Near-Field Cosmology and Chemical Signatures of the First Stars

Timothy C. Beers
NOAO / MSU
The stars with lowest abundances of heavy elements ([Fe/H]) were born from almost pristine gas, at redshifts $z \sim 10$ or higher.

- Corresponds to $\sim 200-300$ Myr after Big Bang.

Surveys over the past 25 years have identified:

- 30000 stars with $[\text{Fe/H}] < -2.0$
- 1000 stars with $[\text{Fe/H}] < -3.0$
- 10 stars with $[\text{Fe/H}] < -4.0$
- 3 stars with $[\text{Fe/H}] < -5.0$

High-resolution spectroscopic determinations of elemental abundances for these stars SHOULD reflect the nucleosynthetic products of early (even FIRST) generation stars.

THIS is Near-Field Cosmology.
What are the Expected Nucleosynthetic Products of First Generation Stars?

- Theory has provided possibilities, but how to choose?
- Let nature direct us to the answer!

- There are an increasing number of stars known, at the lowest [Fe/H], which present a distinctive pattern of elevated abundances for light elements:
  - C, N, O, Na, Mg, Si, Al
  - But NO s-process or r-process enhancements
  - The CEMP-no stars
The Discovery of CEMP Stars

- HK Survey (Beers, Preston, & Shectman 1992)
  - Note that original selection criteria was **Carbon blind**
  - Only based on **perceived weakness** of Ca II H and K lines on objective prism spectra
Exploration of Nature’s Laboratory for Neutron-Capture Processes

<table>
<thead>
<tr>
<th>Neutron-capture-rich stars</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>r-I</td>
<td>0.3 ( \leq [\text{Eu/Fe}] \leq +1.0 ) and ([\text{Ba/Eu}] &lt; 0)</td>
</tr>
<tr>
<td>r-II</td>
<td>([\text{Eu/Fe}] &gt; +1.0) and ([\text{Ba/Eu}] &lt; 0)</td>
</tr>
<tr>
<td>s</td>
<td>([\text{Ba/Fe}] &gt; +1.0) and ([\text{Ba/Eu}] &gt; +0.5)</td>
</tr>
<tr>
<td>r/s</td>
<td>0.0 ( &lt; [\text{Ba/Eu}] &lt; +0.5)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Carbon-enhanced metal-poor stars</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMP</td>
<td>([\text{C/Fe}] &gt; +1.0)</td>
</tr>
<tr>
<td>CEMP-r</td>
<td>([\text{C/Fe}] &gt; +1.0) and ([\text{Eu/Fe}] &gt; +1.0)</td>
</tr>
<tr>
<td>CEMP-s</td>
<td>([\text{C/Fe}] &gt; +1.0), ([\text{Ba/Fe}] &gt; +1.0), and ([\text{Ba/Eu}] &gt; +0.5)</td>
</tr>
<tr>
<td>CEMP-r/s</td>
<td>([\text{C/Fe}] &gt; +1.0) and 0.0 ( &lt; [\text{Ba/Eu}] &lt; +0.5)</td>
</tr>
<tr>
<td>CEMP-no</td>
<td>([\text{C/Fe}] &gt; +1.0) and ([\text{Ba/Fe}] &lt; 0)</td>
</tr>
</tbody>
</table>
CEMP-no Stars are Associated with UNIQUE Light-Element Abundance Patterns (Aoki et al. 2002)

CS 29498-043:  $[\text{Fe/H}] = -3.8; \ [\text{C/Fe}] = +1.9$

A Harbinger of Things to Come!
Last but Definitely Least... (Christlieb et al. 2002; Frebel et al. 2005)

HE 0107-5240  \([\text{Fe/H}] = -5.3 \text{ [C/Fe]} = +3.9\)

It is the **SAME** pattern among the light elements!
Frequencies of CEMP Stars Based on Stellar Populations

- Carbon-Enhanced Metal-Poor (CEMP) stars have been recognized to be an important stellar component of the halo system.

- CEMP stars frequencies are:
  - 20% for $[\text{Fe/H}] < -2.5$
  - 30% for $[\text{Fe/H}] < -3.0$
  - 40% for $[\text{Fe/H}] < -3.5$
  - 75% for $[\text{Fe/H}] < -4.0$

- But Why? - Atmospheric/Progenitor or Population Driven?

- Carollo et al. (2012) suggest the latter
The UMP/HMP Stars are (Almost) ALL CEMP-no Stars

- Aoki et al. (2007) demonstrated that the CEMP-no stars occur preferentially at lower [Fe/H] than the CEMP-s stars.

- About **80%** of CEMP stars are CEMP-s or CEMP-r/s, **20%** are CEMP-no.

- Global abundance patterns of CEMP-no stars incompatible with AGB models at low [Fe/H].
Connections with the Inner/Outer Halo Dichotomy of the Milky Way

- D. Carollo et al. (2007) - Demonstrating existence of inner/outer halo populations, based on 32,360 unique calibration stars from SDSS/SEGUE

- D. Carollo et al. (2010) - Determination of velocity ellipsoids for thick disk, MWTD, inner, outer halos and fractions of various components in local sample (d < 4 kpc)

- D. Carollo et al. (2012) - Description of CEMP frequencies
  - Increasing frequency with declining metallicity
  - Increasing frequency with distance from Galactic plane
  - $f(\text{CEMP})_{\text{OH}} \sim 2 \times f(\text{CEMP})_{\text{IH}}$
The distribution of CEMP stars indicates that there is likely to be more than one source of C production at low metallicity, and that the difference can be associated with assignment to inner/outer halo.

We speculate that the majority of CEMP stars associated with the inner halo will be CEMP-s, while those associated with the outer halo will be CEMP-no.
Connections with high-z DLA Systems
A carbon-enhanced metal-poor damped Lyα system: probing gas from Population III nucleosynthesis?

Ryan Cooke,¹† Max Pettini,¹ Charles C. Steidel,² Gwen C. Rudie² and Regina A. Jorgenson¹

¹Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
²California Institute of Technology, MS 249-17, Pasadena, CA 91125, USA

Accepted 2010 November 1. Received 2010 November 1; in original form 2010 July 29

ABSTRACT
We present high-resolution observations of an extremely metal-poor damped Lyα system (DLA), at \( z_{\text{abs}} = 2.340\, 0972 \) in the spectrum of the QSO J0035−0918, exhibiting an abundance pattern consistent with model predictions for the supernova yields of Population III stars. Specifically, this DLA has \([\text{Fe/H}] \simeq -3\), shows a clear ‘odd–even’ effect, and is C-rich with \([\text{C/Fe}] = +1.53\), a factor of \( \sim 20 \) greater than reported in any other DLA. In analogy to the carbon-enhanced metal-poor stars in the Galactic halo (with \([\text{C/Fe}] > +1.0\)), this is the first known case of a carbon-enhanced DLA. We determine an upper limit to the mass of \(^{12}\text{C}\), \( M(^{12}\text{C}) \leq 200\, \text{M}_\odot \), which depends on the unknown gas density \( n(\text{H}) \); if \( n(\text{H}) > 1\, \text{cm}^{-3} \) (which is quite likely for this DLA given its low velocity dispersion), then \( M(^{12}\text{C}) \leq 2\, \text{M}_\odot \), consistent with pollution by only a few prior supernovae. We speculate that DLAs such as the one discovered here may represent the ‘missing link’ between the yields of Population III stars and their later incorporation in the class of carbon-enhanced metal-poor stars which show no enhancement of neutron-capture elements (CEMP-no stars).
The Song Remains the Same

Figure 7. Comparison of element abundances in the $z_{\text{abs}} = 2.340\,0972$ DLA (filled black boxes) and in Galactic halo stars with an Fe abundance within a factor of 2 of the DLA (open magenta boxes). The numbers below the element labels indicate the number of stars that contributed to the determination of the ‘typical’ stellar abundances, and the heights of the magenta boxes reflect the dispersion of each set of measurements. Top panel: comparison with all CEMP stars that have $-3.34 \leq [\text{Fe/H}] \leq -2.74$. Middle panel: comparison with CEMP-no stars that have $-3.34 \leq [\text{Fe/H}] \leq -2.74$. For this case, the oxygen abundance of a single CEMP-no star is shown by the open circle. Lower panel: comparing the DLA abundance pattern with the stellar abundance patterns of HE0143–0441 (red symbols; a CEMP-s star with $[\text{Fe/H}] = -2.21$, $[\text{Ba/Fe}] = +0.62$ from Cohen et al. 2004) and BD+44°493 (green symbols; a CEMP-no star with $[\text{Fe/H}] = -3.73$, $[\text{Ba/Fe}] = -0.55$ from Ito et al. 2009). Note that in this last panel, we have plotted $[\text{X/Fe}]$ as opposed to $[\text{X/Fe}]$. In all panels the dashed line represents the solar abundance.
Spinstars (CRUMPS) — Massive, rapidly rotating, [Fe/H] < -6.0, produce prodigious CNO, and blow strong mass-losing wind (Meynet et al. 2010)

Faint Supernovae — 25-50 Mo Type Ib SNe with Mixing and Fallback (Nomoto et al. 2008; Kobayashi et al. 2011)
Bottom Line

- CEMP stars in the Galaxy likely have had multiple sources of carbon production
  - CEMP-s in AGB stars
  - CEMP-no in CRUMPS and/or faint SNe

- CEMP-no stars occur preferentially at the lowest metallicities, including 3 of 4 stars known with [Fe/H] < -4.5

- CEMP stars are found in great number in the ultra-faint SDSS dwarf galaxies (likely building blocks of outer halo), some of which have low n-capture abundances

- High-z CE-DLa systems exhibit similar abundance patterns as CEMP-no stars

- We have observed (!) the nucleosynthesis products of first generation stars (Pop III)
Current and Near-Future Surveys at Medium and High Spectral Resolution

- **SDSS/APOGEE** — Collecting high-res near-IR spectra for 100,000 disk/bulge/halo stars

- **AEGIS** — Collecting medium-res AAT optical spectra for 100,000 disk/halo stars (targeting from SkyMapper)

- **LAMOST** — Collecting medium-res optical spectra for 10,000,000 disk/halo stars (20 X SDSS/SEGUE)

- **Gaia-ESO** — Collecting high-res optical VLT spectra of several hundred thousand disk/halo stars for Gaia calibration

- **GALAH** — Will collect high-res optical AAT spectra of one million disk/halo stars
The Gaia Mission - Geometric Distances, RVs, and Proper Motions for ONE BILLION stars

- Gaia is an ambitious mission to chart a three-dimensional map of our Galaxy, the Milky Way.
- Gaia will provide unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars in our Galaxy and throughout the Local Group.
- This amounts to about 1 per cent of the Galactic stellar population.

Consider the impact on nuclear astrophysics - Precise luminosities for all classes of stars known, rather than roughly 20% accuracies known today for most stars today.