Nucleosynthesis in the Dual Core Flashes of Primordial Low-mass Stars: A new s-process site?

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Talk Outline

• Background: Extremely Metal-poor Stars
  – The metal-poor Universe
  – The mystery of the CEMP (Carbon-Enhanced Metal-Poor stars)

• Low mass metal-poor stellar models
  – The neutron “superburst” at [Fe/H] = -6.5
  – Comparing with observations: A binary scenario?

• Summary & Future work
  – Model uncertainties
  – Need for fluid-dynamical models
PART I: Extremely Metal-Poor Stars
In the Beginning...

- Only H and He formed in the Big Bang (+ some trace elements)
- Star formation and stellar evolution different because of lack of metals.
Current Observations: The Low-Metallicity Universe in Perspective

Extragalactic GCs (metal-rich pop.)
Milky Way GCs (metal-rich pop.)
LMC clusters (metal-rich pop.)
Blue compact galaxies
SMC clusters
Damped Lyman-alpha systems
Lyman-alpha systems
Milky Way GCs (metal-poor pop.)
Milky Way halo field stars
Extragalactic GCs (metal-poor pop.)
LMC clusters (metal-poor pop.)

Halo EMP stars: Living Relics

- No Zero metallicity stars discovered yet.

Thesis, Campbell 2007
Metal-poor stars can be studied in great detail because they are so close. They can provide constraints on:

- Big Bang Nucleosynthesis (eg. $^7$Li in Halo stars)
- The nature of Population III, the First Stars
- The First Mass Function, thought to be different at Z=0 (spectrographic observations of metal-poor stars can tell us a lot about the mass distribution of Pop III)
- Ancient Supernovae Yields: MP stars may reflect the chemical signatures of early SNe, constraining those models.
- Metallicity Distribution Function (MDF) of the Galaxy: structure at low metallicity provides constraints on chemical and dynamical evolution models.

→ **Metal-poor stars are very important, they are a link to the very early Universe.**
Observations of individual stars:
Normal MP Stars vs Carbon-Enhanced MP Stars (CEMPs)

CEMPs → 10 to 20% of EMPs!
Where did all the C come from?

1) Massive stars? \((M > 10 \, M_{\odot})\)

- It is generally agreed that primordial supernovae provided the scaled-solar abundances we see in the majority of EMP star. They pre-enriched the gas from which the stars formed (eg. Joggerst et al 2010).

- To match the high abundances of C, N, O in the CEMP stars more 'exotic' explosions are needed – eg. Hypernovae \((M \sim 300 \, M_{\odot})\) eg. Norris et al. 2002) or 'mixing & fallback' SN models (Umeda & Nomoto 2003).

- These scenarios may be realistic since the composition of the most metal-poor stars may have come from individual SNe/HNe.

- Furthermore it may be that these particular CNO-rich donors were selected for, since the CNO-rich gas would have been more efficient at star formation due to the extra coolants (Bromm & Larson 2004, Aoki et al 2006). This theory is given weight by the fact that all of the stars with \([\text{Fe/H}] < -4.0\) are CEMP stars!
Primordial Supernovae Yields
(Best fit, including rotational mixing - Joggerst et al., 2010)

Normal EMP star

CEMP star

Most metal-poor CEMP star
Where did all the C come from?

2) Low-mass stars? ($M < 10 \, M_{\text{sun}}$)

- Although massive stars must have given rise to the chemical patterns in the majority of EMPs, it is possible that low-mass stars gave rise to the excesses in light elements (and s-process elements) seen in the CEMP.
- Since many of the CEMP are unevolved they could not have polluted themselves.
- However binary companions of higher initial masses may have polluted the EMPs, turning them into CEMP.
- The candidates for this pollution are AGB stars, or stars that have undergone Proton Ingestion Episodes (PIEs).
- These companion stars would now be white dwarves.
- If this is the case then it has implications for primordial star formation, giving a clue to the EMP IMF.
Monash Low-mass EMP Stellar Evolution Study

- To investigate the low-mass possibility we calculated a grid of stellar models:
  - **Structural evolution** from MS to end of TP-AGB
  - **Nucleosynthetic evolution with limited network**: up to Sulphur 35 only.
  - **Yields** for the 74 included species (integrated over mass loss history)

**Stellar structure code:** MONSTAR (Monash/Mt Stromlo code)
  - * Standard 1D stellar code
  - + Time-dependent mixing (diffusive)
  - * Can evolve through the Core Helium Flash
  - * No overshoot used (→ Schwarzschild boundary)

**Nucleosynthesis code:** MONSN (‘monsoon’, Monash code)
  - * Post-process code, 500+ reactions (the small network)
  - * Initial abundances taken as a mix of BBN + 25 Msun Pop III supernova yield

The metallicity and mass range of the grid is:

\[
[\text{Fe/H}] = -\infty, -6.5, -5.45, -4.0, -3.0
\]

\[
M = 0.85, 1.0, 2.0, 3.0 \, M_\odot \quad \rightarrow \text{20 Stars}
\]
Results → Model Yields Vs Observations: 

\[ \frac{[C]}{Fe} \]

Campbell & Lattanzio 2008

→ Low-mass EMP stars can supply C!
PART II
Core Helium Flashes in EMP Stars: one possible source for the enrichment of CEMP\(s\)
EMP Peculiar Evolution: The 'Dual Core Flash'

- A proton ingestion episode (PIE) occurs during the normal core He flash of low-mass stars (RGB tip).

- Proton ingestion only occurs in low mass, extremely metal-poor models.

- The result is a double/dual flash (Dual Core Flash, DCF).

![Diagram showing log (L/L_\text{sun}) vs. log (T_{\text{eff}}) with annotations indicating Dual Core Flash (DCF) and conditions M < 1.3 M_\text{sun} and [Fe/H] < -5.]
Dual Core Flash: Details

- 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 are mixed upwards also.
  - This material is later dredged up into the envelope, polluting the surface.
  - Fujimoto et al. (1990) suggested that the excess C in the CEMP s may come from these peculiar surface pollution events.
The network we used for the models did not include s-process nuclides, but we did track the abundance of free neutrons.

We found that the neutron abundance was getting very high during the initial phases of the DCF proton ingestion – a neutron “superburst” was occurring.

The neutrons were being produced by $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reactions.

Maria Lugaro was very excited by this so we made a study into the possible s-processing!
Investigation into the 'Neutron Superburst'

• We used a new extended nucleosynthesis network of 320 nuclear species from H to Bi and 2,336 nuclear reactions with rates from the Joint Institute for Nuclear Astrophysics (JINA) database.

• The post-processing code activates nuclear reactions in the star on the basis of the information on the temperature, density, and convective velocity provided by our original stellar structure model (Campbell & Lattanzio 2008).

• Nuclear burning and convective mixing are both included in the equations of the abundance changes and are thus solved simultaneously.

• The code has been sped up by a factor of a few, but the runs to the end of the neutron superburst still take weeks to months, depending on the spatial resolution.
$3\alpha \rightarrow ^{12}\text{C}(p,\gamma)^{13}\text{N}(\beta^+ + \nu)^{13}\text{C}(\alpha,n)^{16}\text{O} \rightarrow ^{56}\text{Fe} + n$

Poison: $^{13}\text{C}(p,\gamma)^{14}\text{N}(n,p)^{14}\text{C}$

Campbell, Lugaro & Karakas 2010
Resulting abundances as function of time
(sampled at the location of the maximum of the neutron density)

- Strong s-processing!

- Abundances of Ba, Pb reach *absolute* Solar abundances!!

- \([\text{Pb/Fe}] \sim +6\) after dredge-up to surface

- s-process continues until \(^{14}\text{N}\) becomes more abundant than \(^{13}\text{C}\) and soaks up most of the free neutrons.

- \(n\) exposure \(\sim 250\) mbarn\(^{-1}\)

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Campbell, Lugaro & Karakas 2010
PART III: Comparing With Observations
Binary system → Dilution

- HE 1327-2326 is a subgiant, so it cannot have polluted itself (e.g. through a DCF or 3rd dredge-up).
- Its composition could have arisen from binary system mass-transfer via wind accretion or Roche-lobe overflow from a star such as that modelled here, which would now be a white dwarf.
- Subsequent dilution of the accreted material in the envelope of HE 1327-2326 via convection or thermohaline mixing would be expected (Stancliffe & Glebbeek 2008).
- In order to match the [C/Fe] abundance in HE 1327-2326 we applied a dilution factor of 0.003 to the model yield.
- The amount of mass that a binary companion of mass 0.8 Msun would need to accrete from our hypothetical primary star to match the observed C abundance is \( \sim 2.4 \times 10^{-4} \) Msun.
- Using this value in Equation 12 from Suda et al. 2004 gives an expected orbital period of 769 yr. This corresponds to a separation \( \sim 10^4 \) Rsun → a wide binary system.
- This very long period is consistent with the current non-detection of radial velocity variations in HE 1327-2326.
Comparing with HE 1327-2326, the most metal-poor star known, $[\text{Fe/H}] = -5.96$

Dilution factor = 0.003
$[\text{Fe/H}] = -5.70$

Not a perfect fit, but we got this without playing with parameters!
Discussion

→ The differences between the model predictions and the observations of HE 1327-2326 may be within the **model uncertainties**.

→ The total neutron exposure depends on the details of the dual core flash since the rate of expansion of the HeCZ and the **treatment of mixing affects the ingestion of protons**.

![Figure 9 of Joggerst et al (2010)](image)

Lithium is another mismatch since the dual core flash lowers the surface Li abundance by only a factor of two and the diluted composition is basically the same as the initial composition while HE 1327-2326 is heavily depleted in Li. This problem probably needs to be addressed in terms of mixing processes on the secondary star HE 1327-2326. (Note that supernovae produce lots of Li via the neutrino process.)
Conclusions

- The EMP dual core flash + binary system scenario has the **potential to self-consistently reproduce most of the strange overabundances in hyper-metal-poor star HE 1327-2326.** In this case binary systems of roughly solar-mass stars should have formed from hyper-metal-poor gas.
- We need to carefully investigate the neutron superburst: we have models ready to be post-processed for 0.8 and 1 Msun and [Fe/H]=0, -6.5, -5.45.
- We need to evaluate the model uncertainties as the dual core flash is notoriously difficult to simulate.
- The effects of convective overshoot, extra mixing, and rotationally-induced mixing should also be investigated.
- The dual core flash would be **best studied in the framework of multidimensional fluid-dynamic models.**
- We have made a start on this but with inconclusive results... John Lattanzio's new PhD student Stuart Heap will be working on this! :)
- And Richard Stancliffe is working on 3D hydro simulations of a similar event in EMP AGB stars.
2D & 3D Hydrodynamics simulations of a Dual Core Flash
Mocak et al. 2010:

Fig. 17. Temporal evolution of the radial distribution of the (color coded) logarithm of the angular averaged kinetic energy density (in erg g$^{-1}$) of models hellpopIII.2d.1 (left) and hellpopIII.3d (right), respectively. The horizontal dotted lines mark the boundaries of the double convection zone one part being sustained by the helium burning (CVZ-1) and the other one by the CNO cycle (CVZ-2).