Unveiling the chemical origin of stars through nucleosynthetic and observational studies

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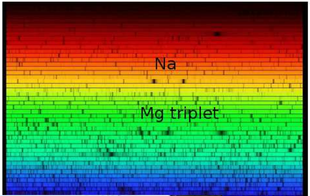
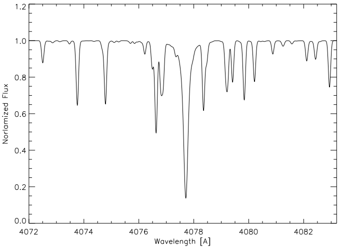
Outline

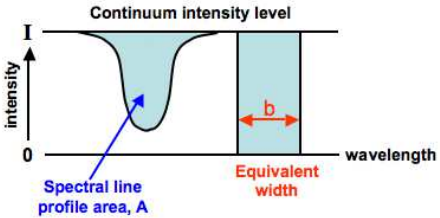
- *Cool stars are the only astrophysical objects in which we can conduct a detailed and precise abundance study of up to ∼70 elements*
- Stellar parameters, abundances, and assumptions
- Tracing astrophysical formation sites using stellar abundances
- Comparing to AGB & (EC)SN yields
- CEMP stars
- How many processes are needed in the early Universe?

Very Large Telescope (VLT) - 8-m mirror



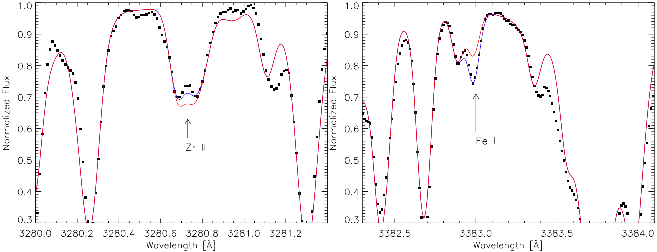
Stellar spectra and equivalent width (W)





Abundance - W - log gf relation; the impact of stellar parameters and atomic data

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

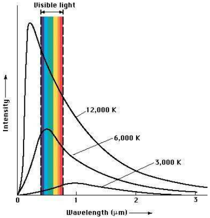


C.J.Hansen et al, 2012

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

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 Alonso et al. 1999, Casagrande et al. 2010:
  $T = a + b(V-K) + c(V-K)^2 + d(V-K)[Fe/H] + ...$
- Excitation potential - based on Fe lines (NLTE sensitive)
- Parallax/distance (π) e.g., Nissen et al. 1997:
  $log\frac{g}{g_{Sun}} = log\frac{M}{M_{Sun}} + 4\frac{T}{T_{Sun}} + 0.4V_o + 2log(\pi) + corrections$
- Ionisation equilibrium from Fe lines (NLTE sensitive)
- Metallicity ([Fe/H]) from equivalent widths of Fe lines

A comparison of two cluster (47Tuc) stars to AGB yields

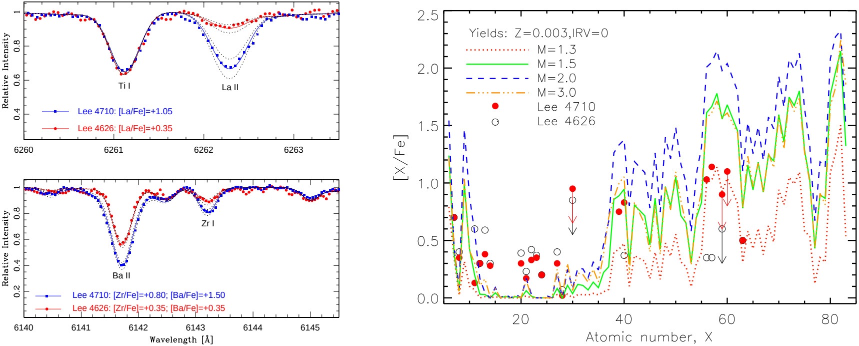


Figure: Comparing two seemingly similar stars to each other and AGB yields from FRUITY; Cordero (CJH) et al. 2015, Cristallo et al. 2011

Stellar spectra, abundances, and [Fe/H]

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

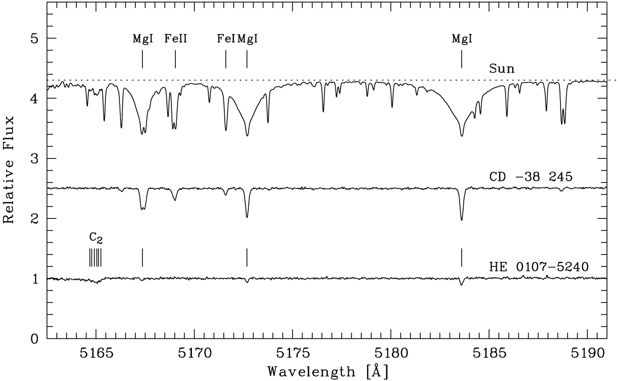


Figure: Top: Solar ([Fe/H] = 0) spectrum – Mg triplet. Bottom: Star with [Fe/H] ∼ -5. Christlieb +2004

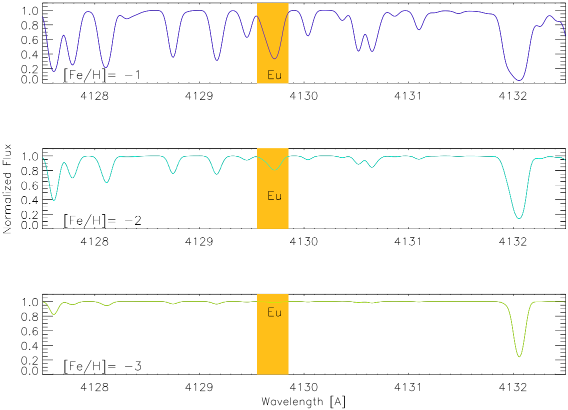
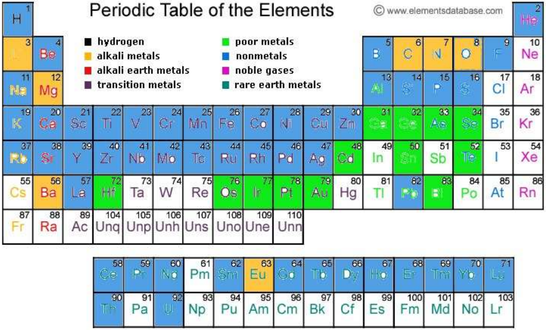


Figure: Observational abundance biases (Hansen et al, 2014b)

Observable elements - with high-resolution instruments



Periodic Table of the Elements

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- ■ 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	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								
			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	

Figure: 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

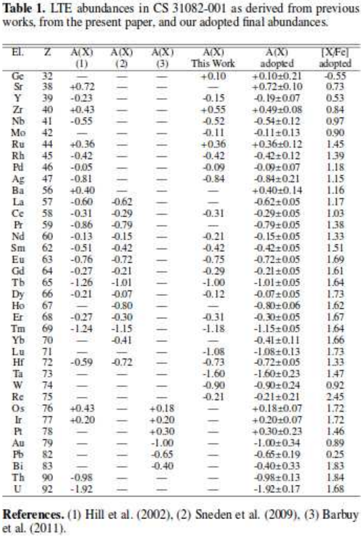


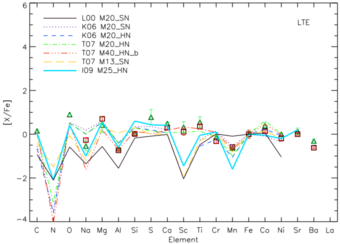
Table 1. LTE abundances in CS 31082-001 as derived from previous works, from the present paper, and our adopted final abundances.

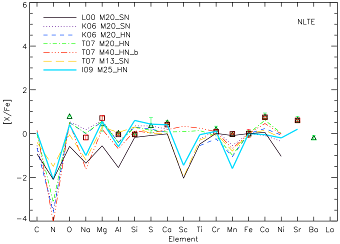
El.	Z	A(X) (1)	A(X) (2)	A(X) (3)	A(X) This Work	A(X) adopted	[X/Fe] adopted
Ge	32	—	—	—	+0.10	+0.10±0.21	-0.55
Sr	38	+0.72	—	—	—	+0.72±0.10	0.73
Y	39	-0.23	—	—	-0.15	-0.19±0.07	0.53
Zr	40	+0.43	—	—	+0.55	+0.49±0.08	0.84
Nb	41	-0.55	—	—	-0.52	-0.54±0.12	0.97
Mo	42	—	—	—	-0.11	-0.11±0.13	0.90
Ru	44	+0.36	—	—	+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).

The most metal-poor (oldest) RR Lyrae stars known C.J.Hansen +2011a

- α-elements serve as tracers of SN Mass (Kobayashi et al. 2006)
- The α/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}





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

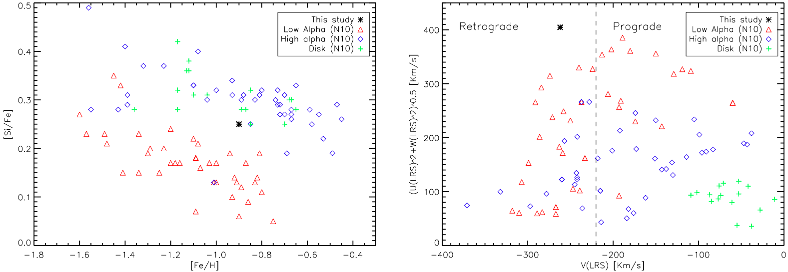


Figure: **CJH et al. 2016b, subm. to A&A: [Mg/Fe] and velocity of the old but [Fe/H]=-0.9 RR Lyrae star.**

Another record holding early Universe star:

Keller et al. 2014: [Fe/H] < -7.1 - origin SN II of M$\sim 60 M_\odot$

Bessel et al. 2015 (3D, NLTE) $\rightarrow$ [Fe/H] < -7.5 & $40 M_\odot$ SN

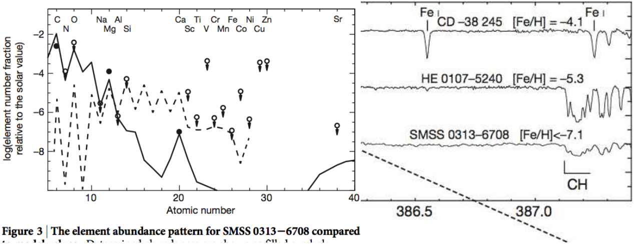


Figure 3 | The element abundance pattern for SMSS 0313−6708 compared

Assumptions: LTE vs NLTE - the impact on stellar parameters

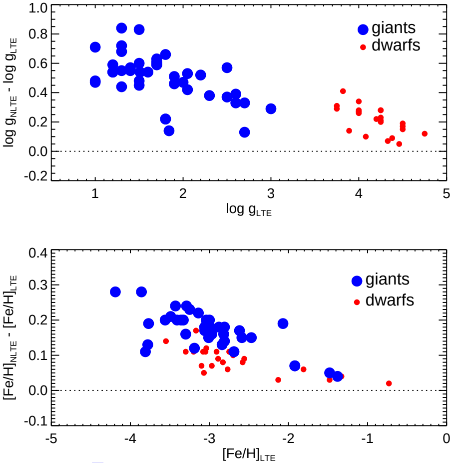


Figure: C.J.Hansen et al. 2013

Assumptions: LTE vs NLTE - Strontium

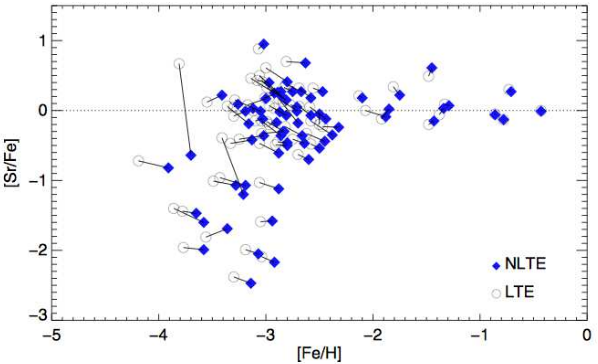
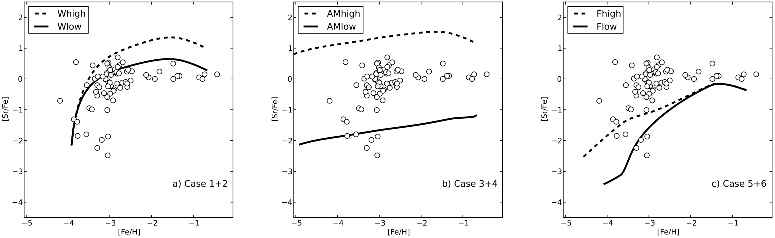


Figure: C.J.Hansen et al. 2013

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 ν–driven winds (Arcones & Montes 2011)
3) Yields from massive fast rotating stars (Frischknecht et al. 2012)

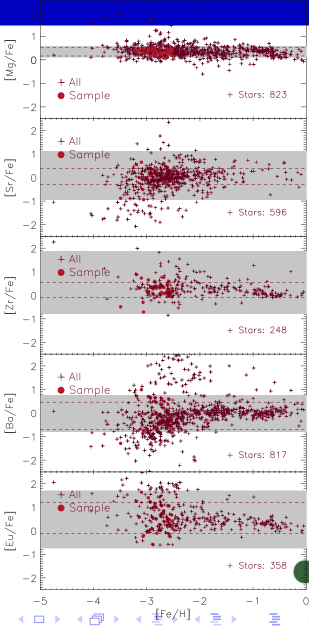


The uncertain yields can cover a large range of stellar abundances. Despite uncertainties we can still make quantitative predictions such as:

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

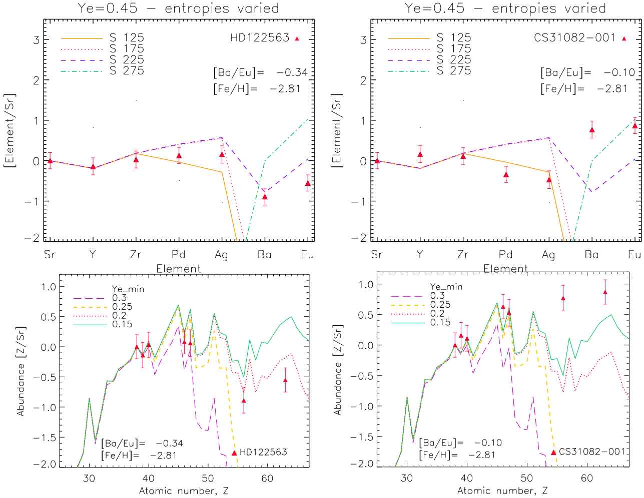
Scatter and multiple formation processes

- 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)

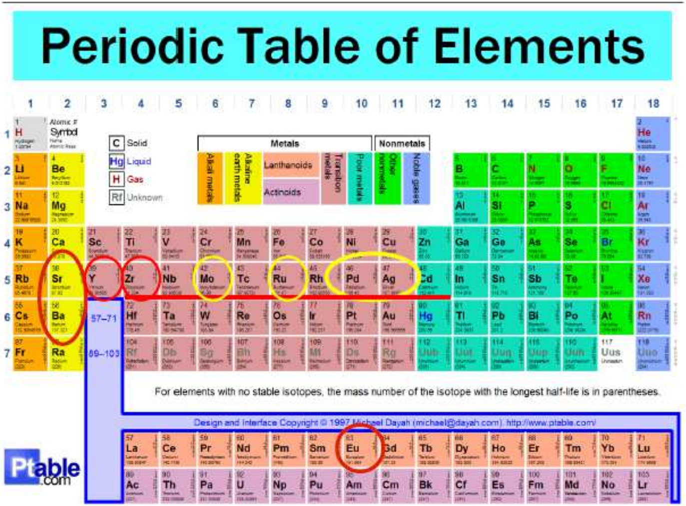


r-poor vs r-rich stars: HD122563 & CS31082-001

(Honda et al. 2007, Hill et al. 2002 & C.J.Hansen et al. 2012)



Selected elements



Galactic chemical evolution of Mo and Ag

$$[\mathrm{Fe/H}] \equiv \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{*} - \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\odot} \tag{3}$$

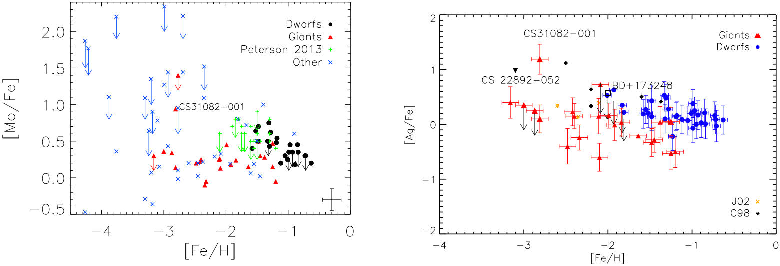
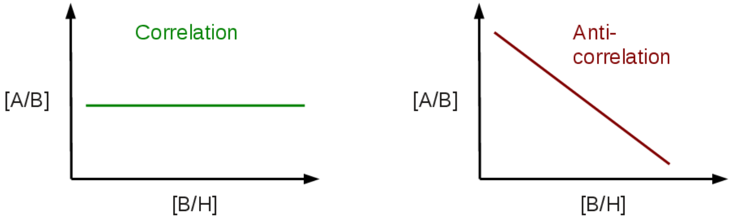


Figure: C.J.Hansen et al. 2014a, 2012, Comparison samples: Roederer et al. 2014, Peterson 2013, Johnson&Bolte 2002, Crawford et al. 1998

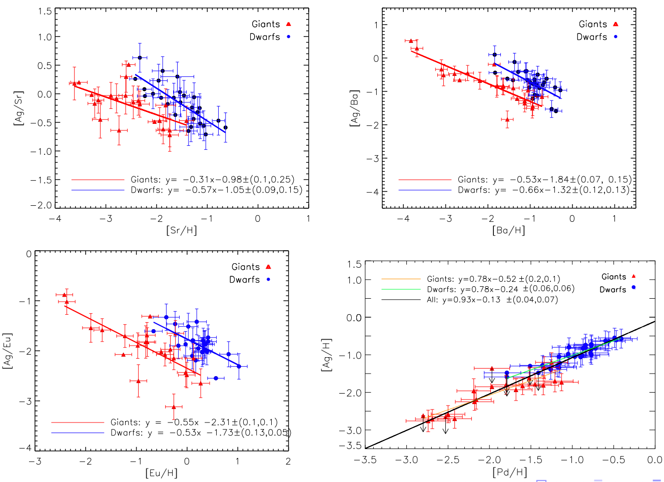
Correlation - Anticorrelation

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

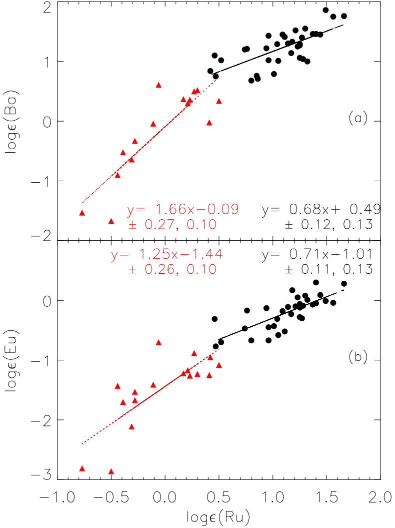
Elements ($38 < Z < 50$) are generally found to anti-correlate with $Z > 56$ elements (Burris et al, 2000, Montes et al, 2007, Francois et al 2007)

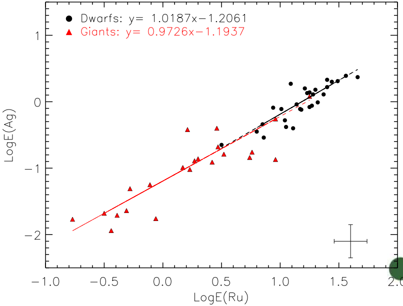


Weak/main s/r-process elements - Sr (85% s), Ba (81% s) and Eu (94% r) Arlandini et al. 1999; C.J.Hansen et al. 2012



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, ν-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

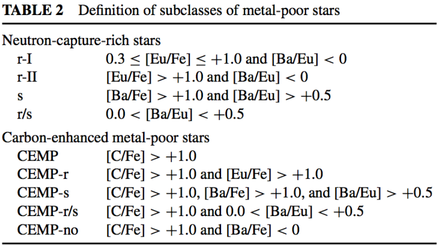
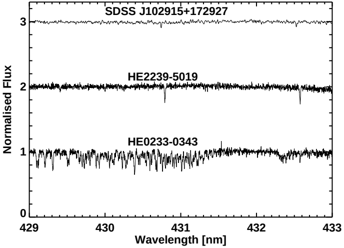


TABLE 2 Definition of subclasses of metal-poor stars

Neutron-capture-rich stars	
r-I	$0.3 \leq$ [Eu/Fe] $\leq +1.0$ and [Ba/Eu] < 0
r-II	[Eu/Fe] $> +1.0$ and [Ba/Eu] < 0
s	[Ba/Fe] $> +1.0$ and [Ba/Eu] $> +0.5$
r/s	$0.0 <$ [Ba/Eu] $< +0.5$
Carbon-enhanced metal-poor stars	
CEMP	[C/Fe] $> +1.0$
CEMP-r	[C/Fe] $> +1.0$ and [Eu/Fe] $> +1.0$
CEMP-s	[C/Fe] $> +1.0$, [Ba/Fe] $> +1.0$, and [Ba/Eu] $> +0.5$
CEMP-r/s	[C/Fe] $> +1.0$ and $0.0 <$ [Ba/Eu] $< +0.5$
CEMP-no	[C/Fe] $> +1.0$ and [Ba/Fe] < 0



CEMP stars

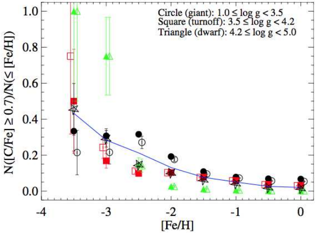
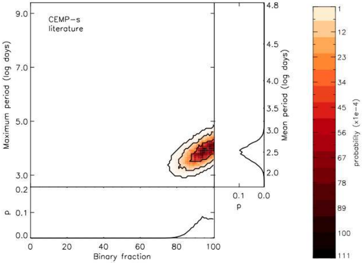


Figure 10. Cumulative frequencies of CEMP stars ([C/Fe] ⩾ +0.7) from the SDSS/SEGUE+LS sample, as a function of [Fe/H], for three different luminosity classes: giants (circles), main-sequence turnoff stars (squares), and dwarfs (triangles). We assume classifications based on the measured surface gravity—giant: 1.0 ⩽ log *g* < 3.5, turnoff: 3.5 ⩽ log *g* < 4.2, and dwarf: 4.2 ⩽



See, e.g., Beers & Christlieb 2005, Aoki et al. 2007, Masseron et al. 2010, Lugaro et al. 2012, Bisterzo 2010,2011, 2012

- Binary fraction increasing with decreasing metallicity.
- CEMP-no, 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)

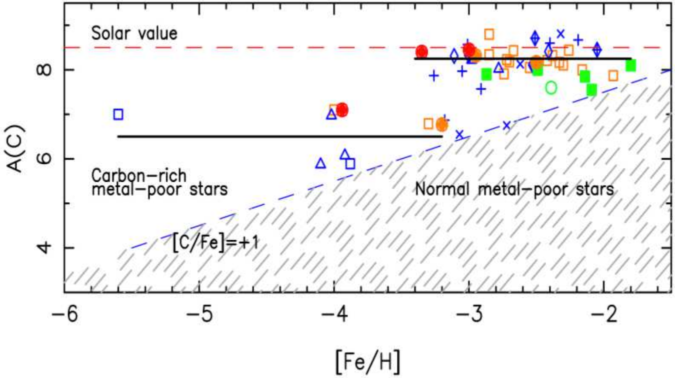


Fig. 14. Abundance of carbon A(C) vs. [Fe/H] in dwarfs and turnoff CEMP stars, following Sivarani et al. (2006, their Table 4), [orange open squares]), Frebel et al. (2005, 2007) [blue open squares], Thompson et al. (2008) [green open circle], Aoki et al. (2009) [blue open diamonds], Behara et al. (2010) [full orange circles], Placco et al.

CEMP-no and CEMP-s stars - Extremely/Ultra metal-poor stars

(Bonifacio et al. 2015)

Bonifacio et al.: TOPoS: II. C-enhanced stars

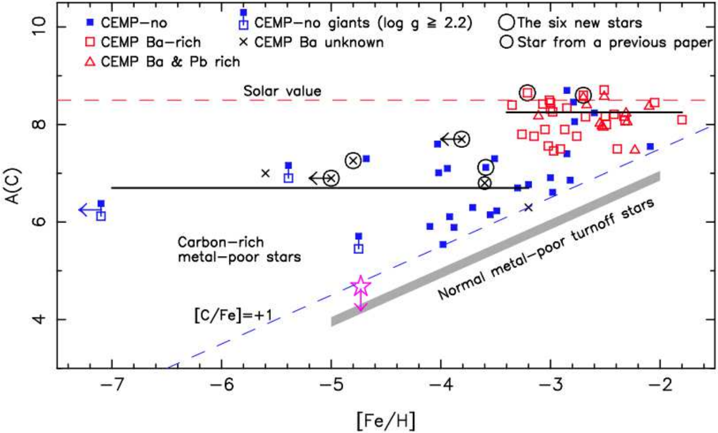
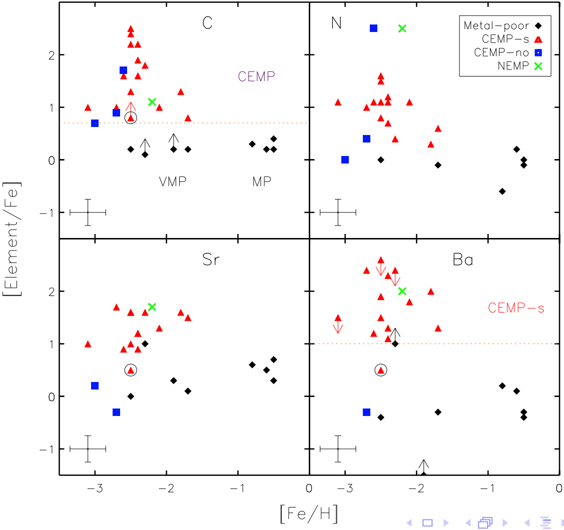


Fig. 6. The carbon abundances A(C) of CEMP stars as a function of [Fe/H]. The stars in the present paper and in Caffau et al. (2013a) are shown with big and small circles, respectively. The other turn-off stars come from the literature (Sivarani et al. 2006; Frebel et al. 2005, 2006; Thompson et al. 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)



CEMP-s and -no stars - different from EMP C-normal stars

This is in agreement with the recent findings Bonifacio et al. 2015

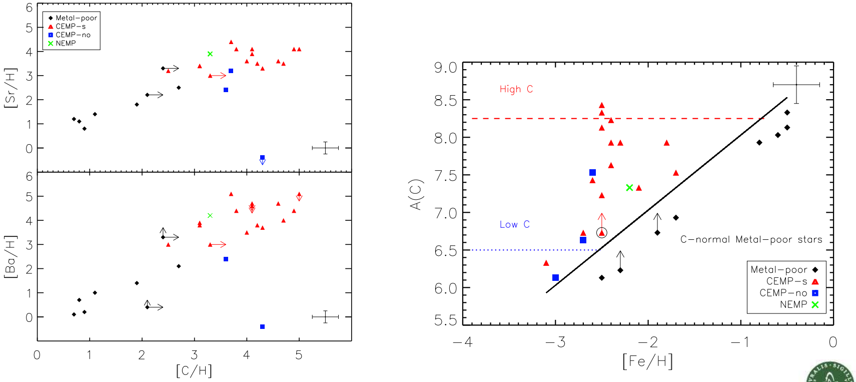


Figure: C.J.Hansen et al. 2016

CEMP-s vs -no stars - and C-normal stars

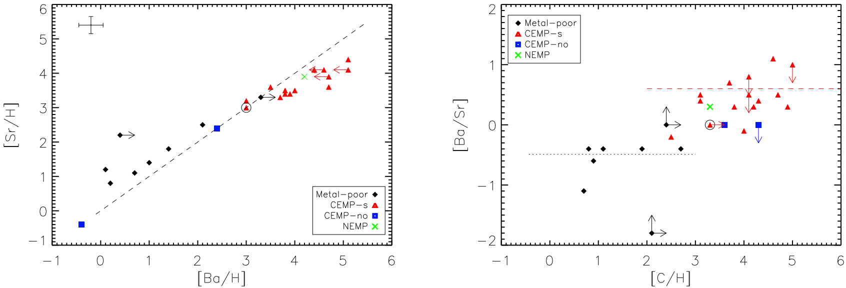


Figure: <[Ba/Sr]> ~ 0.5 for $\sim 2M_\odot$ AGB stars while <[Ba/Sr]> ~ -0.5 matches GCE prediction from spinstars (0 to -1.5). C.J.Hansen et al. 2016

GCE of CEMP and C-normal stars Predictions: Cescutti 2008, 2013

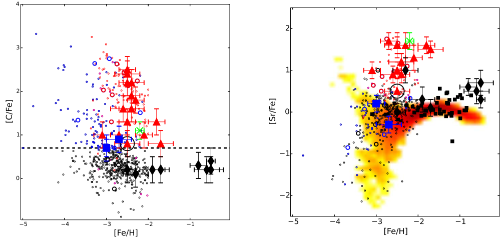
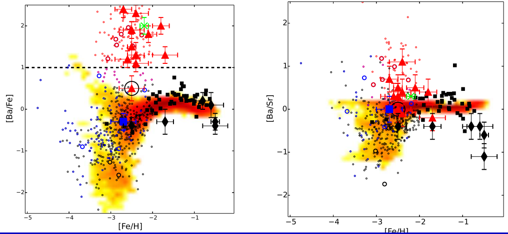
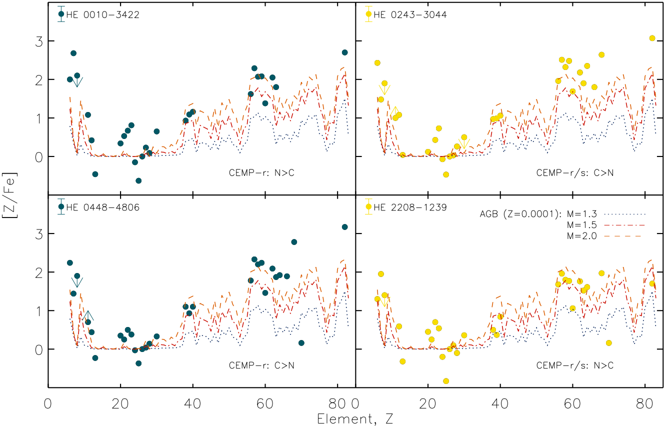


Figure: An r-process + spinstars ([Ba/Sr]~ 0 to -1.5). C.J.Hansen et al. 2016



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*)



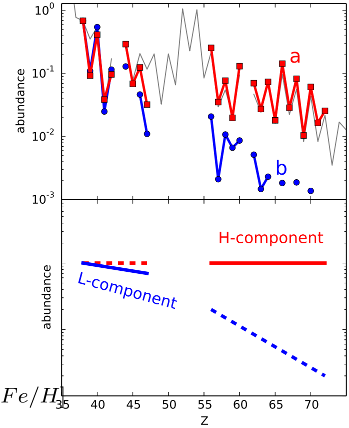
Winds

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=CS22892-052, L=HD122563
M2:
H=CS22892-052, H+L = HD122563
M3:
H+L=CS22892-052, H+L=HD122563
- all stars are mixed Li et al. 2013

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

(C.J.Hansen et al. 2014b)



Winds

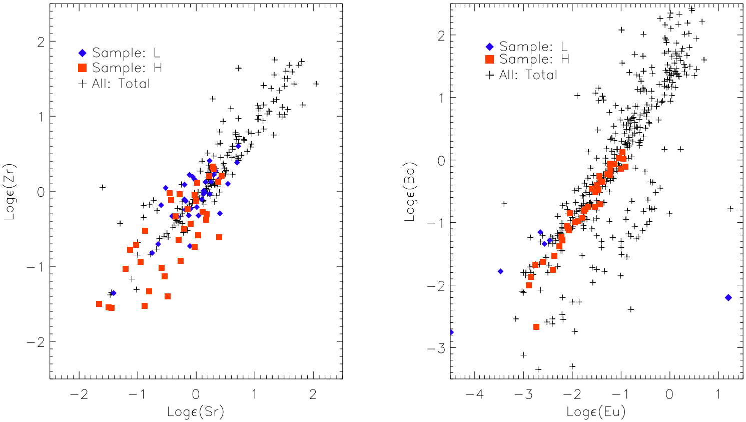


Figure: Robustness of the processes! (C.J.Hansen et al. 2014b)

Winds

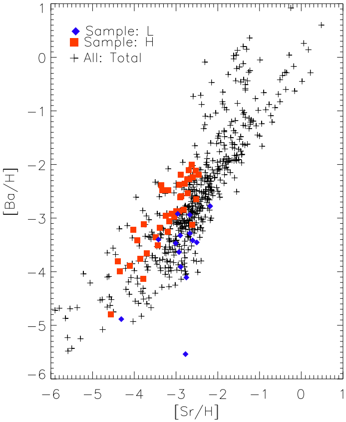
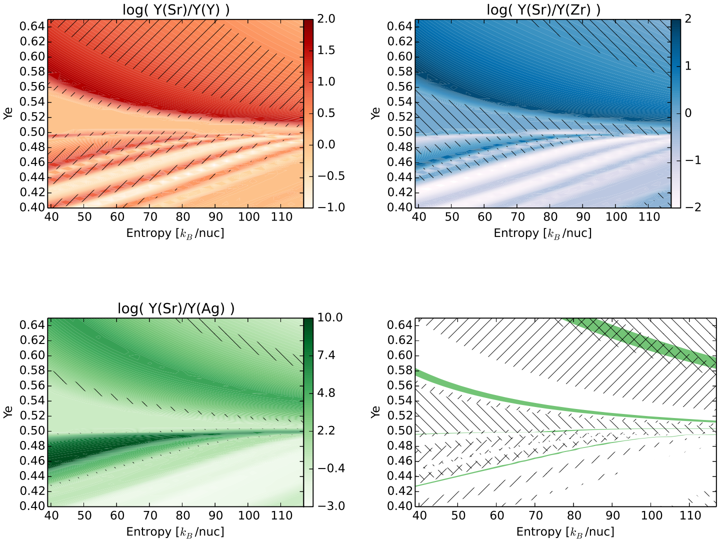


Figure: Differences in Sr and Ba (C.J.Hansen et al. 2014b)

Winds


log(Y(Sr)/Y(Y))
log(Y(Sr)/Y(Zr))
log(Y(Sr)/Y(Ag))
Ye
0.40 0.42 0.44 0.46 0.48 0.50 0.52 0.54 0.56 0.58 0.60 0.62 0.64
Entropy [k_B/nuc]
40 50 60 70 80 90 100 110
2.0 1.5 1.0 0.5 0.0 −0.5 −1.0
2 1 0 −1 −2
10.0 7.4 4.8 2.2 −0.4 −3.0

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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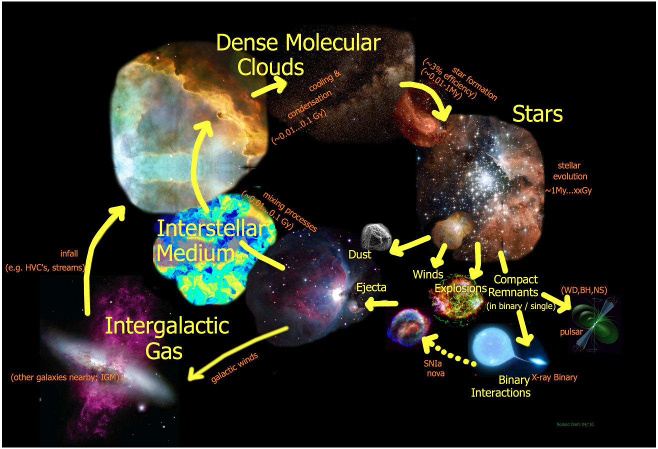
Thank you for listening



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