The first stars

Martin Asplund

2013: MA to EM.“Wouldn’t it be good to have a winter meeting on the Galactic bulge in Sexten?”


Thank you Francesca and Carlo!!!
Cosmic timeline

Big Bang

Cosmic microwave background

First stars and galaxies

Present-day Universe
The first stars

- Probing Big Bang with lithium
- Epoch of Reionization
- Produced first metals in the Universe
- Neutron capture elements and cosmochronology
- CNO: fingerprints of Pop. III stars
- SFR, IMF and mixing in the early Universe
- Galactic archaeology: (dual?) halo vs GC vs dSph
- Any surviving first stars to present-day?
- Where are the oldest stars?
- Nature of the first stars
Formation of the first stars

The very first stars formed at \( z \sim 20 \) (\( t \sim 200 \text{Myr} \)) in mini-halos of \( 10^6-7 \) Msun (Tegmark et al. 1997)
IMF of the first stars

The first stars were typically much more massive than stars today: ~100 M\(_\odot\) (Bromm et al. 2002)

Any survivors?
Low-mass first stars?

Clark et al. 2011:
Disk fragmentation and ejection: $M \sim 1M_{\odot}$

Greif et al. 2011
Where are the first stars?

**Galactic halo**
(HK, HES, SEGUE, SkyMapper etc)

**Dwarf galaxies**
(Gilmore et al. Helmi et al. Frebel et al. etc)
Oldest ≠ Lowest $[\text{Fe/H}]$ ≠ Most metal–poor
Oldest vs most metal-poor

White & Springel 1999
z\sim 20: 
First stars form in largest overdensities that become centers of galaxies

z<10: 
Star–formation in little $[\text{Fe/H}]$–enriched environments (halo, dSph)

No age–$[\text{Fe/H}]$ relation!
Oldest stars in the bulge

Salvadori et al. 2010:

Metal-poor bulge stars with [Fe/H]< -1

"They are in the bulge but not of the bulge" (Tumlinson 2010)

The most metal-poor stars are concentrated towards bulge
Ness et al. 2013,
Garcia Perez et al. 2013:
Only 0.1% of bulge stars with $R_G < 3.5\text{kpc}$ have $[\text{Fe/H}] < -2.0$
The needles in the haystack

Problem: bulge is mostly metal-rich + crowded

Solution: pre-select metal-poor stars from colour
In Nordic mythology, **Embla** was the first woman, born in the middle of the world from the left-overs of giants.
Bulge EMP team

PI=Martin Asplund

Stefan Keller

Louise Howes
(PhD project)

Andy Casey

Alan Alves Brito, Karin Lind, Anna Marino, David Nataf, Melissa Ness, David Yong et al.
First bulge EMP survey

SkyMapper

AAT

VLT+Magellan

Stars @ 2dF

Confirmation

~10,000 stars

High-res (R>40k)

Chemistry

~100 stars

See Louise Howes’ talk!
SkyMapper halo EMP survey

SkyMapper

Photometry Candidates
\(\sim 10^7\) stars

ANU 2.3m

Med-res (R=3k)
Single-object Confirmation
\(\sim 1,000\) stars

VLT+Magellan

High-res (R>40k)
Chemistry
\(\sim 100\) stars
SkyMapper halo EMP team

Stefan Keller

Anna Frebel

Yong

Marino

Jacobson

Lind

Casey

Bessell

Norris

Da Costa

Schmidt

Asplund
SkyMapper

- Located at Siding Spring Observatory
- 1.35m telescope
- $5.7 \, \square^2$ field-of-view
- 256 Mega-pixels
- Automated, remote
- Southern Sky Survey (multi-colour & -epoch)
  - PI: Brian Schmidt
  - Keller et al. 2007

Observations started, teething problems now finally solved

© James Gilbert
SkyMapper camera

- 32 E2V 2k x 4k CCDs
- 5.7 \( \text{\textdegree}^2 \) field-of-view
- 0.5”/pixel
- <seeing> = 1.5”
Sky coverage

Shallow survey starting early 2014 (~1yr)
Targeted, shallower observations already obtained
EMP searches: bulge + halo
SkyMapper filters

Optimized for stellar astrophysics and Galactic archaeology

[Fe/H] sensitive!
Spectroscopic signs of old age

“look-back time”

Chemical evolution

Frebel & Norris 2011
Metallicity sensitivity

Bulge field \((l, b = 0, -10)\)

Ness et al. (2012): med-res spectroscopy (AAOmega)
**Halo: WiFES/ANU 2.3m spectra**

Stellar parameters from flux distribution of medium-resolution spectra: \(T_{\text{eff}}, \log g, [\text{Fe/H}], E(B-V)\)
**EMP survey yields**

SkyMapper halo EMP survey is the most efficient search ever undertaken:  
~1/4 of stars have \([\text{Fe/H}] < -3\)

<table>
<thead>
<tr>
<th>Survey</th>
<th>(N_{MRS})</th>
<th>(N &lt; -2.0)</th>
<th>(N &lt; -2.5)</th>
<th>(N &lt; -3.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HK</td>
<td>2614</td>
<td>11%</td>
<td>4%</td>
<td>1%</td>
</tr>
<tr>
<td>HK colour selection</td>
<td>2140</td>
<td>32%</td>
<td>11%</td>
<td>3%</td>
</tr>
<tr>
<td>HES (turnoff stars)</td>
<td>571</td>
<td>59%</td>
<td>21%</td>
<td>6%</td>
</tr>
<tr>
<td>HES (giants)</td>
<td>643</td>
<td>50%</td>
<td>20%</td>
<td>6%</td>
</tr>
<tr>
<td>SM-EMP</td>
<td>527</td>
<td>69%</td>
<td>33%</td>
<td>18%</td>
</tr>
<tr>
<td>SM-EMP ((m &lt; 0))</td>
<td>260</td>
<td>77%</td>
<td>59%</td>
<td>26%</td>
</tr>
</tbody>
</table>
Magellan high-res follow-up


71 stars observed with Magellan/MIKE (R~30k, S/N~50)

36 new stars with [Fe/H]<−3

Standard 1D LTE abundance analysis
Normal halo abundances

Jacobson et al. 2014 vs Yong et al. 2013
High-res vs medium-res

Keller et al. 2014b
Keller et al., 2014, Nature, in press:
First star without detected iron lines!
[Fe/H] < -7.1
(>50x lower than previous record-holder)
World’s worst title

1\textsuperscript{st} suggestion: \textit{Discovery of a primordial star}
2\textsuperscript{nd}: \textit{Chemistry of a primordial star}
3\textsuperscript{rd}: \textit{A blast from the past}
4\textsuperscript{th}: \textit{Black hole Sun}
5\textsuperscript{th}: \textit{The first star born from the ashes of a primordial supernova}

... 
58\textsuperscript{th}: \textit{Nuclear ashes from a first star explosion}

Final title (thanks a lot Nature editor...):

\textit{A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36-670839.3}
[Fe/H] upper limit

Co-adding the strongest expected Fe I lines

LTE: [Fe/H] < -7.3
Non-LTE: [Fe/H] < -7.1 (Lind et al. 2012)
Pop III fingerprints

Product of a single, low-energy Pop III supernova with extensive fall-back into black hole

![Graph showing element abundance and atomic number with markers for Pair-instability 200Msun SN and Low-energy 60Msun SN.]
Keller et al. 2014a:

\[
\begin{align*}
[\text{Fe/H}] &< -7.1 \\
[\text{Ca/H}] &=-7.0 \\
[\text{Mg/H}] &=-3.8 \\
[\text{C/H}] &= -2.6
\end{align*}
\]

Remarkable \([\text{Fe/H}]\)-poor but not so metal-poor
Critical metallicity for SF

Keller et al. 2014

Caffau et al. 2011

Forbidden zone

Frebel & Norris 2011

1D LTE abundances
Our halo+bulge surveys will be the most efficient surveys for oldest and extremely metal-poor stars where most such stars should reside today.