Stellar observations indicate two primary processes
ECT* Trento

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September 2014
Outline - From Stellar spectra to the r-process(es?)

- Stellar spectra
- Stellar abundances and uncertainties
- Observational indications of a 2nd process
- Meteorites and presolar grains
- Disentangling the primary processes

UVES/VLT high-resolution spectrograph
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UVES/VLT high-resolution spectrograph
Low vs high-resolution spectra

LAMOST (low resolution $R \sim 1800$) and ESO VLT (UVES - high resolution $R \sim 40000$)

Important: Sr may be the only heavy element for which we will be able to derive abundances in low-resolution spectra.
Visual versus near-UV spectral range

A metal-poor giant star (HD122956): Temperature/gravity/[Fe/H] = 4700K/1.5/-1.45
Stellar parameters: Dwarf vs giant stars

Left: A dwarf star (main sequence) with high gravity, high pressure system vs giant star with low gravity, low pressure. Right: Evolution of stars (HR-diagram)
Stellar spectra and equivalent width (W)
The importance of atomic data; Abundance - log gf relation

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

\[\theta = 5040 K/T\]

Since the UV-region of the spectra is crowded we have to carry out spectral synthesis on line lists with accurate atomic data.
The challenge: Deriving abundances from stars that are not enhanced in heavy elements.

Hansen et al, 2014

High-quality observations are needed in the near-UV spectral range - almost impossible with fibre-based instruments.
Stellar spectra, abundances, and [Fe/H]

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

(2)

Observable elements - with high-resolution instruments

Periodic Table of the Elements

Blue: ground based observations, green: space, yellow: isotopic abundances
Record holding star
- CS31082-001
Abundances
of almost 70 elements,
37 of which are heavy elements.

Siqueira Mello et al. 2013

Table 1. LTE abundances in CS 31082-001 as derived from previous works, from the present paper, and our adopted final abundances.

<table>
<thead>
<tr>
<th>El.</th>
<th>Z</th>
<th>A(1)(X)</th>
<th>A(2)(X)</th>
<th>A(3)(X)</th>
<th>A(X) This Work</th>
<th>A(X) adopted</th>
<th>[X:Fe] adopted</th>
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<td>Ge</td>
<td>32</td>
<td>—</td>
<td>—</td>
<td>+0.10</td>
<td>+0.10 ± 0.21</td>
<td>—</td>
<td>-0.55</td>
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<tr>
<td>Sr</td>
<td>38</td>
<td>+0.72</td>
<td>—</td>
<td></td>
<td>—</td>
<td></td>
<td>0.73</td>
</tr>
<tr>
<td>Y</td>
<td>39</td>
<td>-0.23</td>
<td>—</td>
<td>-0.15</td>
<td>-0.19 ± 0.07</td>
<td>0.53</td>
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<td>Zr</td>
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<td>+0.55</td>
<td>+0.49 ± 0.08</td>
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<tr>
<td>Nb</td>
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<td>-0.54 ± 0.12</td>
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<td>Mo</td>
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<td>—</td>
<td></td>
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<td>-0.42</td>
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<td></td>
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<tr>
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<td>—</td>
<td></td>
<td>-0.09 ± 0.07</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>47</td>
<td>-0.81</td>
<td>—</td>
<td></td>
<td>-0.84 ± 0.21</td>
<td>1.15</td>
<td></td>
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<tr>
<td>Sn</td>
<td>50</td>
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<td></td>
<td>+0.40 ± 0.14</td>
<td>1.16</td>
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<td>La</td>
<td>57</td>
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<td></td>
<td>-0.62 ± 0.05</td>
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<tr>
<td>Ce</td>
<td>58</td>
<td>-0.31</td>
<td>-0.29</td>
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<tr>
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<td></td>
<td>-0.79 ± 0.04</td>
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<tr>
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<td>60</td>
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<td></td>
<td>-0.15 ± 0.05</td>
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<td>Sm</td>
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<tr>
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<tr>
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<td>-1.01</td>
<td></td>
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<td>Er</td>
<td>68</td>
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<td>-0.30 ± 0.05</td>
<td>1.67</td>
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<tr>
<td>Tm</td>
<td>69</td>
<td>-1.24</td>
<td>-1.15</td>
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<td>-1.15 ± 0.05</td>
<td>1.64</td>
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</tr>
<tr>
<td>Yb</td>
<td>70</td>
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<td>—</td>
<td></td>
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<td>1.66</td>
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<tr>
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<td>1.73</td>
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<tr>
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<td>72</td>
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<td>-0.72 ± 0.05</td>
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<tr>
<td>Ta</td>
<td>73</td>
<td>-1.60</td>
<td>-1.60</td>
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<td>-1.60 ± 0.23</td>
<td>1.47</td>
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<tr>
<td>W</td>
<td>74</td>
<td>—</td>
<td>—</td>
<td></td>
<td>-0.90 ± 0.24</td>
<td>0.92</td>
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<tr>
<td>Re</td>
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<td>—</td>
<td>—</td>
<td></td>
<td>-0.21 ± 0.21</td>
<td>2.45</td>
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<tr>
<td>Os</td>
<td>76</td>
<td>+0.43</td>
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<td>Ir</td>
<td>77</td>
<td>+0.20</td>
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<tr>
<td>Pt</td>
<td>78</td>
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<tr>
<td>Au</td>
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<td>-0.40</td>
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<td>-0.40 ± 0.33</td>
<td>1.83</td>
<td></td>
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<td>-0.98</td>
<td>—</td>
<td></td>
<td>-0.98 ± 0.13</td>
<td>1.84</td>
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<tr>
<td>U</td>
<td>92</td>
<td>-1.92</td>
<td>—</td>
<td></td>
<td>-1.92 ± 0.17</td>
<td>1.68</td>
<td></td>
</tr>
</tbody>
</table>

References. (1) Hill et al. (2002), (2) Sneden et al. (2009), (3) Barbuy et al. (2011).
What can we learn from stellar abundances?

- HD122563 - proto LEPP star
- Large star-to-star scatter for n-capture elements (e.g. Sr and Ba)

Hansen 2011 & Cowan +2011 (below)
Abundance star-to-star scatter and the 2nd r-process

- $\alpha$ - elements show a very low scatter
- Sr shows a very large scatter

Bonifacio et al, 2009

Hansen et al, 2012
Selected elements

[Image of the Periodic Table of Elements with highlighted elements Eu and Mo.]

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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Camilla Juul Hansen
Stellar observations indicate two primary processes
Sample, Method, and Formation Process:

- Sample consists of 71 stars, 42 dwarfs and 29 giants
- Enhanced as well as ’normal’ stars ($-3.3 < \text{[Fe/H]} < -0.6$)
- UVES and HIRES (high resolution data)
- MARCS 1D atmospheres & MOOG\textsuperscript{1} synthetic spectrum code

\textsuperscript{1}Sneden 73, version 2010, Assuming LTE
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)

![Graph showing correlation and anticorrelation](image)
Weak s-process elements - Sr (85%) and Y (92%) Arlandini et al 1999

Hansen et al, 2012

![Graph 1: Sr/H vs [Sr/H]]

- Giants: $y = -0.31x - 0.98 \pm (0.1, 0.25)$
- Dwarfs: $y = -0.57x - 1.05 \pm (0.09, 0.15)$

![Graph 2: Y/H vs [Y/H]]

- Giants: $y = -0.45x - 1.8 \pm (0.09, 0.16)$
- Dwarfs: $y = -0.53x - 1.3 \pm (0.17, 0.12)$
Main s-process (Ba) and main r-process (Eu)

Ag is not formed by the main r or main s-process.
A different “LEPP/weak” process

Hansen et al, 2012

Stellar observations indicate two primary processes
Continuing with a direct correlation between two elements (A, B)
Mo – weak s or LEPP? → *Not LEPP – but Ru is*

Hansen et al., 2014

Stellar observations indicate two primary processes
Galactic chemical evolution of Mo and Ru

Hansen et al, 2014
This is why silver is interesting:

Ag, Ru, and Pd are produced by a second ’weak’ r-process/LEPP
Summary: Observational indications of a 2nd r-process

- Ag, Pd, and Ru correlate - they are produced by the same process (LEPP/weak r/...)
- Ru+Ag do not correlate with weak s-process elements; Sr & Y
- Ru+Ag do not correlate with Ba (main s-process at solar metallicity) or Eu (94% main r-process element; Arlandini et al 1999)
- Mo is less weak r/LEPP and more weak+main s (some main r and p-process)
- → Mo is a very mixed element; it has more in common with the lighter than the heavy elements.
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Presolar grains: $r$-, $s$-, and $p$-process contributions to Mo and Ru

(Dauphas +2004)

<table>
<thead>
<tr>
<th>Element/Isotope</th>
<th>92</th>
<th>94</th>
<th>95</th>
<th>96</th>
<th>97</th>
<th>98</th>
<th>100</th>
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<tr>
<td>Mo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ru</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Process</td>
<td>$p$</td>
<td>$p$</td>
<td>$s + r$</td>
<td>$s$</td>
<td>$s + r$</td>
<td>$s + r$</td>
<td>$r$</td>
</tr>
</tbody>
</table>

Presolar grains can be enriched by only one AGB star. Anomalies in abundances can therefore indicate a heterogeneous gas which in turn means that the nebula/cloud was not uniformly mixed – or general variations of $^x$Mo due to variations in the contribution from process $x$ to the gas....
s-process in grains and stars

Solid symbols are stars, open symbols SiC grains Hansen et al, 2014, Pellin et al.
Stellar observations indicate two primary processes
From this sample we eliminate stars with:

- \([\text{Fe/H}] < -2.5\) - removes most s-process contamination
- \([\text{C/Fe}] < 0.9\) - removes most CEMP stars
- \([\text{Ba/Fe}] < 1.0\) - removes CEMP-s and Ba-rich binaries
- Min. 5 abundance detections (i.e., not upper limits)
- \([\text{C/N}] < -0.4\) and \([\text{N/Fe}] > 0.5\) - removes self-enriched stars
Assumptions: There are 3 robust processes: r-process, LEPP, P-component.
M1: r=CS22892-052, LEPP=HD122563
M2: r=CS22892-052, r+LEPP = HD122563
M3:
\[ r+\text{LEPP}=\text{CS22892-052}, \ r+\text{LEPP}=\text{HD122563} \]
- all stars are mixed
Stellar observations indicate two primary processes
Stellar observations indicate two primary processes
Robustness of the r-process!

Camilla Juul Hansen
Stellar observations indicate two primary processes

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Conclusion

- A second process is needed to explain Ag, Ru & Pd
- This second “LEPP” is different from the s-processes and the main r-process
- Mo is produced by all processes - p,s, and r - this is detectable
- Mo and Ru are important heavy elements as they can trace various formation processes and thereby provide information on the formation of stars, meteorites, and Earth.
- Two processes seem sufficient to explain the stellar abundances and their scatter within the uncertainty (0.32dex) - may be too large = could hide other contributions
- Room for improvement:
  → 3D self-consistent SN models,
  → optimized yield predictions,
  → 3D+NLTE abundance corrections for heavy elements and
  → mixing processes in the ISM.
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 (\(\pi\)):
  \[ \log \frac{g}{g_{Sun}} = \log \frac{M}{M_{Sun}} + 4\frac{T}{T_{Sun}} + 0.4V_o + 2\log(\pi) + \text{corrections} \]
- Ionisation equilibrium from Fe lines (NLTE sensitive)
- Metallicity ([Fe/H]) from equivalent widths of Fe lines