On the Peculiar Lives of Low-Mass Primordial Stars

Simon W. Campbell
Monash Centre for Astrophysics
After the Big Bang came the ‘Dark Ages’ – no stars to light up the Universe yet.

When the first stars did start to form they did so from gas that was devoid of metals.

This affects Star Formation since protostellar gas clouds are thought to cool – and thereby collapse into stars – via metal lines.

Initially assumed that all of the First Stars must have been massive (M > 10M☉).

Since massive stars have very short lifetimes, this means that there should be none of the first generation of stars left today.

However primordial star formation theory is far from settled.

In fact the theoretical ‘minimum metals required’ for low mass star formation has evolved with the discovery of stars with lower and lower metal content!

Possibility remains that low-mass Pop III stars could have formed (fragmentation, cooling via H2).
So low-mass (very) EMP stars did form! Pop III not detected (yet).
The Most Metal-Poor Object Known (as of 2006)

- HE 1327-2326
- Galactic Halo star
- MS or Subgiant
- $[\text{Fe/H}] = -5.45$

**But also:**
- Very high $[\text{C, N, O}]$
- $[\text{C/Fe}] = +4!$

Figure: Chandra image of the spiral galaxy NGC 5746 (hot halo)
Interestingly, EMP stars are often found to contain high levels of carbon \( \Rightarrow \) “CEMPs”

Campbell 2007 (PhD thesis)
Where does all that Carbon come from?

- Special “weak” supernovae?
- Or maybe low-mass stars?
  - Let’s see if a low-mass star can even make so much carbon...
Case study: Evolution of a $0.85 \, M_\odot$ Population III Star
Pop III (Z=0) 0.85 M☉: 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.

'Normal' star versus Pop III star: Hydrogen burning

(Total L = L_{pp} + L_{cno})

All L from pp-chains in Z=0 star

All RGB L from CNO cycles in metal-rich star
Z=0, 0.85 $M_\odot$: Internal Structure, MS

pp-chains have a *much* weaker $T$ dependence than CNO cycle $\Rightarrow$ fundamental change in structure.

- **Blue = Zero metallicity**
- **Dashed = GC metallicity**
- 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

![Graph showing energy release vs. temperature (MK)](image)

- Hotter all round
- Denser core
- Low opacity
- Higher energy production: pp burn
**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 = convection
- Blue line = H burn
- Dashed line = He burn

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 stars!
The EMP "Dual Core Flash" (DCF)

- The mixing of protons downwards into high temperature regions naturally causes very rapid H burning.
  
  → Hydrogen Flash!

- The He flash is still ongoing → hence name 'dual flash'.

- He burning products (C, O) are mixed upwards also.

- This material is later dredged up into the envelope, polluting the surface...

Again, this unique to EMP stars!
Neutron-capture elements may be produced during a DCF, since the protons should react with the $^{12}\text{C}$ produced by the He burning, to produce $^{13}\text{C}$, and this can produce neutrons.

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

Interestingly the neutron density in this rough plot from my thesis is $\sim 10^{14}\text{ cm}^{-3}$.

This neutron density is much higher than s-process densities!

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

This simulation had a limited nuclear network, so more investigation was required.

**Possible s/r-Process during the DCF?**

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- This simulation had a limited nuclear network, so more investigation was required.
Larger network confirmed the high neutron densities: \(10^{14}\) to \(10^{15}\) cm\(^{-3}\)

- So intermediate between s & r-process.
- Is this the site for the newly identified CEMP-i stars?
Summary in Mass-Metallicity Plane

- Pollution summary for our grid of models in the initial mass-[Fe/H] plane.
- 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)

DCF & DSF are peculiar to EMP models  BONUS CARBON! :)

Campbell & Lattanzio 2008
Getting the C to the EMPs: Binary mass transfer

- So it seems low-mass EMP stars can produce lots of carbon, but it usually happens in the late phases of a star’s life (end of RGB, start of AGB).
- How can we get this carbon onto the surfaces of currently observed EMP stars, which are primarily MS and RGB stars?
- Due to their faster evolution, slightly more massive stars (>~0.85 M☉) could have been binary companion mass donors to the currently observed CEMPs.
- The donor stars would be now be WDs.
1D stellar evolution theory was not designed to model these violent events!

Caveat: Many Uncertainties.

Models predict even more C below about [Fe/H] = -5.0. This is due to additional pollution from the DCFs, which only start to occur at this metallicity.

Model Yields Vs Observations: [C/Fe]

Campbell & Lattanzio 2008
Current/Future work:
Trying to get a handle on turbulent mixing & burning uncertainties using 3D Hydro Simulations

Early attempt at 3D Dual Core Flash:

Recent hydro simulation, oxygen burning shell:

Mocak, Campbell, et al., 2010

3D Hydro collaborators: Miro Mocak, Casey Meakin, Dave Arnett
Observations of EMP halo stars show increasing frequency of carbon-rich stars with decreasing metallicity.

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.

So the observations may be explained by this peculiar evolution of low-mass EMP stars.

However the C-rich gas must somehow get to the currently observed CEMP stars – possibly through binary mass transfer?

High neutron exposures in the dual flashes (‘neutron superbursts’) appear to also give s- and i-process like heavy element patterns, as recently identified in some CEMPs.

WARNING: *Many model uncertainties*, and a huge chemical parameter space to match – only a few elements discussed here.

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