutron densities in DCFs: $10^{13}$ to $10^{15}$ n/cm$^3$

- This is intermediate between s & r-process: the ‘i-process’ (Cowan & Rose 1977)
- At the time we didn’t have a big enough network to follow the i-process properly (only 320 isotopes)...
- Note this model was $[\text{Fe}/\text{H}] = -6.5$, 1.0 Msun.
Back to Abate’s CEMP-s, CEMP-r/s plot

- Colour scale is Population synthesis model (stellar density).
- It can produce CEMP-s stars (binaries) but *cannot* produce CEMP s/r stars.
- The input to these population models are stellar model yields. Stellar models are not reproducing the observations.
- Could it be the ‘Neutron Superburst’? -- this event was not included in the population synthesis…

DCF neutron superburst model!
At $[\text{Fe/H}] = -5.8$
(Campbell, Lugaro & Karakas 2010)

Red Model = AGB s-process
Black Model = Pre-enriched in r (+ AGB)

Abate et al., 2015
As noted, our network was not sufficient to follow the full i-process. More recently a couple of groups (Dardelet+2015, Hampel+2016) have made single-zone nucleosynthesis calculations, with large i-process-capable reaction networks. Thermodynamic conditions are taken to represent the AGB proton-ingestion site. They find a very good match between observed CEMP-r/s observations and their i-process abundance patterns. Has been suggested to rename CEMP-r/s to CEMP-i :)
In which stars do these events happen?

- Pollution summary for our grid of $Z=0$ and EMP models in the initial mass- $[\text{Fe/H}]$ plane.
- **Yields available!** (Campbell & Lattanzio 2008)
- Colour-coded by pollution events that contribute the most to the yields:
  - **DCF** = “Dual Core Flash” (RGB TIP)
  - **DSF** = “Dual Shell Flash” (start of AGB)
  - **3DU** = “Third dredge-up” (AGB)
  - **HBB** = “Hot Bottom Burning” (AGB)

Possible SNe 1.5, see Gil-Pons+ 2013

**DCFs are peculiar to EMP models** → **BONUS CARBON & n-capture elements!**

DSFs are similar but occur on AGB
The next step is to couple an i-process-capable network with a stellar structure calculation, for a self-consistent simulation.

Importantly, the energy from some reactions that are not usually taken into account becomes significant, for example: \( ^{13}\text{C}(\alpha,n)\ ^{16}\text{O} \) (Cristallo et al. 2009).

We are currently running models using the KEPLER stellar code (Heger [Monash], Woosley, Weaver et al.), which has an adaptable nuclear network (up to Astatine).

Kepler has recently been used for s/i-process in massive stars (Banerjee, Qian & Heger 2018).
Caveats

- **Reaction rates** of unstable nuclei are mostly theoretical, so uncertain → uncertainty in abundance patterns.

- Also, the DCF is really a 3D hydrodynamical event – the assumptions about convection (MLT; cf. Meridith Joyce’s talk) and mixing (diffusive) in the 1D codes must have a strong effect on the results...

- Woodward, Herwig, et al. have been working on a similar event in low-Z AGB stars, using 3D hydrodynamics (pictured right).

- Our group attempted a 3D simulation of a DCF around the same time...

Herwig et al. 2011
Past/Future work:
Trying to get a handle on turbulent mixing & burning uncertainties using 3D Hydro Simulations

Early attempt at 3D Dual Core Flash:

Recent 3D hydro simulation, oxygen burning shell:

Miroslav Mocak (IAA ULB Brussels, MPA Garching)

Mocak, Campbell, et al., 2010

3D Hydro collaborators: Miro Mocak, Casey Meakin, Dave Arnett
Summary/Fin

- Many EMP stellar models show violent burning episodes that lead to severe surface pollution, including carbon.
  - More ways to produce C in stars of low metallicity!
  - Way to go low-mass stars! :)

- So the existence of at least some CEMPs may be explained by this peculiar evolution of low-mass EMP stars.

- High neutron exposures in the dual flashes (‘neutron superbursts’) appear to also give i-process heavy element patterns, as identified in some CEMP stars (CEMP-s/r)

Current/future work:

- We are computing stellar models coupled to large nuclear reaction networks to model these events self-consistently.

- Also trying to reduce the model uncertainties by making 3D hydrodynamic models of these events.

Postdoc job ad!
- 3D Hydrodynamics & nucleosynthesis, at Monash Uni, Australia.
- Start latest Sep/2019.

PhD Student Ad!
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