Unveiling the chemical origin of stars through nucleosynthetic and observational studies

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February 2016
Outline

- *Cool stars are the only astrophysical objects in which we can conduct a detailed and precise abundance study of up to $\sim 70$ elements*
- Stellar parameters, abundances, and assumptions
- Tracing astrophysical formation sites using stellar abundances
- Comparing to AGB & (EC)SN yields
- CEMP stars
- How many processes are needed in the early Universe?
Very Large Telescope (VLT) - 8-m mirror
Stellar spectra and equivalent width (W)
Abundance - $W - \log gf$ relation; the impact of stellar parameters and atomic data

\[
\log W = \log(\text{const}) + \log(A) + \log(gf\lambda) - \theta\chi - \log(\kappa) \quad (1)
\]

Since the UV-region of the spectra is crowded we have to carry out spectral synthesis on line lists with accurate atomic data.
Two ways of deriving abundances:

- Equivalent width and synthetic spectra
- We need to know the stellar parameters: Temperature, gravity, metallicity and velocity (small scale)
- Model atmosphere (e.g. MARCS) and synthetic spectrum code (e.g. MOOG)
- Assumptions: 1D, LTE – one local temperature, black body radiation (Planck), Maxwellian velocity distribution, Boltzmann and Saha describe excitation and ionisation
- Line lists with atomic and molecular information (excitation potential and log gf)
Temperature, gravity and metallicity

- The color of a star depends on two factors: Temperature and metallicity

- Color (V-K) calibration \( T = a + b(V - K) + c(V - K)^2 + d(V - K)[Fe/H] + \ldots \)

- Excitation potential - based on Fe lines (NLTE sensitive)

- Parallax/distance \((\pi)\) e.g., Nissen et al. 1997:
  \[ \log \frac{g}{g_{Sun}} = \log \frac{M}{M_{Sun}} + 4 \frac{T}{T_{Sun}} + 0.4V_o + 2\log(\pi) + corrections \]

- Ionisation equilibrium from Fe lines (NLTE sensitive)

- Metallicity \([Fe/H]\) from equivalent widths of Fe lines
A comparison of two cluster (47Tuc) stars to AGB yields

Figure: Comparing two seemingly similar stars to each other and AGB yields from FRUITY; Cordero (CJH) et al. 2015, Cristallo et al. 2011
Stellar spectra, abundances, and $[\text{Fe/H}]$

$$[\text{Fe/H}] \equiv \log(N_{\text{Fe}}/N_{\text{H}})^{*} - \log(N_{\text{Fe}}/N_{\text{H}})^{\odot}$$ (2)

**Figure:** Top: Solar ($[\text{Fe/H}] = 0$) spectrum – Mg triplet. Bottom: Star with $[\text{Fe/H}] \sim -5$. Christlieb +2004
Figure: Observational abundance biases (Hansen et al, 2014b)
Observable elements - with high-resolution instruments

Periodic Table of the Elements

Figure: Blue: ground based observations, green: space, yellow: isotopic abundances

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Record holding star
- CS31082-001
Abundances
of almost 70 elements,
37 of which are heavy elements.
Siqueira Mello et al. 2013
• $\alpha$-elements serve as tracers of SN Mass (Kobayashi et al. 2006)
• The $\alpha$/odd-$Z$ elements provide information on, e.g., the explosion energy
• The amounts of Sc, Ti and Zn can be linked to $Y_e$
• In-/complete Si-burning elements may provide clues on the $T_{peak}$

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A peculiar high-velocity RR Lyrae star →
$V_{\text{los}} \sim -400\text{km/s}$ – A bulge or halo star? Kicked from a SN Ia or stripped from an accreted dwarf galaxy?

Figure: CJH et al. 2016b, subm. to A&A: [Mg/Fe] and velocity of the old but [Fe/H]=-0.9 RR Lyrae star.
Another record holding early Universe star:
Keller et al. 2014: $[\text{Fe/H}] < -7.1$ - origin SN II of $M \sim 60 M_\odot$
Bessel et al. 2015 (3D, NLTE) $\rightarrow [\text{Fe/H}] < -7.5$ & $40 M_\odot$ SN
Assumptions: LTE vs NLTE - the impact on stellar parameters

Figure: C.J. Hansen et al. 2013
Assumptions: LTE vs NLTE - Strontium

Figure: C.J.Hansen et al. 2013
Chemical evolution of Sr C.J.Hansen et al. 2013
1) Yields from faint EC SN II (Wanajo et al. 2011 - B. Mueller’s talk)
2) Yields from $\nu$–driven winds (Arcones & Montes 2011)
3) Yields from massive fast rotating stars (Frischknecht et al. 2012)
The uncertain yields can cover a large range of stellar abundances. Despite uncertainties we can still make quantitative predictions such as:

- Faint EC SN are well constrained due to the selfconsistent 2D models and match the observations fairly well (despite slight overpredictions).
- \(\nu\)-driven winds are promising but need to be better constrained.
- Massive stars may facilitate an early s-process which creates small amounts of Sr.
Scatter and multiple formation processes

- Weak s-process: $Z \sim < 40$ (or 42)
- Main s-process - broad atomic range - typically Ba ($Z = 56$) and heavier
- Weak r-process: $40 < Z < 50$
- Main r-process - possibly full range - or $Z > 50$ (C.J.Hansen et al. 2014b)
r-poor vs r-rich stars: HD122563 & CS31082-001

Selected elements

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.
Galactic chemical evolution of Mo and Ag

\[ [\text{Fe/H}] \equiv \log\left(\frac{N_{\text{Fe}}}{N_{\text{H}}}\right)_* - \log\left(\frac{N_{\text{Fe}}}{N_{\text{H}}}\right)_{\odot} \]  

\[ (3) \]

**Figure:** C.J. Hansen et al. 2014a, 2012, Comparison samples: Roederer et al. 2014, Peterson 2013, Johnson & Bolte 2002, Crawford et al. 1998

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Correlation - Anticorrelation
If two elements are created by the same process, they most likely grow in the same way (correlate).
Elements (38 < Z < 50) are generally found to anti-correlate with Z > 56 elements (Burris et al, 2000, Montes et al, 2007, Francois et al 2007)
Weak/main s/r-process elements - Sr (85% s), Ba (81% s) and Eu (94% r) Arlandini et al. 1999; C.J.Hansen et al. 2012
Ru not main s or main r (C.J.Hansen et al. 2014a)
Two r-processes
Ru, Pd, and Ag are formed by the weak r-process

• The main r-process creates the heaviest elements ($Z > 56$) in a very robust way
• The ’weak’ r-process creates the intermediately heavy ($37 < Z < 50$) - range uncertain
• Possible formation sites are neutron star (NS) mergers (main r), and ECSN, $\nu$-driven winds (weak r)
Carbon Enhanced Metal-Poor stars (CEMP stars) – why care?
Between 40% and 100% of EMP stars are CEMP stars!
The ∼ 10 most metal-poor stars known
Keller et al. 2014, T.T.Hansen (CJH) et al. 2015
and C-normal: Caffau et al. 2011

**TABLE 2** Definition of subclasses of metal-poor stars

<table>
<thead>
<tr>
<th>Neutron-capture-rich stars</th>
<th>Carbon-enhanced metal-poor stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>r-I</td>
<td>CEMP</td>
</tr>
<tr>
<td>0.3 ≤ [Eu/Fe] ≤ +1.0 and [Ba/Eu] &lt; 0</td>
<td>[C/Fe] &gt; +1.0</td>
</tr>
<tr>
<td>r-II</td>
<td>CEMP-r</td>
</tr>
<tr>
<td>[Eu/Fe] &gt; +1.0 and [Ba/Eu] &lt; 0</td>
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</tr>
<tr>
<td>s</td>
<td>CEMP-s</td>
</tr>
<tr>
<td>[Ba/Fe] &gt; +1.0 and [Ba/Eu] &gt; +0.5</td>
<td>[C/Fe] &gt; +1.0 and [Ba/Fe] &gt; +1.0, [Ba/Eu] &gt; +0.5</td>
</tr>
<tr>
<td>r/s</td>
<td>CEMP-r/s</td>
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<tr>
<td>0.0 &lt; [Ba/Eu] &lt; +0.5</td>
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</tr>
<tr>
<td></td>
<td>CEMP-no</td>
</tr>
<tr>
<td></td>
<td>[C/Fe] &gt; +1.0 and [Ba/Fe] &lt; 0</td>
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</tbody>
</table>
CEMP stars


- Binary fraction increasing with decreasing metallicity.
- CEMP-\(n\), CEMP-\(r\) \(\sim\) 18\% & CEMP-\(s\) - almost all \( (> 80\%\) 

Lucatello et al. 2005, Lee et al. 2013, Starkenburg et al. 2014, Abate et al. 2015a,b,
T.T.Hansen et al. 2015b,c
CEMP-no and CEMP-s stars - unmixed dwarfs

(Spite et al. 2013)

Fig. 14. Abundance of carbon $A(C)$ vs. $[\text{Fe/H}]$ in dwarfs and turnoff CEMP stars, following Sivarani et al. (2006, their Table 4), [orange open squares], Frebel et al. (2005, 2007) [blue open squares], Thompson et al. (2008) [green open circle], Aoki et al. (2009) [blue open diamonds], Behara et al. (2010) [full orange circles], Placco et al.
CEMP-no and CEMP-s stars - Extremely/Ultra metal-poor stars
(Bonifacio et al. 2015)

**Abundances**

**Assumptions**

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**2. r-process**

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**Winds**

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**Fig. 6.** The carbon abundances $A(C)$ of CEMP stars as a function of $[\text{Fe/H}]$. The stars in the present paper and in Caffau et al. (2013a) are shown with big and small circles, respectively. The other turn-off stars come from the literature (Sivarani et al. 2006; Frebel et al. 2005, 2006; Thompson et al. 2008; Aoki et al. 2008; Behara et al. 2010; Masseron et al. 2010, 2012; Yong et al. 2013; Cohen et al. 2013; Li et al. 2015). The CEMP-no
X-shooter CEMP stars
(C.J. Hansen et al. 2016)

[Diagram showing abundance plots for C, N, Sr, and Ba against [Fe/H].]
CEMP-s and -no stars - different from EMP C-normal stars
This is in agreement with the recent findings Bonifacio et al. 2015

Figure: C.J.Hansen et al. 2016
CEMP-s vs -no stars - and C-normal stars

Figure: $<[\text{Ba/Sr}]> \sim 0.5$ for $\sim 2M_\odot$ AGB stars while $<[\text{Ba/Sr}]> \sim -0.5$ matches GCE prediction from spinstars (0 to $-1.5$). C.J.Hansen et al. 2016
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GCE of CEMP and C-normal stars Predictions: Cescutti 2008, 2013

Figure: An r-process + spinstars ([Ba/Sr] ~ 0 to −1.5). C.J.Hansen et al. 2016
CEMP-r stars - fallback SN + AGB + ???
CEMP-s/r stars - i-process enriched

T.T. Hansen (CJH) et al. 2015 (Mishenina et al. 2015 – see C. Ritter’s talk)
Assumptions (C-normal stars):
There are 2 robust processes:
main r-process (H), weak r (L) as in, e.g., Qian & Wasserburg 2007.
M1: $H=\text{CS22892-052}, \ L=\text{HD122563}$
M2: $H=\text{CS22892-052}, \ H+L=\text{HD122563}$
M3: $H+L=\text{CS22892-052}, \ H+L=\text{HD122563}$
- all stars are mixed Li et al. 2013

\[ Y_{calc}(Z) = (C_H Y_H(Z) + C_L Y_L(Z)) \times 10^{[Fe/H]} \]

(C.J.Hansen et al. 2014b)
Figure: Robustness of the processes! (C.J.Hansen et al. 2014b)
Figure: Differences in Sr and Ba (C.J.Hansen et al. 2014b)
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Conclusion:

- We can use stellar abundances to constrain the nuclear synthetic formation processes, but it is important to know how the 1D, LTE assumptions affect these abundances.
- Some yield predictions are still very uncertain.
- The formation of some CEMP stars remains a puzzle.
- Outlook: 3D, NLTE corrected heavy element abundances. Better constrained yields based on self-consistent exploding SN models (3D).
- Large homogeneously analysed samples and more complete abundance patterns - not just for GCE of single elements - but the surveys can be used to find important targets for detailed blue follow-up observations.
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Thank you for listening

Finally thanks to my collaborators: A. C. Andersen, S. Andreivsky, A. Arcones, N. Christlieb, C. Fröhlich, F. Montes, H. Hartmann, M. Bergemann, B. Nordström, P. Jofre, the 4MOST team, LSW & others.

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