

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

INT workshop

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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

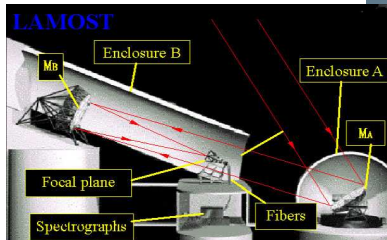


Fig. 1.—The essential components of an astronomical spectrograph.

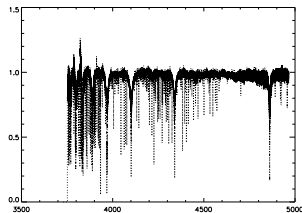
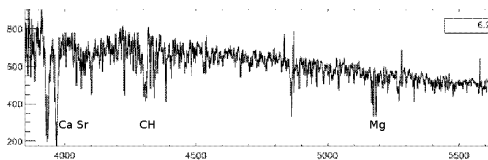
Simple sketch of a spectrograph –
Massey et al.



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



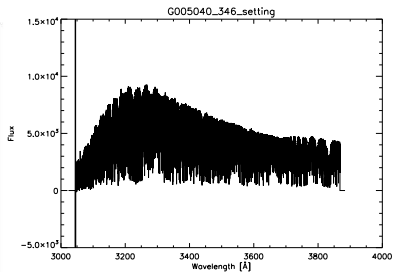
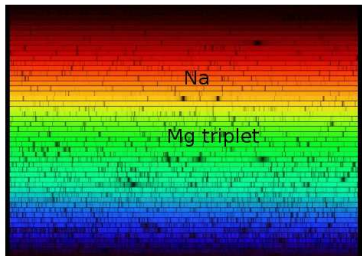
LAMOST vs UVES spectra



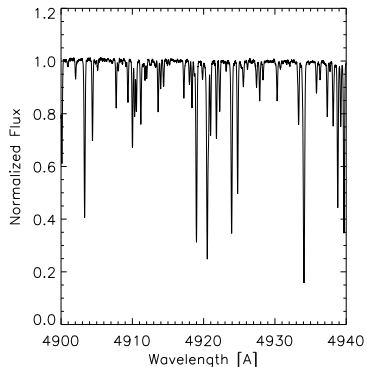
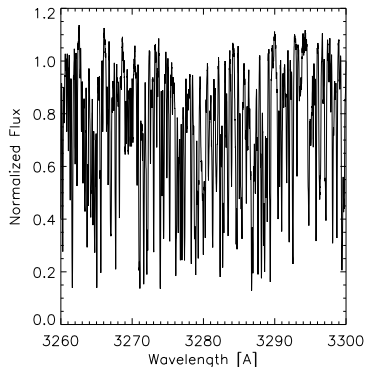
LAMOST (low resolution $R \sim 1800$) and ESO VLT (UVES - high resolution $R \sim 40000$)

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

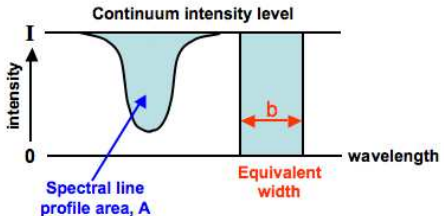
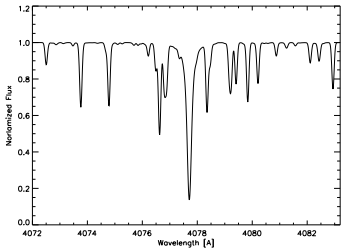


Visual versus near-UV spectral range



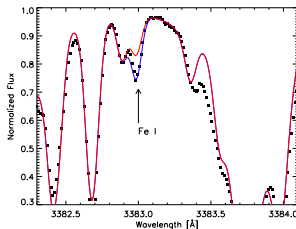
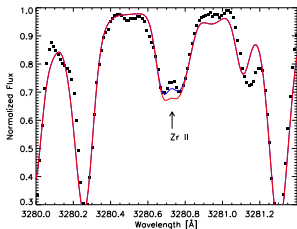
A metal-poor giant star (HD122956): Temperature/gravity/[Fe/H] =
4700K/1.5/-1.45

Stellar spectra and equivalent width (W)



The importance of atomic data; Abundance - log gf relation

$$\log W = \log(const) + \log(A) + \log(gf\lambda) - \theta\chi - \log(\kappa) \quad (1)$$

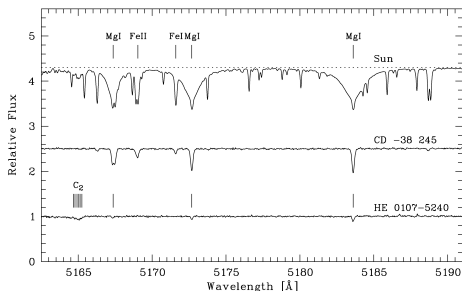


Hansen et al, 2012

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]

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



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

Periodic Table of the Elements © www.elementsdatabase.com

1 H																	2 He														
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne														
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar														
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr														
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Au	49 Hg	50 Tl	51 Pb	52 Bi	53 Po	54 At														
55 Cs	56 Ba	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Uun																						

Legend:

- hydrogen (black)
- alkali metals (yellow)
- alkali earth metals (orange)
- transition metals (purple)
- poor metals (green)
- nonmetals (blue)
- noble gases (pink)
- rare earth metals (teal)

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



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

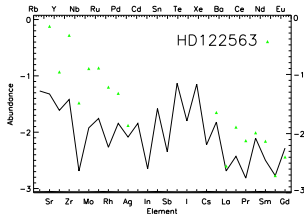
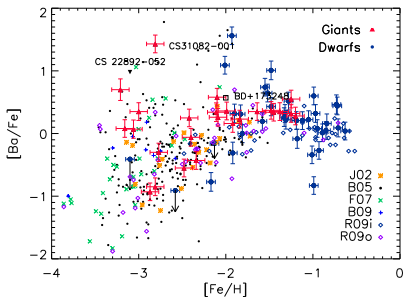
Table 1. LTE abundances in CS 31082-001 as derived from previous works, from the present paper, and our adopted final abundances.

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

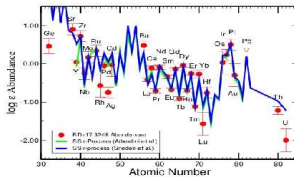
References. (1) Hill et al. (2002), (2) Sneden et al. (2009), (3) Barbuy et al. (2011).

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)



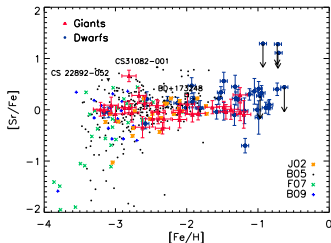
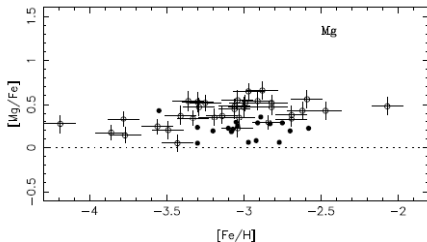
Hansen 2011 & Cowan +2011 (below)



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

Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18																							
1 H Hydrogen 1.00794	Alchem. # Symbd Name Atomic #																2 He Helium 4.002602																							
3 Li Lithium 6.941	4 Be Beryllium 9.012182	<table border="1"> <tr> <td>C</td><td>Solid</td> </tr> <tr> <td>Hg</td><td>Liquid</td> </tr> <tr> <td>H</td><td>Gas</td> </tr> <tr> <td>RI</td><td>Unknown</td> </tr> </table>										C	Solid	Hg	Liquid	H	Gas	RI	Unknown	<table border="1"> <tr> <td>Metals</td> <td>Nonmetals</td> </tr> <tr> <td>Alkali metals</td> <td>Other nonmetals</td> </tr> <tr> <td>Alkaline earth metals</td> <td>Noble gases</td> </tr> <tr> <td>Transition metals</td> <td></td> </tr> <tr> <td>Lanthanoids</td> <td></td> </tr> <tr> <td>Actinoids</td> <td></td> </tr> </table>			Metals	Nonmetals	Alkali metals	Other nonmetals	Alkaline earth metals	Noble gases	Transition metals		Lanthanoids		Actinoids		5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00644	8 O Oxygen 15.999	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
C	Solid																																							
Hg	Liquid																																							
H	Gas																																							
RI	Unknown																																							
Metals	Nonmetals																																							
Alkali metals	Other nonmetals																																							
Alkaline earth metals	Noble gases																																							
Transition metals																																								
Lanthanoids																																								
Actinoids																																								
11 Na Sodium 22.98976928	12 Mg Magnesium 24.304											13 Al Aluminum 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948																							
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.6305	33 As Arsenic 74.9216	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80																							
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.363	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29																							
55 Cs Cesium 132.90545196	56 Ba Barium 137.327	57-71 Lanthanoids																																						
87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinoids																																						

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

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57 La Lanthanum 138.90547	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium (152)	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92532	66 Dy Dysprosium 162.50014	67 Ho Holmium 164.930329	68 Er Erbium 167.259	69 Tm Thulium 168.93048	70 Yb Ytterbium 173.054688	71 Lu Lutetium 174.967
88 Ac Actinium (227)	90 Th Thorium 232.0377	91 Pa Protactinium 231.036889	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	105 Lr Lawrencium (260)

Sample, Method, and Formation Process:

- Sample consists of 71 stars, 42 dwarfs and 29 giants
- Enhanced as well as 'normal' stars ($-3.3 < [\text{Fe}/\text{H}] < -0.6$)
- UVES and HIRES (high resolution data)
- MARCS 1D atmospheres & MOOG¹ 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)

¹Snedden 73, version 2010, Assuming LTE

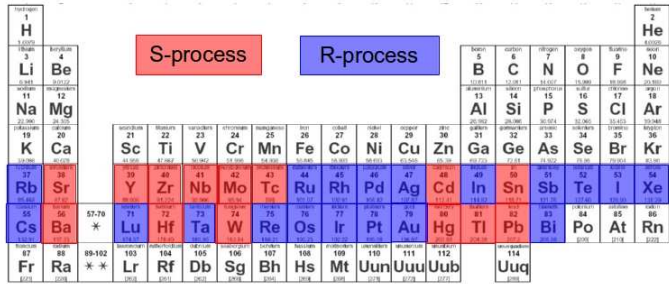
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¹Snedden 73, version 2010, Assuming LTE

Correlations

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



* Lanthanide series

57	58	59	60	61	62	63	64	65	66	67	68	69	70
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb

** Actinide series

89	90	91	92	93	94	95	96	97	98	99	100	101	102
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

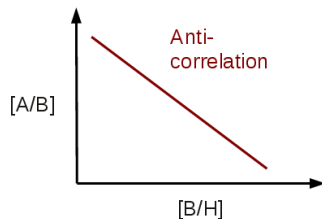
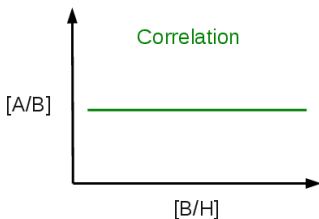


Correlations

Correlation - Anticorrelation

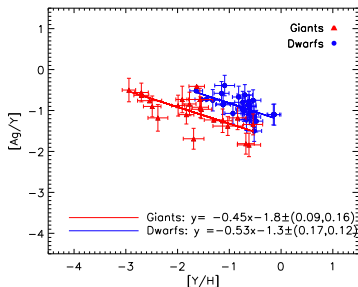
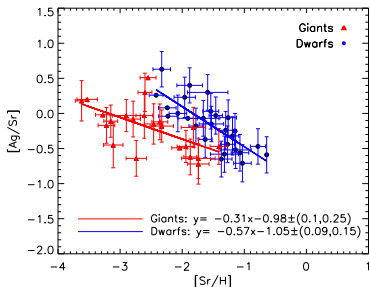
If two elements are created by the same process, they most likely grow in the same way (correlate).

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)

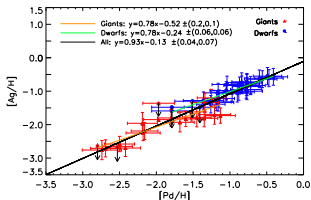
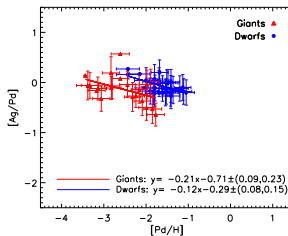
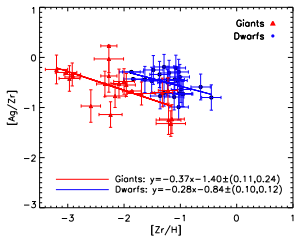


Weak s-process elements - Sr (85%) and Y (92%) Arlandini et al 1999

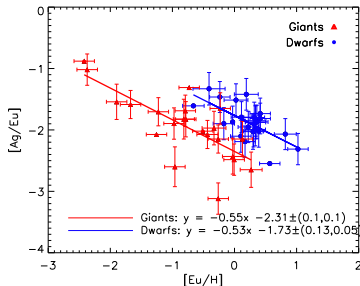
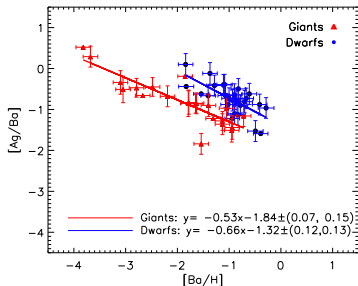
Hansen et al, 2012



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



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

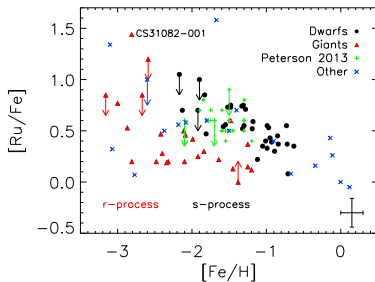
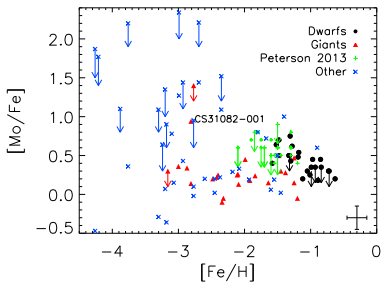


Hansen et al, 2012

This is why silver is interesting:

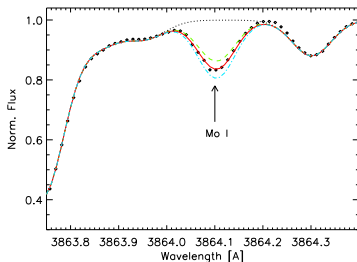
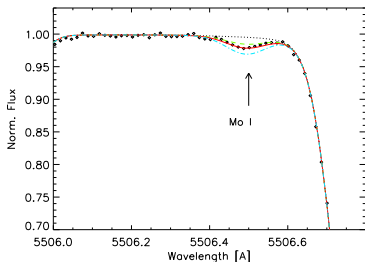
Ag (and Pd) is produced by a second 'weak' r-process/LEPP

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.

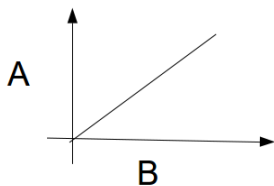


High-quality observations are needed in the near-UV spectral range
- almost impossible with fibre-based instruments.

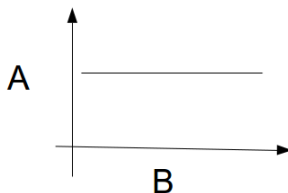
What can we learn about Mo and Ru?

A more direct approach to test if two elements (A, B) correlate

Correlation

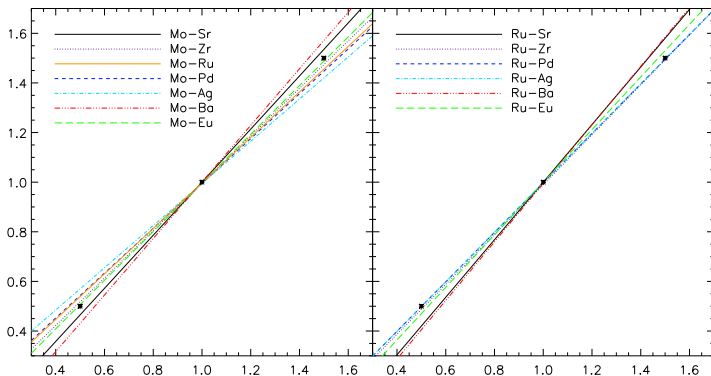


Anti-correlation



What can we learn about Mo and Ru?

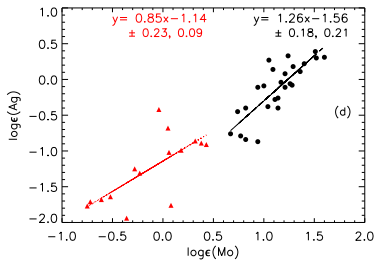
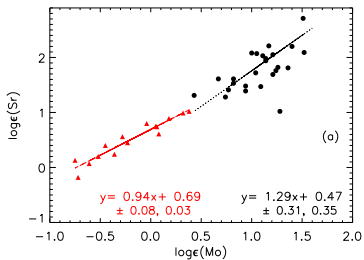
Fitting the entire sample = 1 process creates it all..?



Large uncertainties and scatter found between Sr-Mo and Ag-Mo.

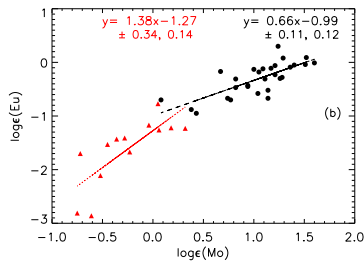
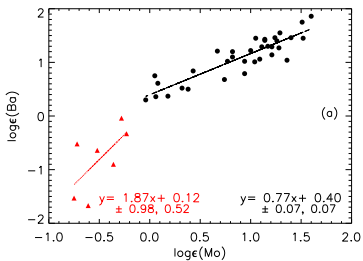
Can this be improved by fitting two processes/contributions?

Mo – weak s or LEPP? → *Not LEPP*

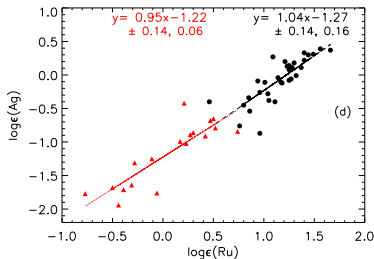
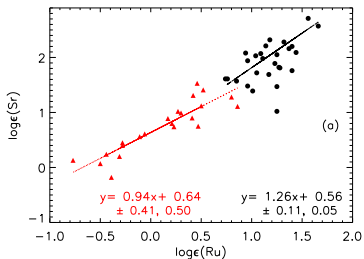


Hansen et al, 2014

Mo – main s or r?

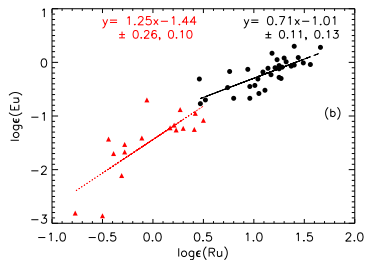
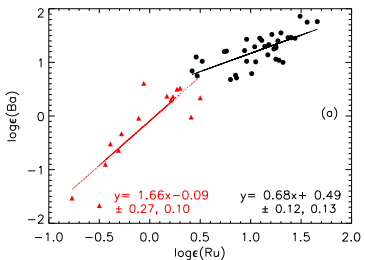


Ru – weak s or LEPP? → LEPP!

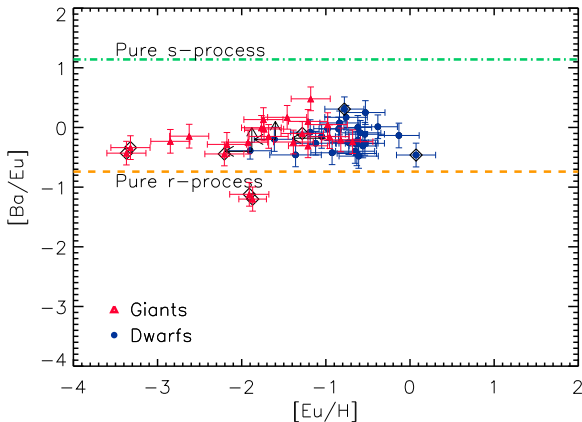


Hansen et al, 2014

Ru – main s or r?

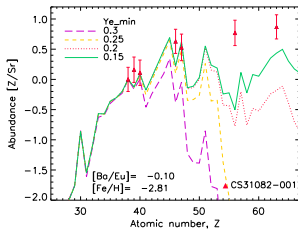
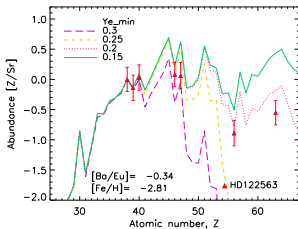
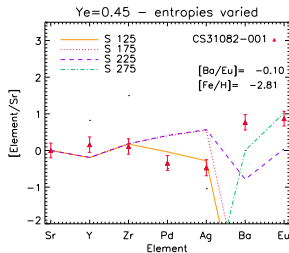
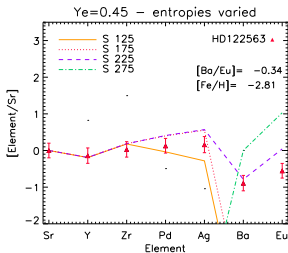


Pure r-process yields (Hansen et al, 2012)



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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Isotopic abundances needed → presolar grains from meteorites?



Periodic Table of the Elements © www.elementsdatabase.com

- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

1 H																	2 He														
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne														
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar														
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr														
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe														
55 Cs	56 Ba	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn																						
																		90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

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

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

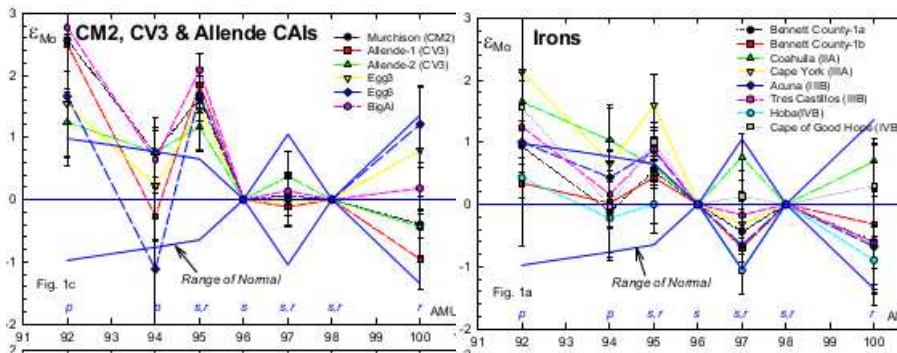
(Dauphas +2004)

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 ^xMo due to variations in the contribution from process x to the gas....

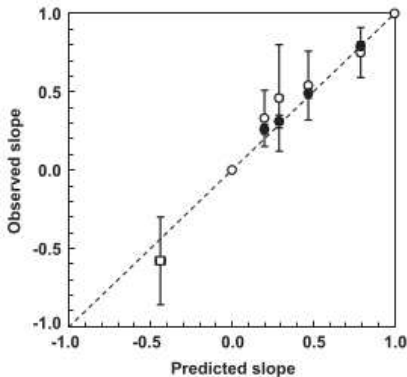
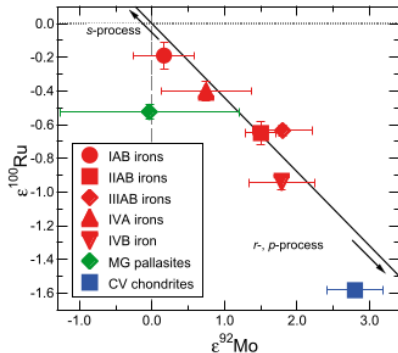
Anomalies - improved method!



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).



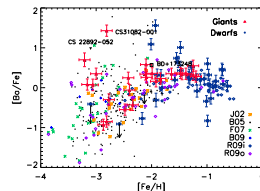
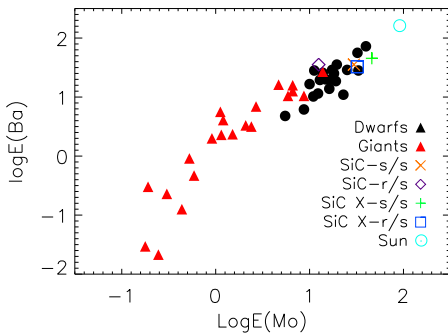
Earth

- 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) → 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



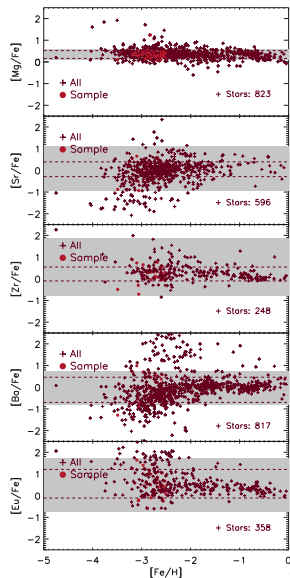
Solid symbols are stars, open symbols SiC grains Hansen et al, 2014, Pellin et al. 2006, Nicolussi et al. 1997

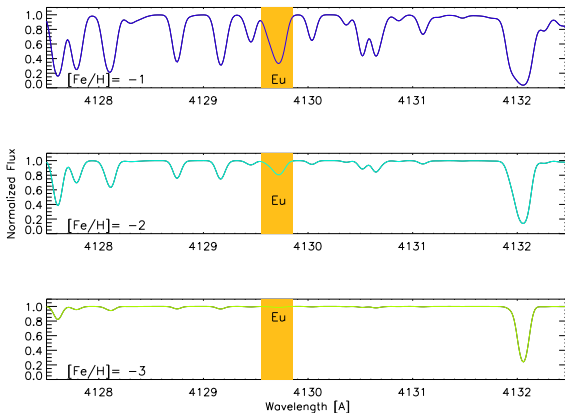
Conclusion

- 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





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

From this sample we eliminate stars with:

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

Assumptions:

There are 3 robust processes:
r-process, LEPP, P-component.

M1:

$r = \text{CS22892-052}$, $\text{LEPP} = \text{HD122563}$

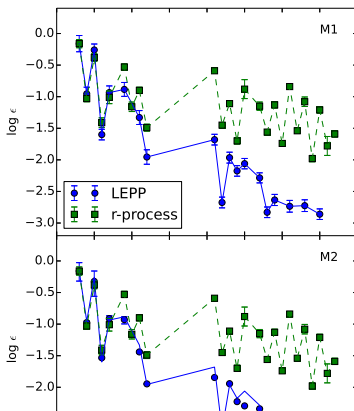
M2: $r = \text{CS22892-052}$,

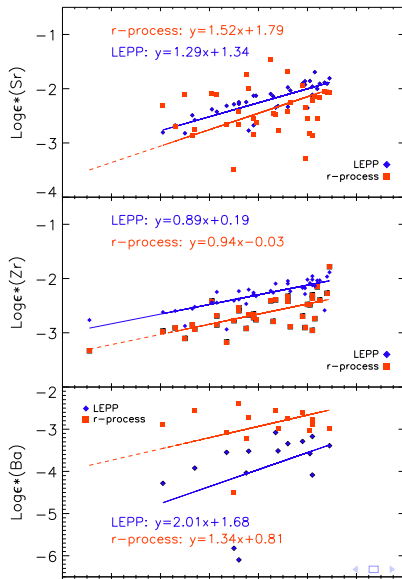
$r + \text{LEPP} = \text{HD122563}$

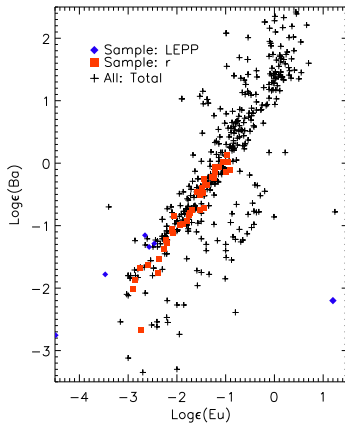
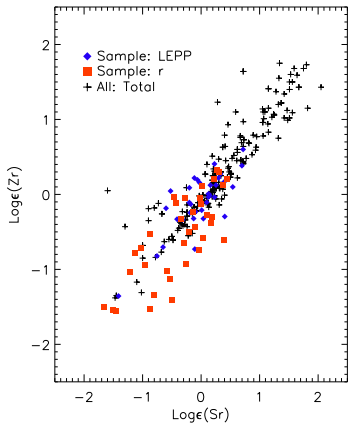
M3: $r + \text{LEPP} = \text{CS22892-052}$,

$r + \text{LEPP} = \text{HD122563}$

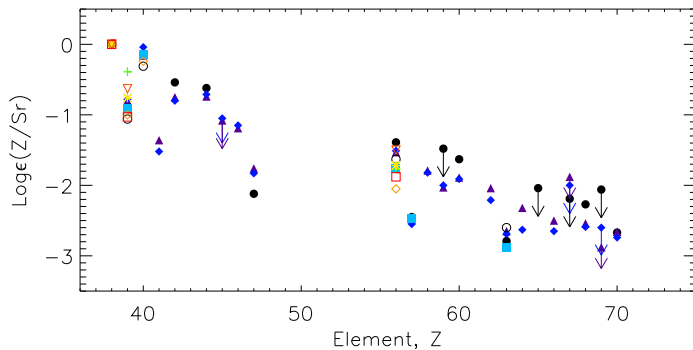
- all stars are mixed



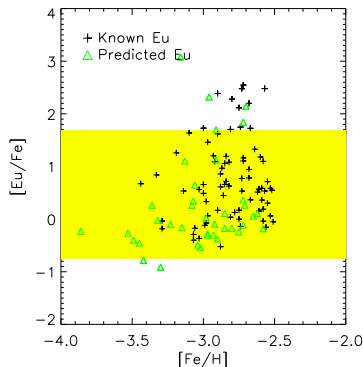
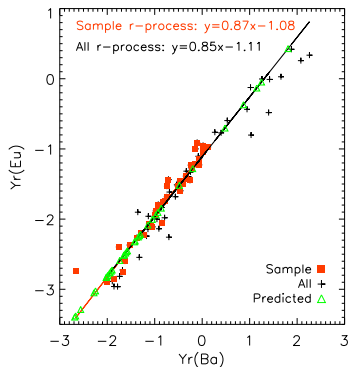




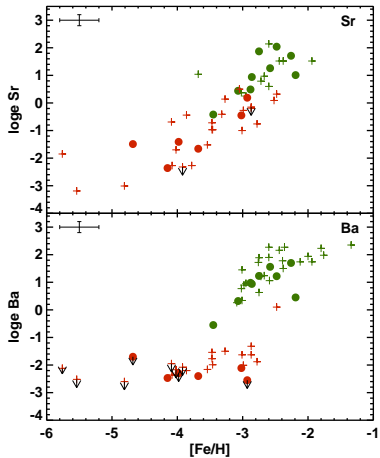
Robustness of the processes! (Hansen et al, 2014 subm. to ApJ)



Robustness of the LEPP!



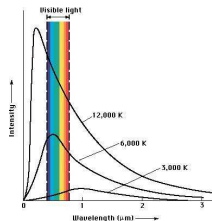
Robustness of the r-process!



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:

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

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

- Parallax/distance (π):

$$\log \frac{g}{g_{Sun}} = \log \frac{M}{M_{Sun}} + 4 \frac{T}{T_{Sun}} + 0.4V_o + 2 \log(\pi) + \text{corrections}$$

- Ionisation equilibrium from Fe lines (NLTE sensitive)
- Metallicity ([Fe/H]) from equivalent widths of Fe lines