Observational Indications of Two Primary Processes Producing Elements from Sr to Eu

INT workshop

Camilla Juul Hansen

Heidelberg University, ZAH

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ARI ITA LSW

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

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

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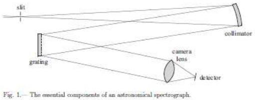
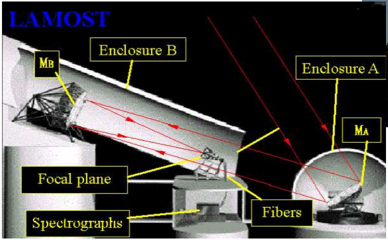
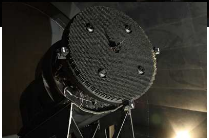
Very Large Telescope (VLT) - 8-m mirror



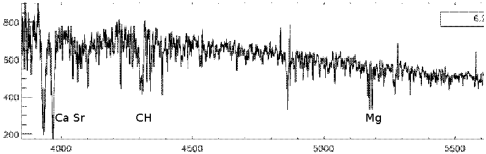
Simple sketch of a spectrograph – Massey et al.

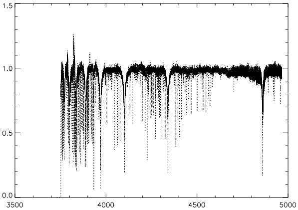
Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) — 4-m mirror, 4000 fibres $\rightarrow 10000$ stars/night or $2 \cdot 10^6$ stars/year





LAMOST vs UVES spectra

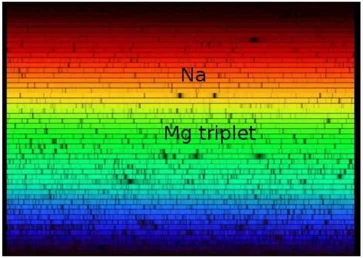


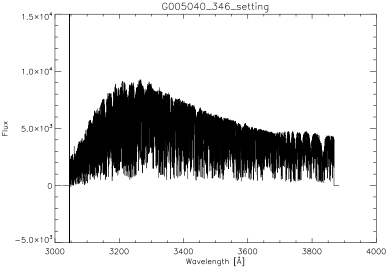


LAMOST (low resolution $R \sim 1800$) and ESO VLT (UVES - high resolution $R \sim 40000$)

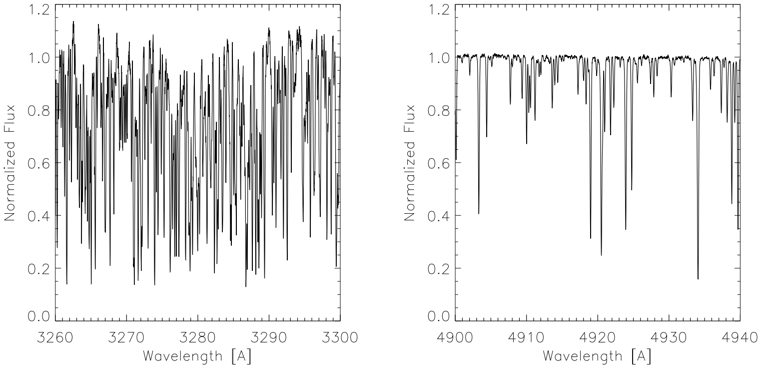
Important: Sr may be the only heavy element for which we will be able to derive abundances in low-resolution spectra.

Stellar spectra – 2D to 1D



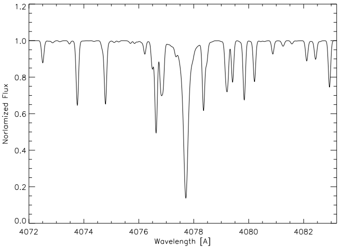


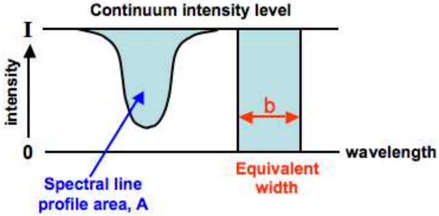
Visual versus near-UV spectral range



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

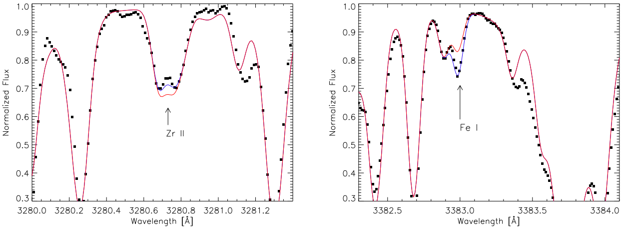
Stellar spectra and equivalent width (W)





The importance of atomic data; Abundance - log gf relation

$$\log \mathrm{W} = \log(const) + \log(A) + \log(gf\lambda) - \theta\chi - \log(\kappa) \qquad (1)$$

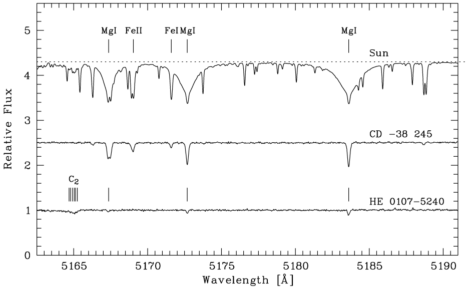


Hansen et al, 2012

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

Stellar spectra, abundances, and [Fe/H]

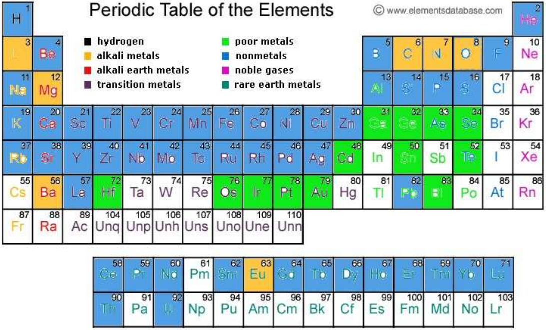
$$[\mathrm{Fe/H}] \equiv \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{*} - \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\odot} \tag{2}$$



Top: Solar ([Fe/H] = 0) spectrum – Mg triplet. Bottom: Star with [Fe/H] ∼ -5. Christlieb +2004

Some of the most metal-poor stars!
See the next talk by Terese Hansen

Observable elements - with high-resolution instruments



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

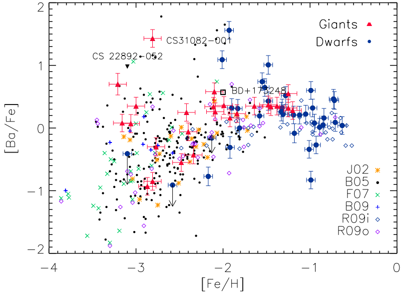
Table 1. LTE abundances in CS 31082-001 as derived from previous works, from the present paper, and our adopted final abundances.

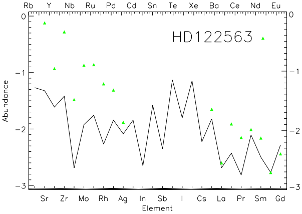
El.	Z	A(X) (1)	A(X) (2)	A(X) (3)	A(X) This Work	A(X) adopted	[X/Fe] adopted
Ge	32	—	—	—	+0.10	+0.10±0.21	-0.55
Sr	38	+0.72	—	—	—	+0.72±0.10	0.73
Y	39	-0.23	—	—	-0.15	-0.19±0.07	0.53
Zr	40	+0.43	—	—	+0.55	+0.49±0.08	0.84
Nb	41	-0.55	—	—	-0.52	-0.54±0.12	0.97
Mo	42	—	—	—	-0.11	-0.11±0.13	0.90
Ru	44	+0.36	—	—	+0.36	+0.36±0.12	1.45
Rh	45	-0.42	—	—	-0.42	-0.42±0.12	1.39
Pd	46	-0.05	—	—	-0.09	-0.09±0.07	1.18
Ag	47	-0.81	—	—	-0.84	-0.84±0.21	1.15
Ba	56	+0.40	—	—	—	+0.40±0.14	1.16
La	57	-0.60	-0.62	—	—	-0.62±0.05	1.17
Ce	58	-0.31	-0.29	—	-0.31	-0.29±0.05	1.03
Pr	59	-0.86	-0.79	—	—	-0.79±0.05	1.38
Nd	60	-0.13	-0.15	—	-0.21	-0.15±0.05	1.33
Sm	62	-0.51	-0.42	—	-0.42	-0.42±0.05	1.51
Eu	63	-0.76	-0.72	—	-0.75	-0.72±0.05	1.69
Gd	64	-0.27	-0.21	—	-0.29	-0.21±0.05	1.61
Tb	65	-1.26	-1.01	—	-1.00	-1.01±0.05	1.64
Dy	66	-0.21	-0.07	—	-0.12	-0.07±0.05	1.73
Ho	67	—	-0.80	—	—	-0.80±0.06	1.62
Er	68	-0.27	-0.30	—	-0.31	-0.30±0.05	1.67
Tm	69	-1.24	-1.15	—	-1.18	-1.15±0.05	1.64
Yb	70	—	-0.41	—	—	-0.41±0.11	1.66
Lu	71	—	—	—	-1.08	-1.08±0.13	1.73
Hf	72	-0.59	-0.72	—	-0.73	-0.72±0.05	1.33
Ta	73	—	—	—	-1.60	-1.60±0.23	1.47
W	74	—	—	—	-0.90	-0.90±0.24	0.92
Re	75	—	—	—	-0.21	-0.21±0.21	2.45
Os	76	+0.43	—	+0.18	—	+0.18±0.07	1.72
Ir	77	+0.20	—	+0.20	—	+0.20±0.07	1.72
Pt	78	—	—	+0.30	—	+0.30±0.23	1.46
Au	79	—	—	-1.00	—	-1.00±0.34	0.89
Pb	82	—	—	-0.65	—	-0.65±0.19	0.25
Bi	83	—	—	-0.40	—	-0.40±0.33	1.83
Th	90	-0.98	—	—	—	-0.98±0.13	1.84
U	92	-1.92	—	—	—	-1.92±0.17	1.68

References. (1) Hill et al. (2002), (2) Sneden et al. (2009), (3) Barbuy et al. (2011).

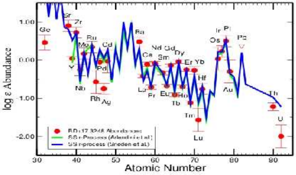
What can we learn from stellar abundances?

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





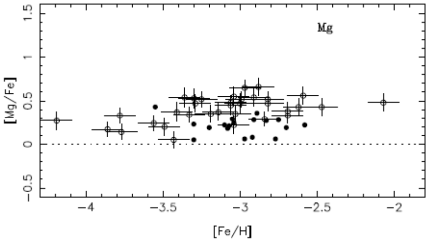
Hansen 2011 & Cowan +2011 (below)

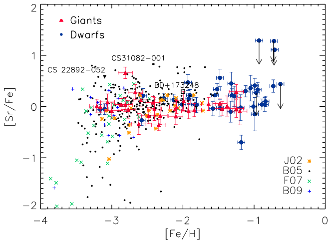


Abundance star-to-star scatter and the 2nd r-process

- α - elements
  show a very low scatter
- Sr shows a very large scatter

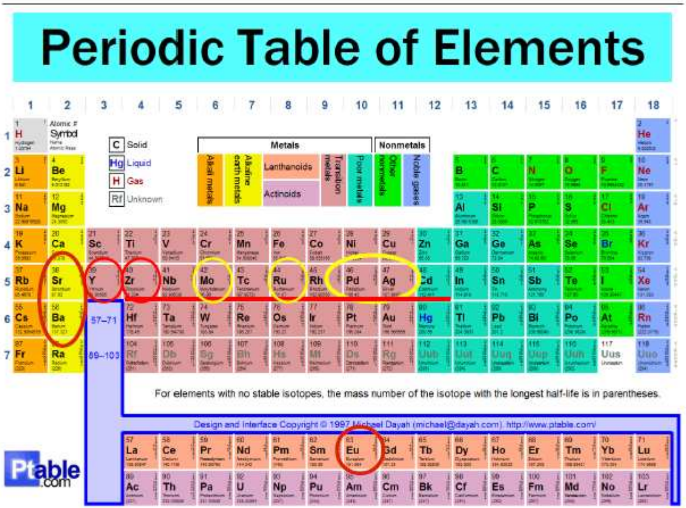
Bonifacio et al, 2009





Hansen et al, 2012

Selected elements



Sample, Method, and Formation Process:

- Sample consists of 71 stars, 42 dwarfs and 29 giants
- Enhanced as well as 'normal' stars ($-3.3 <$[Fe/H]< -0.6)
- UVES and HIRES (high resolution data)
- MARCS 1D atmospheres & MOOG[1] synthetic spectrum code
- Element and formation process:
- Sr 85% s-process (weak s-process/α-rich/p-rich)
- Y 92% s-process (weak s)
- Zr 83% s-process (less weak s)
- Mo 50% s-process (the remaining 50% is from r+p-process)
- Ru 30% s-process (70% weak r-process?)
- Pd 46% s-process (54% r-process - some 'weak' r?)
- Ag 79% r-process ('weak' r?)
- Ba 81% main s-process (AGB stars)
- Eu 94% main r (Arlandini +1999)

[1] Sneden 73, version 2010, Assuming LTE

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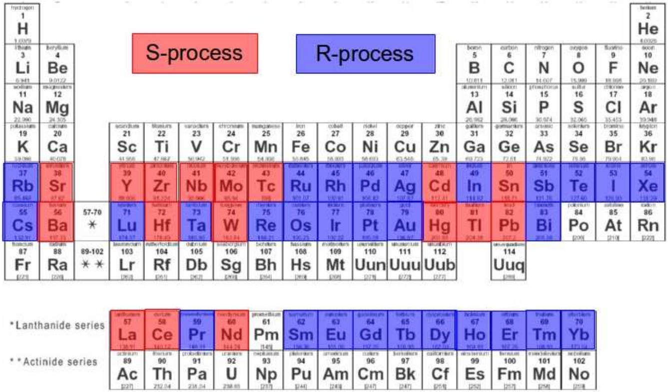
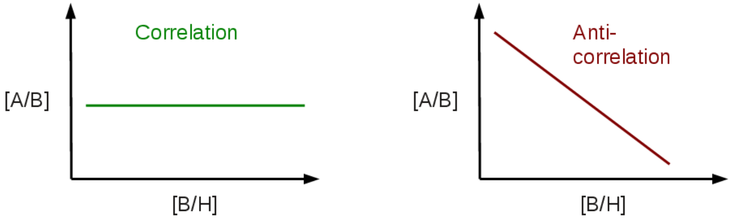
r- and s-process elements (Arlandini+1999)



Correlation - Anticorrelation

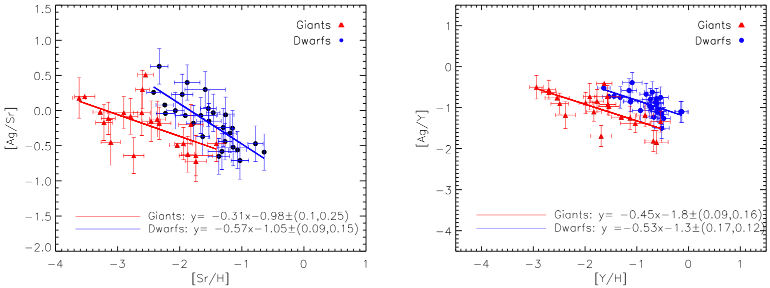
If two elements are created by the same process, they most likely grow in the same way (correlate).

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)

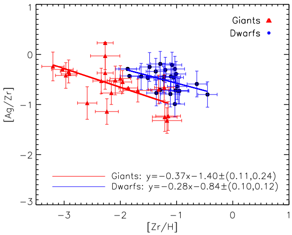


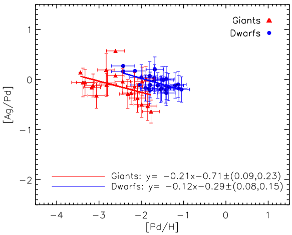
Weak s-process elements - Sr (85%) and Y (92%) Arlandini et al 1999

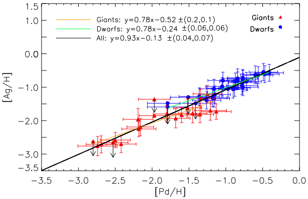
Hansen et al, 2012



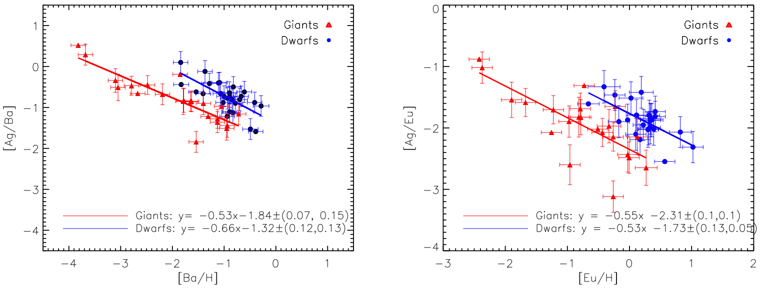
Weak s-process and weak r-process/LEPP elements







Main s-process and main r-process elements - Ba (81%) and Eu (94%)



Hansen et al, 2012

This is why silver is interesting:

Ag (and Pd) is produced by a second 'weak' r-process/LEPP

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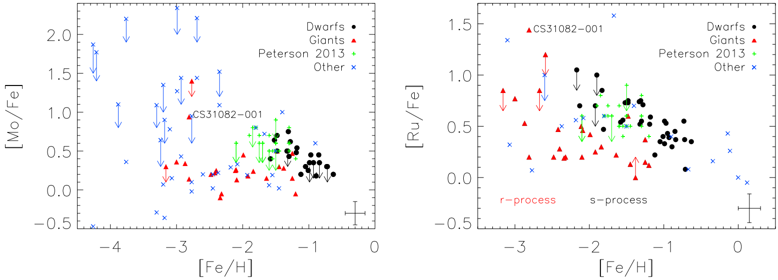
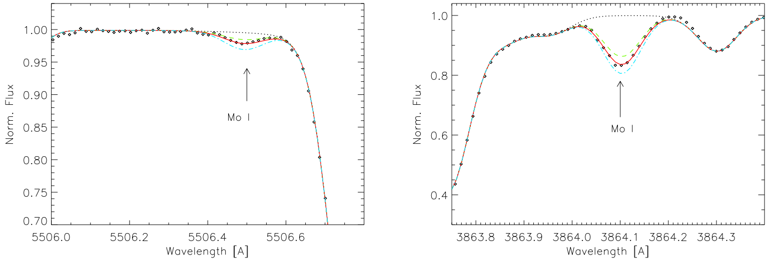
Mo and Ru may also be created by this 'LEPP' process



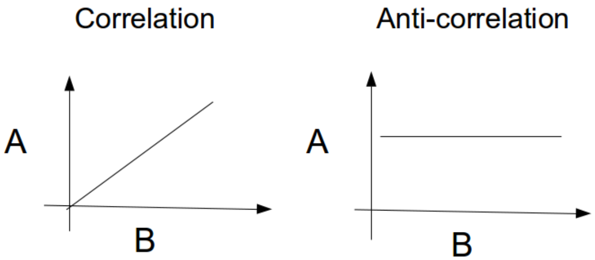
Hansen et al, 2014

The challenge: Deriving abundances from stars that are not enhanced in heavy elements.

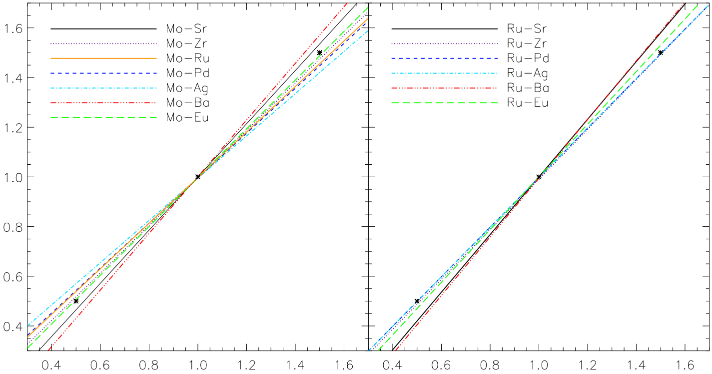


High-quality observations are needed in the near-UV spectral range - almost impossible with fibre-based instruments.

What can we learn about Mo and Ru?
A more direct approach to test if two elements (A, B) correlate

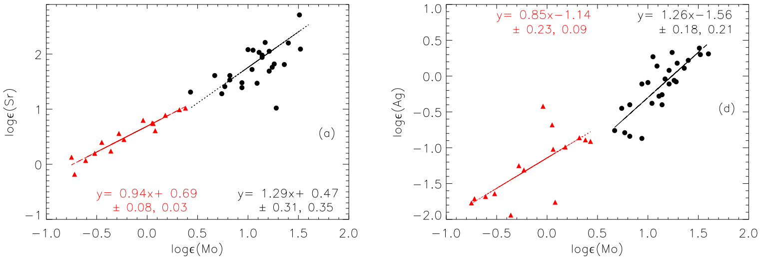


What can we learn about Mo and Ru?
Fitting the entire sample = 1 process creates it all..?



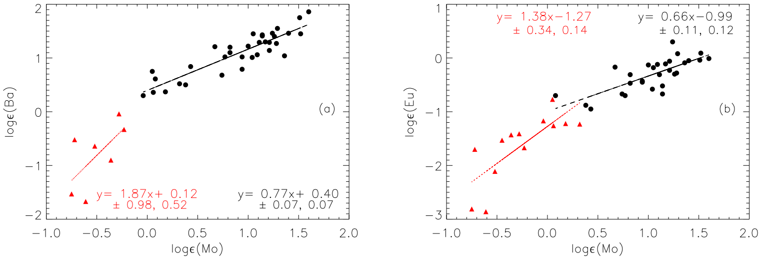
Large uncertainties and scatter found between Sr-Mo and Ag-Mo.
Can this be improved by fitting two processes/contributions?

Mo – weak s or LEPP? → *Not LEPP*

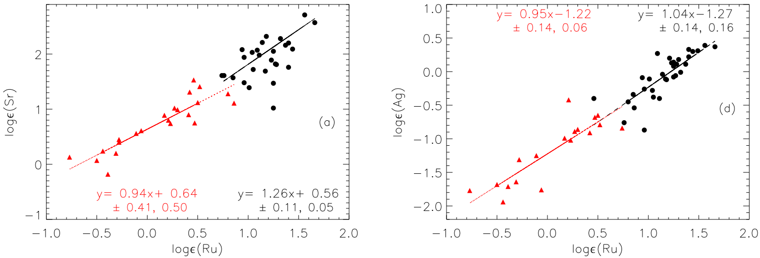


Hansen et al, 2014

Mo – main s or r?

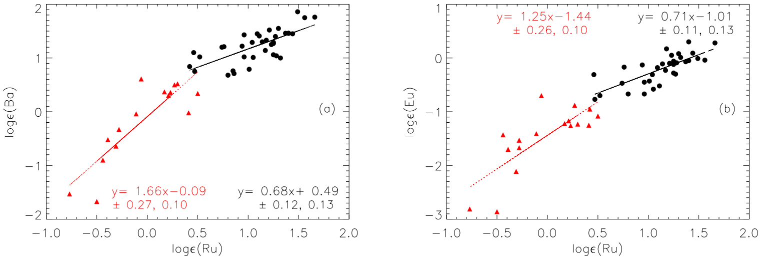

y= 1.87x+ 0.12
± 0.98, 0.52
y= 0.77x+ 0.40
± 0.07, 0.07
(a)
logϵ(Ba)
logϵ(Mo)
y= 1.38x−1.27
± 0.34, 0.14
y= 0.66x−0.99
± 0.11, 0.12
(b)
logϵ(Eu)
logϵ(Mo)

Ru – weak s or LEPP? → LEPP!

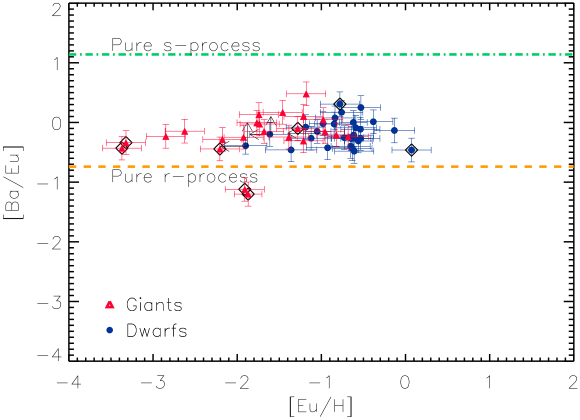


Hansen et al, 2014

Ru – main s or r?

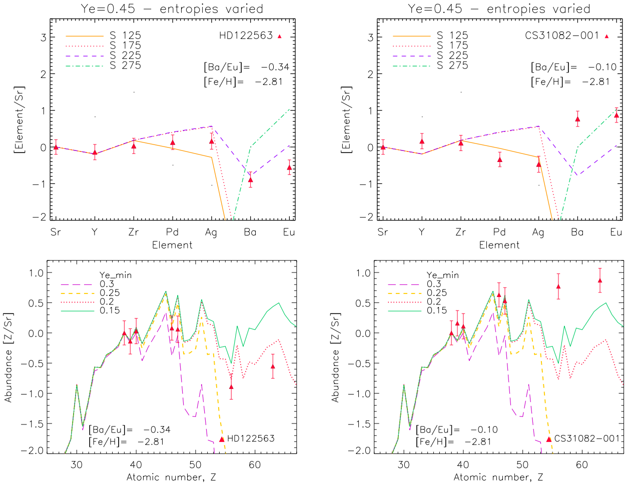

y= 1.66x−0.09
± 0.27, 0.10
y= 0.68x+ 0.49
± 0.12, 0.13
(a)
logϵ(Ba)
logϵ(Ru)
y= 1.25x−1.44
± 0.26, 0.10
y= 0.71x−1.01
± 0.11, 0.13
(b)
logϵ(Eu)
logϵ(Ru)

Pure r-process yields (Hansen et al, 2012)



r-poor vs r-rich stars: HD122563 & CS31082-001

(Honda et al,2006, Hill et al, 2002 & Hansen et al, 2012)



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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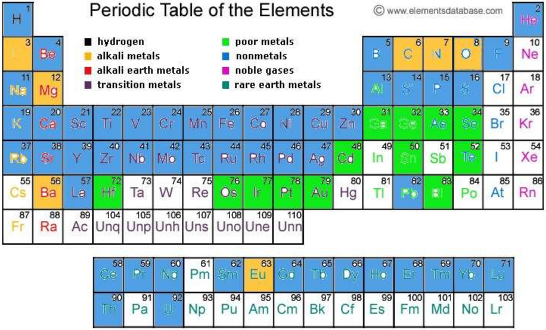
- Ag, Pd, and Ru correlate - they are produced by the same process (LEPP/weak r/...)
- Ru+Ag do not correlate with weak s-process elements; Sr & Y
- Ru+Ag do not correlate with Ba (main s-process at solar metallicity) or Eu (94% main r-process element; Arlandini et al 1999)
- Mo is less weak r/LEPP and 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.

Isotopic abundances needed → presolar grains from meteorites?



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

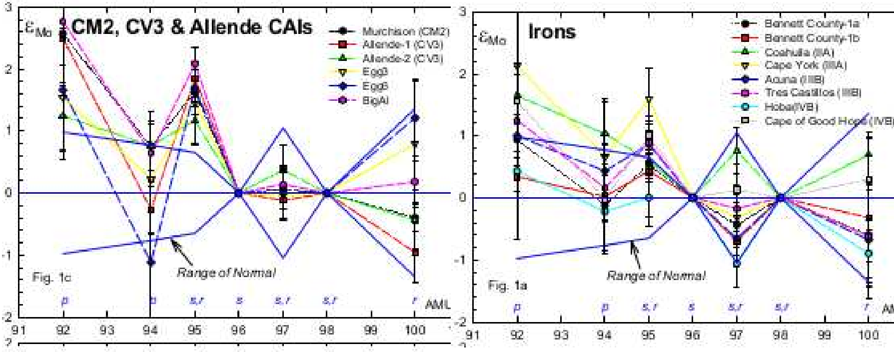
Presolar grains: r-,s-, and p-process contributions to Mo and Ru

(Dauphas +2004)

Element/Isotope							
Mo	92	94	95	96	97	98	100
Ru	96	98	99	100	101	102	104
Process	p	p	s + r	s	s + r	s + r	r

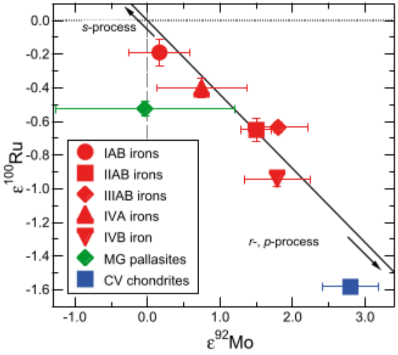
Presolar grains can be enriched by only one AGB star.
Anomalies in abundances can therefore indicate a heterogeneous gas which in turn means that the nebula/cloud was not uniformly mixed – or general variations of ^{x}Mo due to variations in the contribution from process x to the gas....

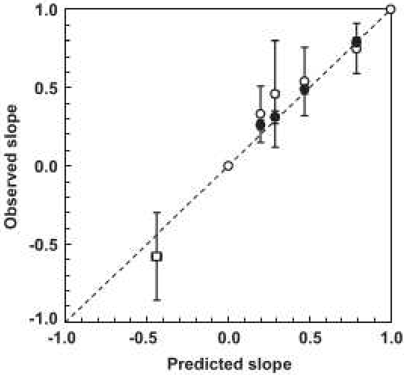
Anomalies - improved method!



Chen et al, 2004

The slope of these correlations match s-process predicted slopes (for bulk meteorites). Dauphas et al, 2004





Dauphas et al therefore believe that the reason for anomalies is variations in the s-process (but cannot fully exclude r- and p-process decoupling).

Earth

- The Mo-Ru (cosmic) correlation reflects a mixing line between pure s and Solar composition. All meteorites follow this correlation.
- The Earth also follows this cosmic correlation - this is quite interesting because:
- Ru is highly siderophile and therefore sinks into the core
- Mo is moderately siderophile and will stay in the mantle (like noble metals) $\longrightarrow$ The same Mo-Ru correlation for meteorites would not a priori be expected for the Earth's mantle....
- Since the Mo-Ru correlation is true for the Earth's mantle, Ru must be delivered to the mantle after the core formed by a late accretion event which was of similar composition to the gas that first enriched the mantle in Mo.

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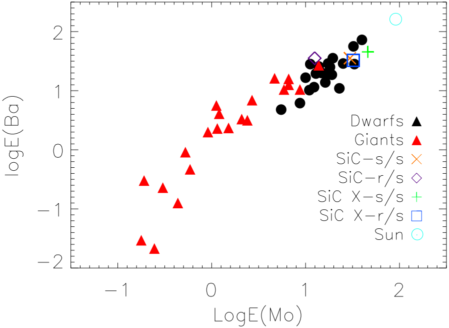
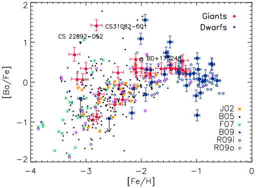
s-process in grains and stars





Solid symbols are stars, open symbols SiC grains Hansen et al, 2014, Pellin et al. 2006, Nicolussi et al. 1997

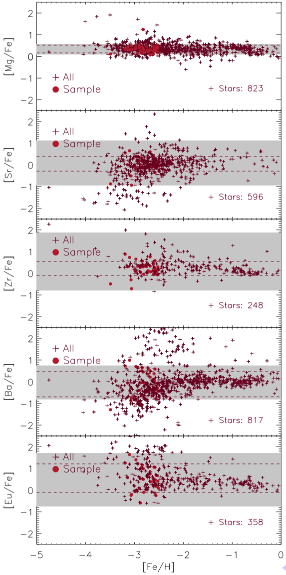
Conclusion

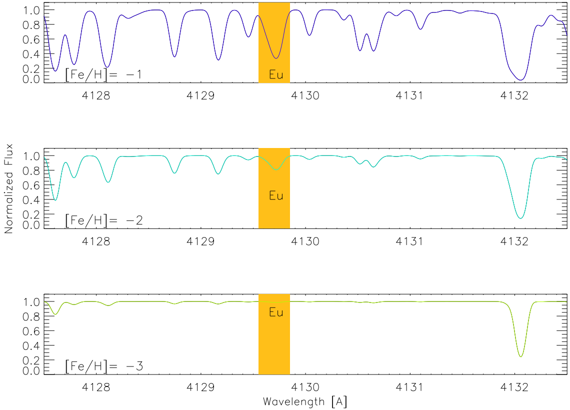
- A second process is needed to explain Ag, Ru & Pd
- This second "LEPP" is different from the s-processes and the main r-process
- Mo is produced by all processes - p,s, and r - this is detectable
- Mo and Ru are important heavy elements as they can trace various formation processes and thereby provide 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.

Material for discussion: Observational indicators for formation processes -

1) Correlations
2) star-to-star abundance scatter
3) Abundance pattern from observations
4) Uncertainties
5) CEMP stars

r/LEPP


[Mg/Fe]
+ All
Sample
+ Stars: 823
[Sr/Fe]
+ Stars: 596
[Zr/Fe]
+ Stars: 248
[Ba/Fe]
+ Stars: 817
[Eu/Fe]
+ Stars: 358
[Fe/H]

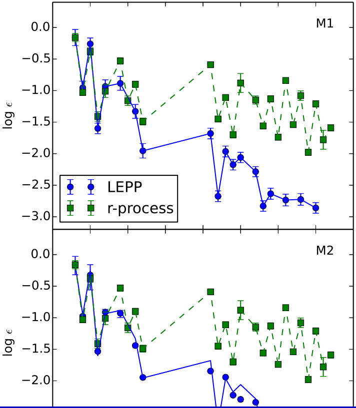


Observational abundance biases (Hansen et al, 2014 subm. to ApJ)

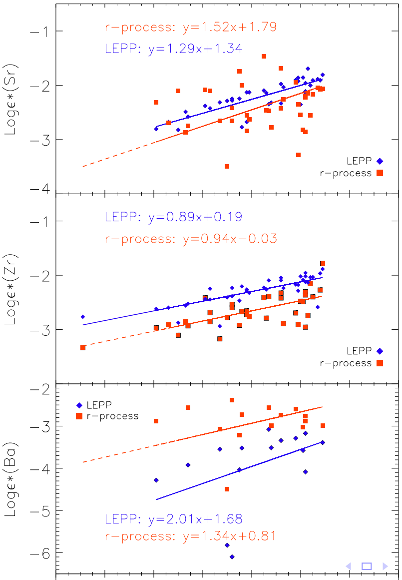
From this sample we eliminate stars with:

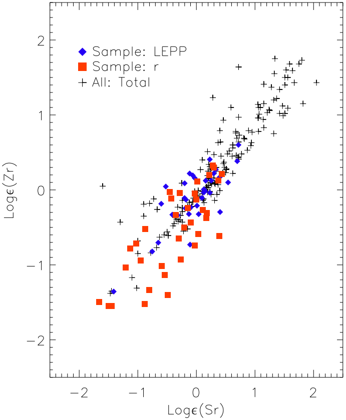
- [Fe/H] < -2.5 - removes most s-process contamination
- [C/Fe] < 0.9 - removes most CEMP stars
- [Ba/Fe]< 1.0 - removes CEMP-s and Ba-rich binaries
- Min. 5 abundance detections (i.e., not upper limits)
- [C/N]< -0.4 and [N/Fe]> 0.5 - removes self-enriched stars

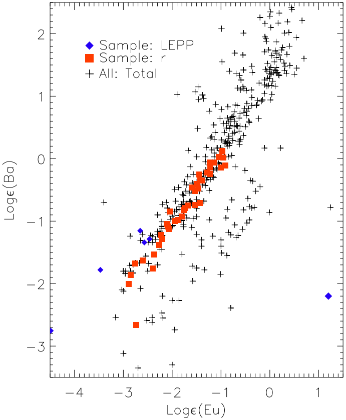
Assumptions:
There are 3 robust processes:
r-process, LEPP, P-component.
M1:
r=CS22892-052, LEPP=HD122563
M2: r=CS22892-052,
r+LEPP = HD122563
M3: r+LEPP=CS22892-052,
r+LEPP=HD122563
- all stars are mixed



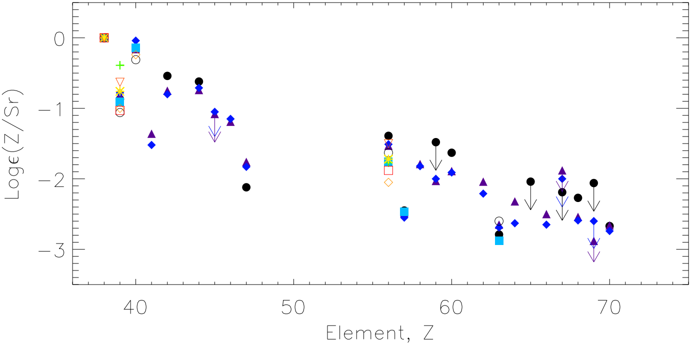
r/LEPP


r−process: y=1.52x+1.79
LEPP: y=1.29x+1.34
Logϵ*(Sr)
LEPP
r−process
LEPP: y=0.89x+0.19
r−process: y=0.94x−0.03
Logϵ*(Zr)
LEPP
r−process
LEPP
r−process
Logϵ*(Ba)
LEPP: y=2.01x+1.68
r−process: y=1.34x+0.81

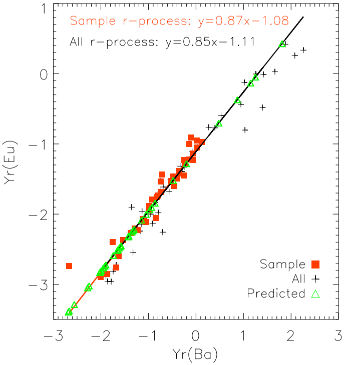


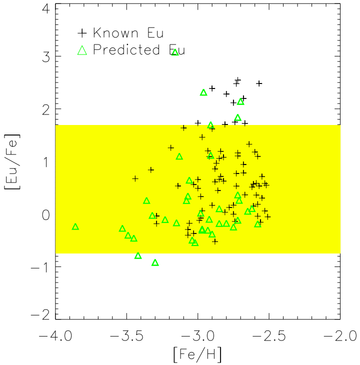


Robustness of the processes! (Hansen et al, 2014 subm. to ApJ)

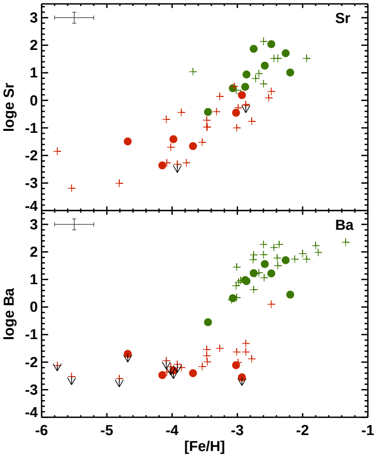


Robustness of the LEPP!





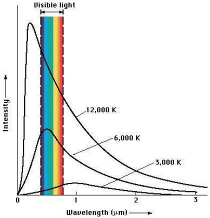
Robustness of the r-process!



CEMP stars

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:
  $T = a + b(V-K) + c(V-K)^2 + d(V-K)[Fe/H] + ...$
- Excitation potential - based on Fe lines (NLTE sensitive)
- Parallax/distance (π):
  $log\frac{g}{g_{Sun}} = log\frac{M}{M_{Sun}} + 4\frac{T}{T_{Sun}} + 0.4V_o + 2log(\pi) + corrections$
- Ionisation equilibrium from Fe lines (NLTE sensitive)
- Metallicity ([Fe/H]) from equivalent widths of Fe lines