Discovery of the Chemical Signature of First-Generation Massive Stars

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Expected Signatures

- First-generation objects of high mass presumably formed from metal-free gas
  - Lived short lives (Myrs not Gyrs)
  - Exploded
  - Distributed (pre or post explosion) their nucleosynthetic products

- Next-generation objects formed from the gas polluted by first-generation objects
  - A wider range of masses allowed, perhaps including stars with main-sequence lifetimes > a Hubble time
  - Further star formation (Pop II) contributed additional material, and diluted the signatures of first/next-generation stars

- We should look for a characteristic set of abundance signatures ONLY found among the lowest metallicity stars
Expected Signatures

- Among the lowest metallicity stars, there are two basic “families”
  - Stars with enhanced abundances of carbon (CEMP stars), and other light elements (including the lowest \([\text{Fe/H}]\) star yet discovered), and lack of over-abundances of neutron-capture elements (CEMP-no stars)
  - Associated with production by “faint SNe” - progenitors with mass on the order of 10-100 \(\text{Mo}\) undergoing mixing and fallback, or rapidly rotating mega metal-poor (MMP; \([\text{Fe/H}] < -6.0\)) stars, both of which eject large amount of CNO, but little heavy metals. Low-mass stars formed with the help of C, O cooling
  
- Stars with “normal” carbon and light-element abundances, apparently formed with cooling other than C, O - perhaps by silicates?
  
- Possibly associated with production by first-generation objects of high mass (100-1000 \(\text{Mo}\)), which produce large amounts of heavy metals, but little carbon
Carbon-Enhanced Metal-Poor (CEMP) stars have been recognized to be an important stellar component of the halo system.

CEMP star frequencies are:
- 20% for $[\text{Fe/H}] < -2.5$
- 30% for $[\text{Fe/H}] < -3.0$ EMP
- 40% for $[\text{Fe/H}] < -3.5$
- 75% for $[\text{Fe/H}] < -4.0$ UMP
- 100% for $[\text{Fe/H}] < -5.0$ HMP

But Why? - Atmospheric/Progenitor or Population Driven?

Carollo et al. (2012) suggest the latter.
Thousands of CEMP Stars Identified by SDSS/SEGUE

TABLE 4
CUMULATIVE FREQUENCIES OF CEMP STARS FOR THREE DIFFERENT CARBON ABUNDANCE CRITERIA

<table>
<thead>
<tr>
<th>[Fe/H]</th>
<th>([\text{C/Fe}] \geq +0.5)</th>
<th>([\text{C/Fe}] \geq +0.7)</th>
<th>([\text{C/Fe}] \geq +1.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(N_{C})</td>
<td>(F_{C})</td>
<td>(N_{C})</td>
</tr>
<tr>
<td>+0.0</td>
<td>11622</td>
<td>0.05±0.01</td>
<td>5001</td>
</tr>
<tr>
<td>−0.5</td>
<td>11548</td>
<td>0.06±0.01</td>
<td>4996</td>
</tr>
<tr>
<td>−1.0</td>
<td>10792</td>
<td>0.11±0.01</td>
<td>4861</td>
</tr>
<tr>
<td>−1.5</td>
<td>8386</td>
<td>0.16±0.01</td>
<td>3914</td>
</tr>
<tr>
<td>−2.0</td>
<td>3799</td>
<td>0.25±0.01</td>
<td>2029</td>
</tr>
<tr>
<td>−2.5</td>
<td>775</td>
<td>0.30±0.01</td>
<td>549</td>
</tr>
<tr>
<td>−3.0</td>
<td>106</td>
<td>0.34±0.03</td>
<td>89</td>
</tr>
<tr>
<td>−3.5</td>
<td>21</td>
<td>0.57±0.12</td>
<td>16</td>
</tr>
</tbody>
</table>

Lee et al. (2013) - CEMP stars from SDSS/SEGUE + Literature Sample
Cumulative Frequencies of CEMP Stars

![Graph showing cumulative frequencies of CEMP stars. The x-axis represents [Fe/H] and the y-axis represents N([C/Fe] ≥ 0.7)/N(≤ [Fe/H]). The graph includes data points and error bars for SDSS/SEGUE+LS and SDSS/SEGUE.]
Differential Frequencies of CEMP Stars
### Exploration of Nature’s Laboratory for Neutron-Capture Processes

<table>
<thead>
<tr>
<th>Neutron-capture-rich stars</th>
</tr>
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<tbody>
<tr>
<td>r-I</td>
</tr>
<tr>
<td>r-II</td>
</tr>
<tr>
<td>s</td>
</tr>
<tr>
<td>r/s</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Carbon-enhanced metal-poor stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMP</td>
</tr>
<tr>
<td>CEMP-r</td>
</tr>
<tr>
<td>CEMP-s</td>
</tr>
<tr>
<td>CEMP-r/s</td>
</tr>
<tr>
<td>CEMP-no</td>
</tr>
</tbody>
</table>

Beers & Christlieb ARAA (2005)
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]
Carbon Enhancement Associated with s-process Patterns (Aoki et al. 2002)

LP 625-44: \([\text{Fe/H}] = -2.7; \ [\text{C/Fe}] = +2.0\)

LP 625-44 was the first s-process-rich MP star with Pb measured
Carbon Enhancement Associated with \( r \)-process Patterns (CS 22892-052; McWilliam et al. 1995; Sneden et al. 2000)

CS 22892-052: \([\text{Fe/H}] = -3.1; [\text{C/Fe}] = +1.0\)

CS 22892-052 was the first highly \( r \)-process-rich MP star discovered
CEMP-no Stars are Associated with UNIQUE Light-Element Abundance Patterns (Aoki et al. 2002)

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

Harbingers of Things to Come!
Last but Definitely NOT Least... (Christlieb et al. 2002; Frebel et al. 2005)

HE 0107-5240  [Fe/H] = -5.3  [C/Fe] = +3.9

It is the SAME pattern among the light elements!
Ito et al. (2009) report on discovery that BD+44 is an [Fe/H] = −3.8, CEMP-no star; more detailed observations by Ito et al. (2013)

Light-element abundance patterns similar to those for other CEMP-no stars

Previous RV monitoring by Carney et al. indicate no variation at levels > 0.5 km/s over past 25 years

The same is true for other CEMP-no stars with available RV monitoring (Hansen et al. 2013, and in prep; Norris et al. 2013)
Something You Don’t Often See

An Object of COSMOLOGICAL Significance with Diffraction Spikes
Abundance Pattern Compared to 25 $M_\odot$ Mixing/Fallback Model

Ito et al. (2013) : Note the low N, compared with some other CEMP-no stars with enhanced N
Bottom Line (previously...)

- CEMP stars in the Galaxy likely have had **multiple sources** of carbon production
  - CEMP-s in AGB stars
  - CEMP-no in massive (50-100 $M_\odot$) rapidly rotating MMP stars
  - CEMP-no in intermediate high-mass (25-50 $M_\odot$) “faint” SNe

- CEMP-no stars occur preferentially **at the lowest metallicities**, including the 6 of the 8 stars known with $[\text{Fe/H}] < -4.0$

- CEMP stars are found in **substantial numbers** in the ultra-faint SDSS dwarf galaxies, some of which have low n-capture abundances

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

- We have observed (!) the nucleosynthesis products of first generation stars (Pop III) -- **At least SOME** of them!
As If Right on Cue ...

- Nature - March, 2014!

A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36-670839.3


- Announcement of the discovery of a star with metallicity [Fe/H] < -7.1 -- more than 10,000,000 times lower than the Sun

- And of course, it is a CEMP-no star, with the same light element abundance pattern, and detectable (but very low) Li
A Comparison of the spectrum of SMSS J0313 with other UMP ([Fe/H] < -4) and HMP ([Fe/H] < -5) stars demonstrating lack of detectable Fe lines. Keller et al., Nature (2014)
A comparison of the spectrum of SMSS J0313 with other UMP ([Fe/H] < -4) and HMP ([Fe/H] < -5) stars in the regions of CaII K. Note extremely high relative velocity to interstellar line.
Observed Elemental Abundance Pattern for SMSS J031300.36-670839.3 ([Fe/H] < -7.1)

Note singular detections of C, Mg, and Ca - Everything else is an upper limit!  (Keller et al. 2014)
Evidence for Something Missing

- The SDSS ultra-faint dwarf spheroidal galaxies have been shown to possess large numbers of CEMP-no stars, similar in nature to those found in the (outer) halo of the MW. Perhaps pointing to their origin in such structures.

- Not all stars with [Fe/H] < -2.5 are carbon-enhanced, in particular for the abundance range -3.5 < [Fe/H] < -2.5.
  - Including at least one star, with [Fe/H] ~ -5.0, and a number with [Fe/H] ~ -4.0, without the detection of the chemical signature of CEMP-no stars.

- It has been argued (e.g., Ji et al. 2014) that Si dust cooling may be responsible for the formation of low-mass, C-normal stars.
  - But where did the Si come from?
SEGUE-1: An Unevolved Fossil Galaxy from the Early Universe (Frebel et al. 2014)

SDSS CMD for stars in SEGUE-1. Remarkably, three of the giants have $[\text{Fe/H}] < -3.5$, and all three of them are CEMP-no stars. It seems likely that disrupted UF dSph galaxies could account for the CEMP-no stars found in the outer halo of the MW.
Two Populations with $[\text{Fe/H}] < -3.0$ (Norris et al. 2013)

Note that the CEMP-no stars (red) generally exhibit enhanced light elements, while the C-normal stars (black) do not.

Suggestive of cooling (and fragmentation channels other than fine-structure cooling from C and O)
Cooling from Si-Based Dust (Ji et al. 2014)

Distribution of measured $[\text{Si}/\text{H}]$ for a sample of EMP stars. Symbols above the green line indicate stars for which Si dust cooling is sufficient to cause fragmentation.

Black squares are CEMP-no stars, and could have cooled from C & O.
ONE HUNDRED FIRST STARS: PROTOSTELLAR EVOLUTION AND THE FINAL MASSES

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ABSTRACT

We perform a large set of radiation hydrodynamic simulations of primordial star formation in a fully cosmological context. Our statistical sample of 100 First Stars shows that the first generation of stars has a wide mass distribution $M_{\text{popIII}} = 10 \sim 1000 \, M_\odot$. We first run cosmological simulations to generate a set of primordial star-forming gas clouds. We then follow protostar formation in each gas cloud and the subsequent protostellar evolution until the gas mass accretion onto the protostar is halted by stellar radiative feedback. The accretion rates differ significantly among the primordial gas clouds that largely determine the final stellar masses. For low accretion rates, the growth of a protostar is self-regulated by radiative feedback effects, and the final mass is limited to several tens of solar masses. At high accretion rates the protostar’s outer envelope continues to expand, and the effective surface temperature remains low; such protostars do not exert strong radiative feedback and can grow in excess of 100 solar masses. The obtained wide mass range suggests that the first stars play a variety of roles in the early universe, by triggering both core-collapse supernovae and pair-instability supernovae as well as by leaving stellar mass black holes. We find certain correlations between the final stellar mass and the physical properties of the star-forming cloud. These correlations can be used to estimate the mass of the first star from the properties of the parent cloud or of the host halo without following the detailed protostellar evolution.
Projected gas density distribution at $z \sim 25$ for five primordial star-forming clouds in a cube of 15 kpc on a side.

Circles show a zoom of the central 1 pc regions at the star-formation epoch.
Final predicted distribution of calculated stellar masses for 110 First Stars

Hirano et al. (2014)
Aoki et al. (Science, in press)

A Chemical Signature of First-Generation Super-Massive Stars

W. Aoki, N. Tominaga, T. C. Beers, S. Honda, Y. S. Lee

Abstract: Numerical simulations of structure formation in the early Universe predict the formation of some fraction of stars with masses several hundred times the solar mass. No clear evidence of supernovae from such super-massive stars has, however, yet been found in the chemical compositions of Milky Way stars. Here we report on an analysis of a very metal-poor star, SDSS J001820.5−093939.2, which possesses elemental-abundance ratios that differ significantly from any previously known star. This star exhibits low [$\alpha$-element/Fe] ratios and large contrasts between the abundances of odd and even element pairs, such as Sc/Ti and Co/Ni. Such features have been predicted by model calculations of the nucleosynthesis associated with a pair-instability supernova of a 130-260 solar-mass star, or a core-collapse supernova of an even more massive star. The result suggests that the mass distribution of first-generation stars might extend to 100 solar masses or larger, possibly up to 1000 solar masses.
SDSS J0018-0939 is a cool (Teff ~ 4600) main-sequence star with [Fe/H] = -2.5, NOT carbon-enhanced, and with elemental-abundance ratios unlike any previously studied very low-metallicity star.

Abundance ratios between adjacent odd- and even-element pairs are very low: [Na/Mg] = -0.56, [Sc/Ti] < -0.99, [Co/Ni] = -0.77.

In addition, the n-capture elements are quite low compared to other VMP stars: [Sr/Fe] < -1.8, [Ba/Fe] < -1.3.

Frequency (~ 1/500) similar to frequency of high-mass progenitors predicted by Karlsson et al. (2008)
● SDSS J0018-0939 ▲ comparison star (G39-36)
(standard) Core collapse supernova model
- SDSS J0018-0939
  - PISN model
  - Core-collapse very-massive star model
Alternative Supernova Models (compare RED)

- Core-collapse SN, $M = 25$ Mo
  - High energy (black) / low $C$, $\alpha$
  - Low energy (purple) / low Co

- Core-collapse SN, $M = 25$ Mo (black); Type Ia SN + core-collapse SN (purple)
  - Timescale problems!

- PISN, $M = 130$ Mo (black)

- Very-massive star, $M = 1000$ Mo (purple)
The Path Forward

- Expansion of numbers of identified CEMP stars, in particular with \([\text{Fe}/\text{H}] < -2.5\), which include both CEMP-s and CEMP-no stars, both from HK/HES and the ~ 5-10 million medium-res spectra coming from LAMOST

- High-resolution follow-up spectroscopy of a core sample of 100-200 CEMP stars, in order to assign classifications based on heavy elements, and to determine CNO, alpha elements, and other light element abundances

- Radial velocity monitoring of CEMP stars, in order to determine binary nature, as well as characterize correlations between chemical patterns and nature of the detected binary

- Establishment of the frequency of such objects as SDSS J0018-0939, based on high-resolution spectroscopic surveys of the many thousands of stars known with \([\text{Fe}/\text{H}] < -2.5\)

- Refinement of model-based SN abundance patterns for PISN and super-massive stars

- Full numerical GCE models, taking into account the effects of local mixing, in order to match frequencies of CEMP stars and C-normal stars, as well as Li-depletion phenomenon for very metal-poor stars