11th Russbach School on Nuclear Astrophysics

Strongly r-process enhanced stars: constraining the pure r-process Ba/Eu abundance ratio from observations

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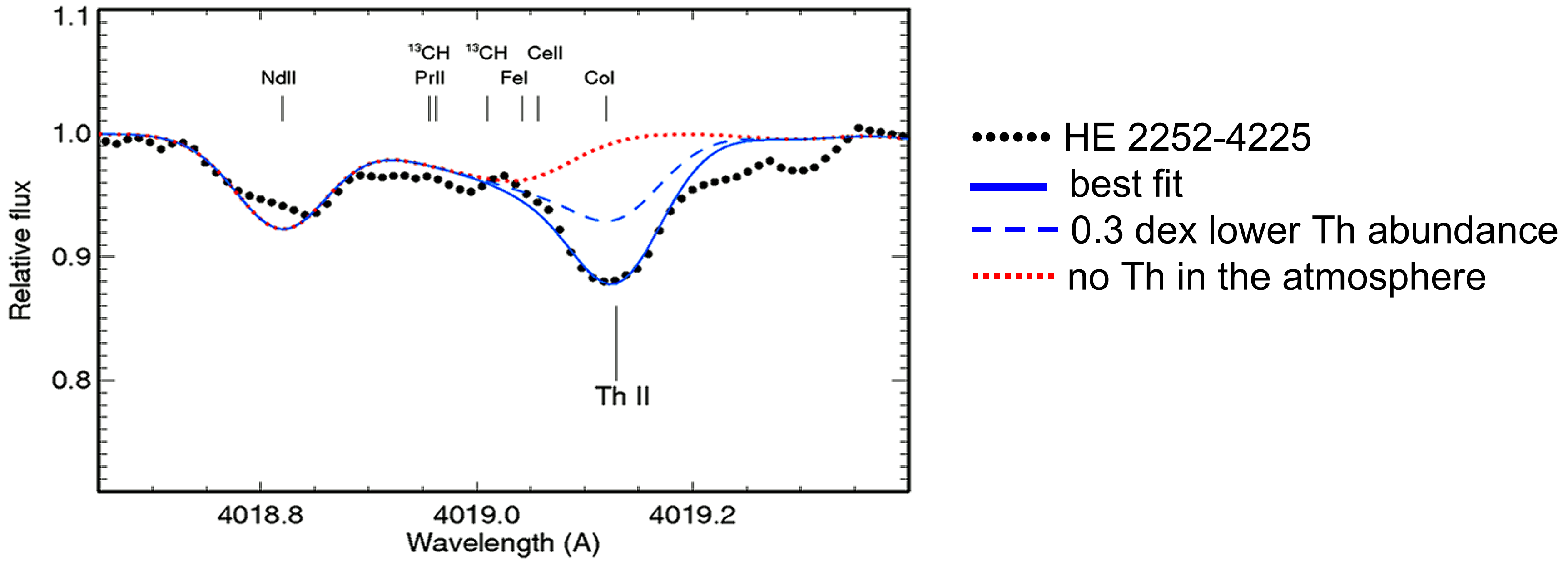
March 10-14, 2014, Russbach, Austria

Outline of this lecture

- ✶ How to determine stellar chemical abundances?
  - Basics of stellar atmosphere and line formation modelling.
  - Uncertainties in derived abundances.

- ✶ Ba and Eu abundances of r-II stars:
  - Why Ba/Eu?
  - Why r-II stars?
  - Observations vs. r-process models.

Stellar element abundance is obtained from fitting theoretical spectra to observed spectral data



Observed spectrum should be of high resolution, high S/N ratio, wide wavelength coverage.

HE 2252-4225, $V \approx 15^m$
It takes 9 hours to obtain 3400-6810 Å with
$R = \lambda/\Delta\lambda \approx 60\ 000$, $S/N \approx 100$
using 8-m telescope VLT (ESO, Chile), spectrograph UVES.

Calculations of theoretical spectra

Stellar atmosphere

Radiation escapes into space from thin layer on top of the stellar core.

Geometrically thin ($H \sim 10^{-3} R$), but optically thick ($\tau_\nu > 1$).

No generation of energy. Energy transport by radiation and convection.

Step I: compute temperature and pressure stratifications.

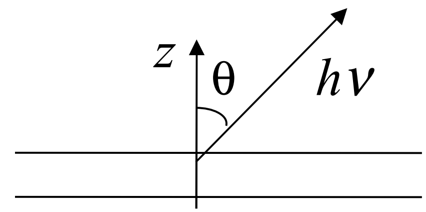
Model atmosphere, assumptions:

- ✓ composed of homogeneous layers (1D-geometry),
- ✓ static,
- ✓ in radiative and convective equilibrium.

Model atmosphere, parameters:

- effective temperature T_{eff}, measure of emergent flux, $F = \sigma T^4$
- surface gravity log g,
- chemical composition, $\{\varepsilon_i\}$

Step II: solve radiation transfer (RT) equation at line frequencies



$$\mu \frac{dI_\nu(z,\mu)}{dz} = -\chi_\nu(z) I_\nu(z,\mu) + \eta_\nu(z)$$

$\mu = cos\ \theta$

Opacity $\chi_\nu = \chi_\nu^c + \chi_\nu^l$ emissivity $\eta_\nu = \eta_\nu^c + \eta_\nu^l$

Continuum opacity χ_ν^c : photoionization of H, He, metals, Rayleigh, Thomson scattering, etc.

Line absorption: $\chi_\nu^l = \chi_\nu^l(n_{A,r,i}, f_{ij}, \gamma_R, \gamma_4, \gamma_6, HFS, IS)$

number density of absorbers ($n_{A,r,i}$)

Atomic parameters ($f_{ij}, \gamma_R, \gamma_4, \gamma_6, HFS, IS$)

Emissivity: how to compute?

- Local thermodynamic equilibrium (LTE)

(thermal processes): $\eta_\nu / \chi_\nu = B_\nu(T)$

- non-LTE:

$$\eta_\nu^l / \chi_\nu^l = \frac{2h\nu_{ij}^3}{c^2} \frac{1}{\frac{n_i}{n_j}\frac{g_j}{g_i} - 1}$$

How to compute $n_{A,r,i}$?

- LTE: $n_{A,r,i} = f(T, p)$ from the Saha-Boltzmann equations.

LTE is invalid in line formation layers

– mean free-path of photons is large,

– radiation field is far from TE.

- Non-LTE: $n_{A,r,i}$ are determined from balance among radiative and collisional population and de-population processes.

Statistical equilibrium (SE) equations: $dn_i/dt = 0$

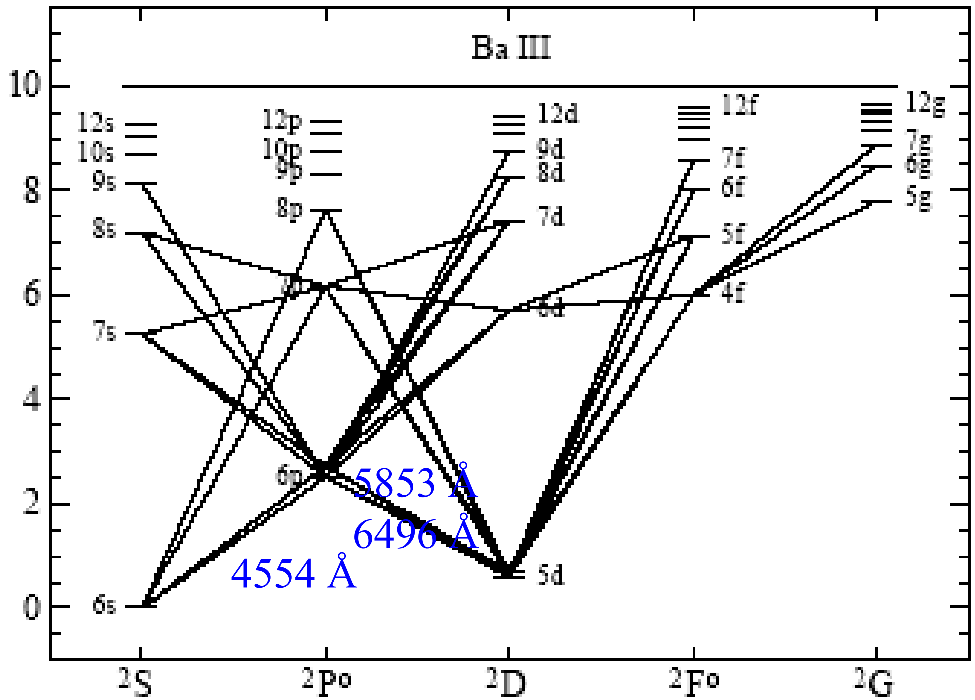
$$\left\{ \sum_{j \neq i} n_j \left(R_{ji} + C_{ji} \right) = n_i \sum_{j \neq i} \left(R_{ij} + C_{ij} \right) \right\} \quad i = 1, \ldots NL$$

+

$$\mu \frac{dI_\nu(z,\mu)}{dz} = -\chi_\nu(z) I_\nu(z,\mu) + \eta_\nu(z)$$

Solution of combined SE and RT equations

- Maxwellian velocity distribution, $T_e = T_A = T_i$
- Real atomic term structure is represented by model atom.



Atomic term structure of Ba II

Excitation and ionization state of the matter at any depth point depends on physical conditions throughout the atmosphere.

$$n_i = f\left(n_1, \ldots, n_{NL}, J_1, \ldots, J_{NF}\right)$$

Influence of departures from LTE on Ba abundances of CS 22892-052, 4800/1.5/-3.1

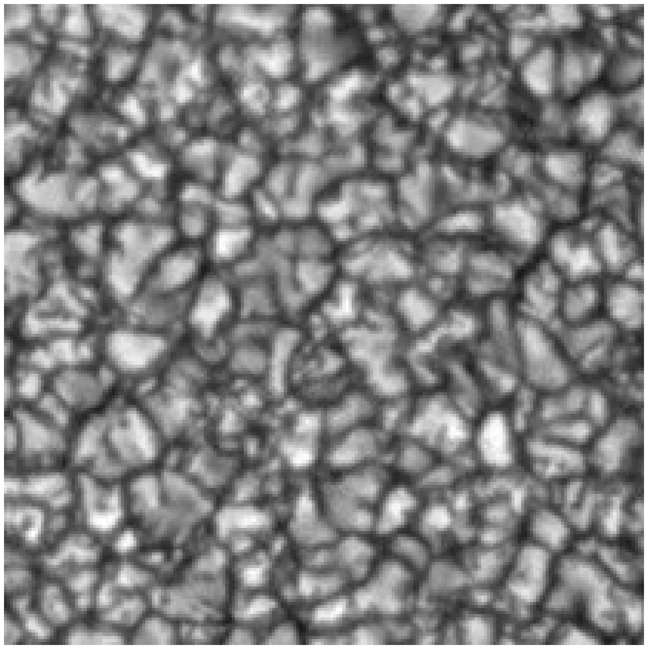
Mean abundance, $\log \varepsilon = \log n_{Ba}/n_H + 12$

	LTE	non-LTE
Ba II 4554, 4934	0.02±0.07	-0.18±0.01
Ba II subordinate lines	0.02±0.11	-0.15±0.02

Note dramatic reduction of statistical error, when moving from LTE to non-LTE.
This favours non-LTE line formation for Ba II.

Convection in outer layers of cool stars affects vertical T profiles and creates horizontal T inhomogeneities.

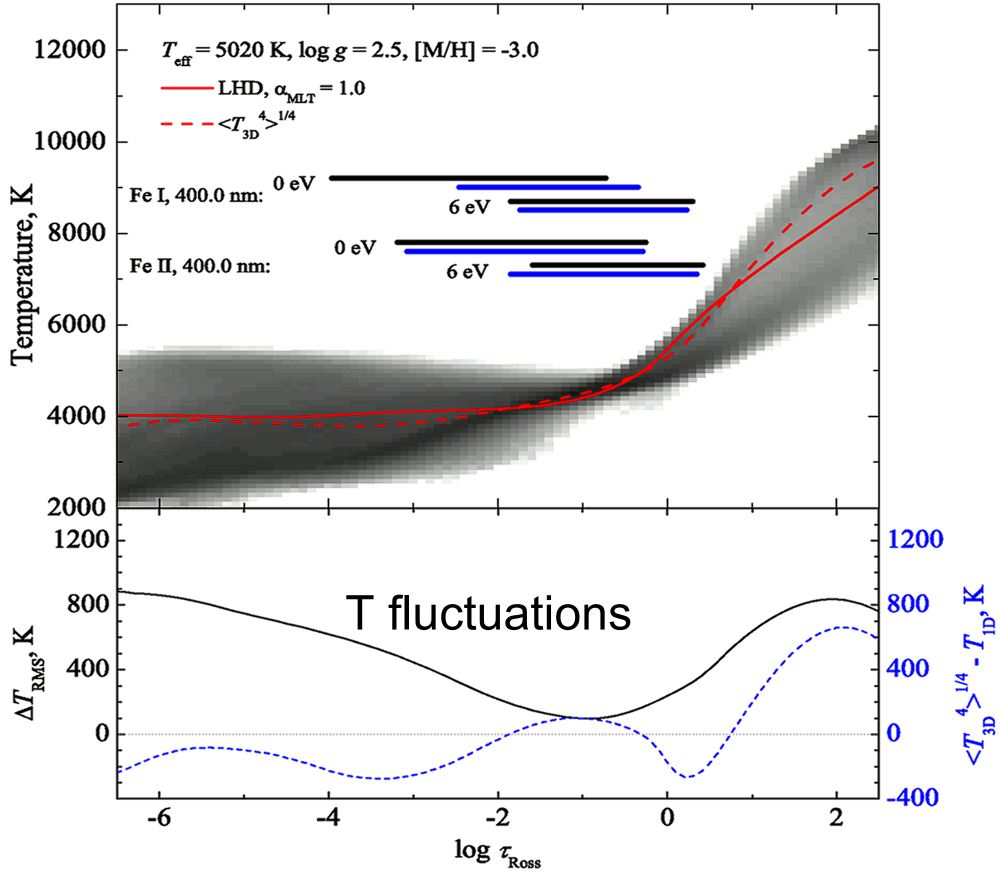
Sveden Vacuum Solar Telescope



Solar granulation.

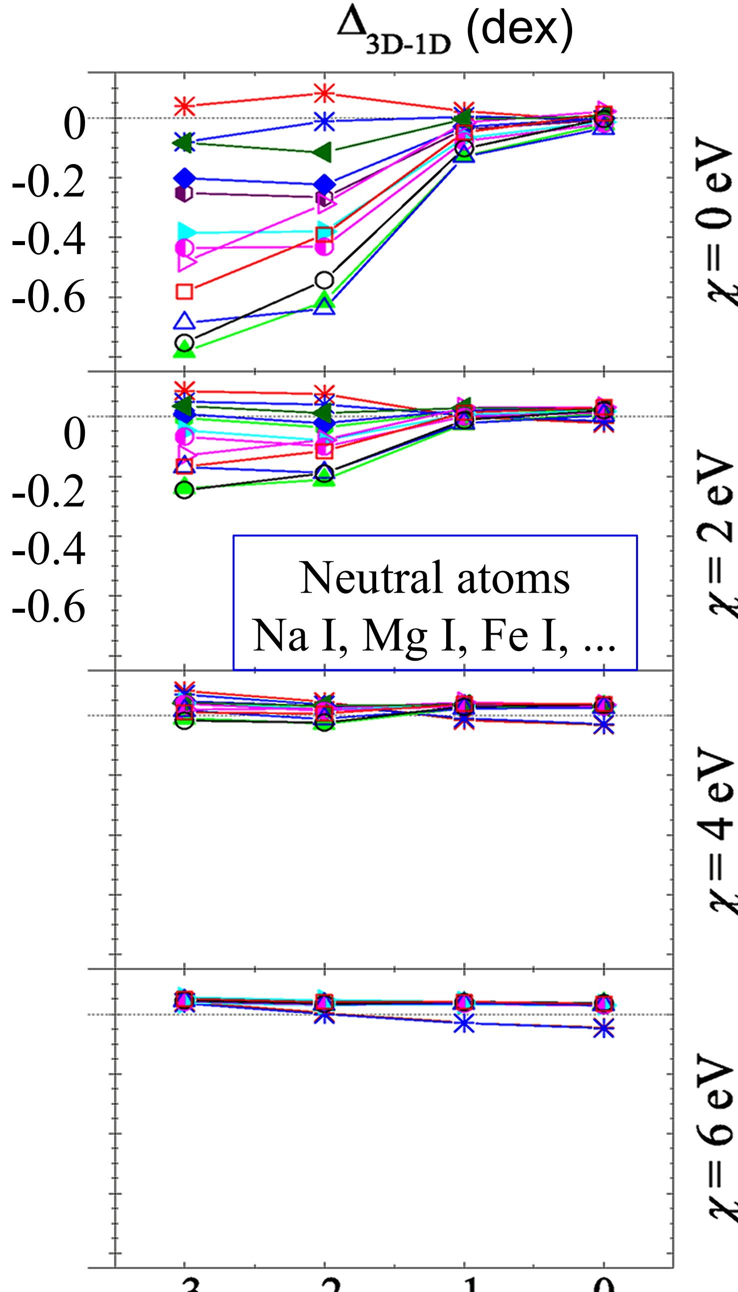
Size of area: ~65 000 km,

granule: ~1 000 km.

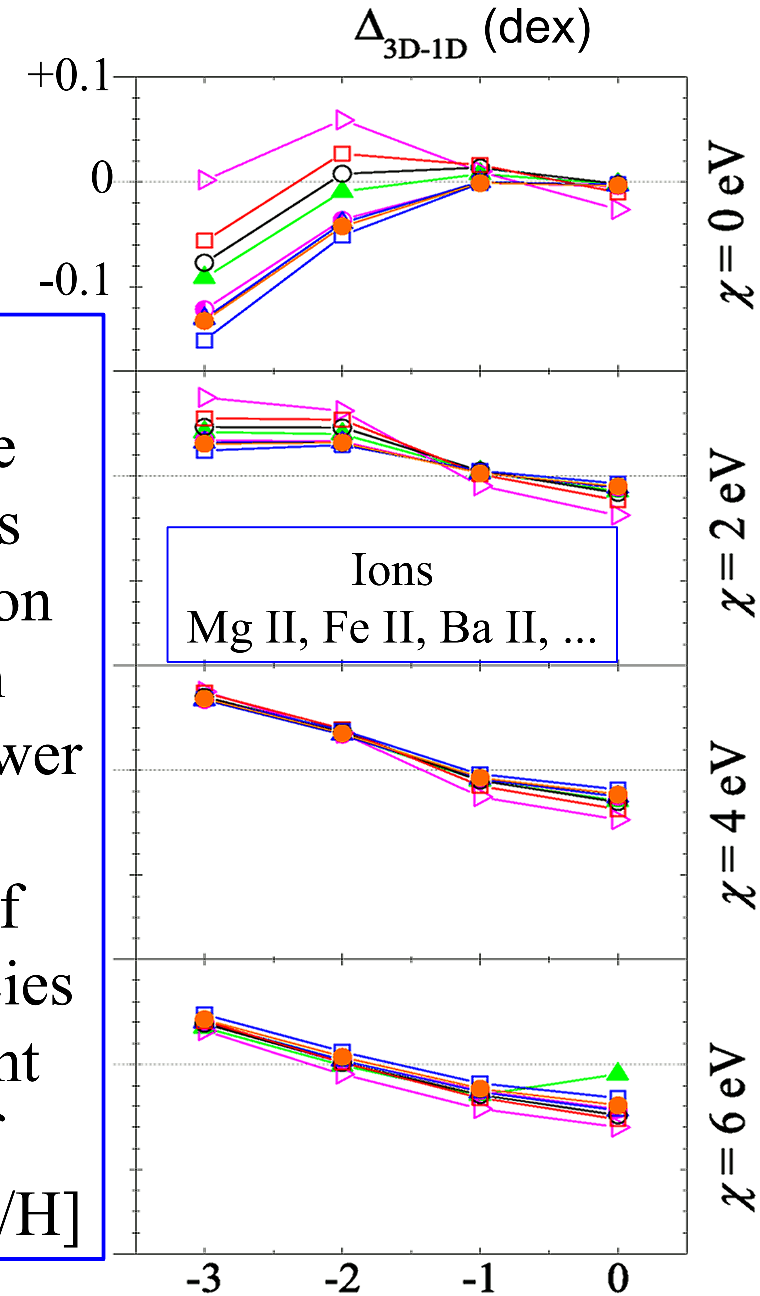


T profiles in 3D hydrodynamical CO[5]BOLD model atmosphere 5020/2.5/-3

Dobrovolskas et al. (2013)



3D-1D abundance corrections depending on excitation energy of lower level, χ, for lines of various species in cool giant models of different [Fe/H]

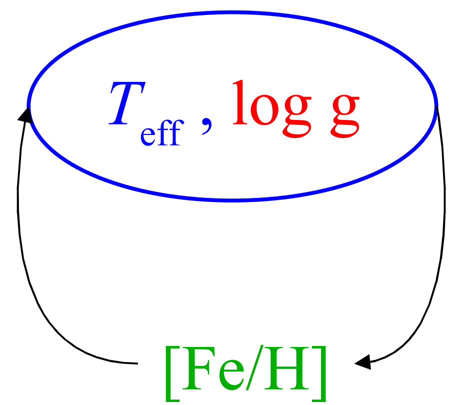


Dobrovolskas et al. (2013)

Before determination of chemical abundances one needs to determine atmospheric parameters T_{eff}, log g, [Fe/H]

T_{eff}
- total flux and diameter measurements, $f_{obs} = \sigma T_{eff}^4 \times \theta^2$,
- photometric colors *V-K*, *b-y*, *etc.*
- spectroscopic methods: Balmer line profiles, *EW* ratios

Surface gravity, log g
- mass and radius measurements, $g = G M/R^2$
- distance, T_{eff}, mass,
- *EW* ratios (Fe I/Fe II, Ca I/Ca II, ...)
  Caution! Departures from LTE for Fe I, Ca I.



Iterative procedure, in most cases

[Fe/H]
- from lines of iron.

Uncertainty in stellar parameters and effect on abundances

Edvardsson et al. (1993)

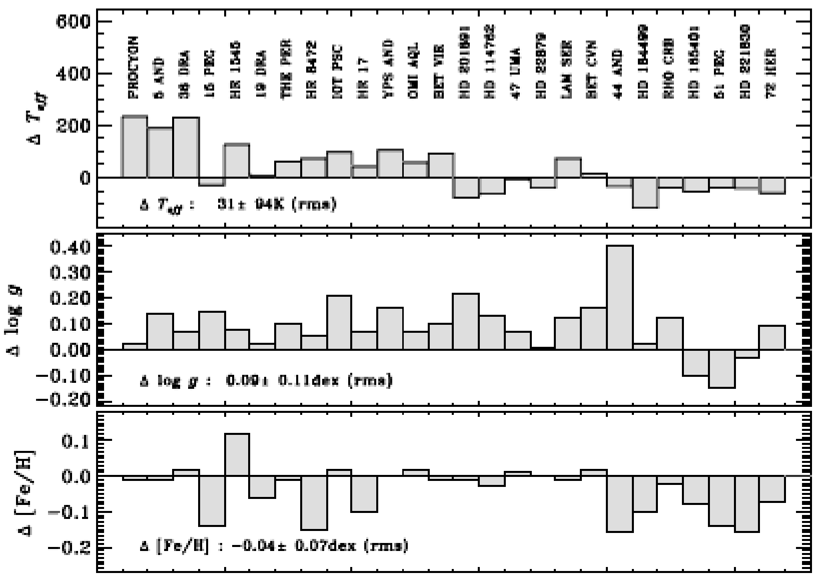
T_{eff} from b-y, $\sigma(T_{eff})$ = 100 K

g from c_1 $\sigma(\log g)$ = 0.1

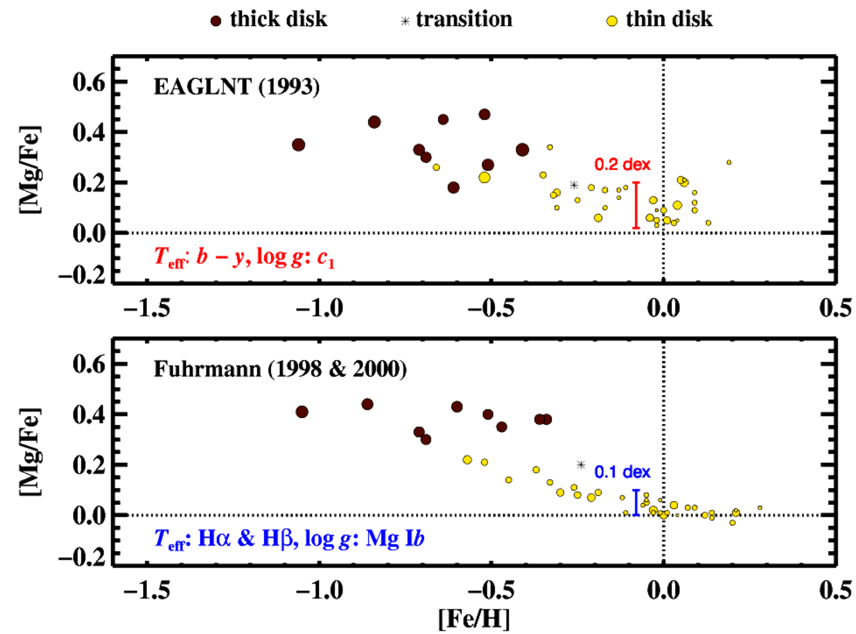
Fuhrmann (1998, 2000)

Hα, Hβ

Mg Ib



Differences in T_{eff}, log g, [Fe/H] between two studies



Spectroscopic stellar parameters lead to smaller scatter of [Mg/Fe]

Uncertainties in derived element abundances

HD 122563 is nearby (d = 237 pc), well studied cool VMP giant:

T_{eff} = 4600±60 K (*Creevey et al.* 2012), log g(Hip) = 1.60±0.07,

[Fe/H] = -2.56±0.07 (*Mashonkina et al.* 2011)

LTE abundances of heavy elements in HD 122563

based on Subaru/HDS spectra

	Honda et al. (2006)	*Mashonkina et al.* (2008)	
T_{eff} =	4570±100	4600±60	
log g =	1.1±0.3 (Fe I/Fe II, LTE)	1.5±0.2 (Hipparcos)	
[Fe/H] =	-2.77±0.19	-2.53±0.07	
log ε(Sr) =	-0.12	0.07	Δlog ε = -0.19
log ε(Ba) =	-1.65	-1.36	-0.29
log ε(Eu) =	-2.77	-2.62	-0.15

Why is Ba/Eu important?

Heavy elements ($Z > 30$) originate from

✓ slow (*s*-) process:

- main component ($A=90-208$), AGB stars of 2-4 M_{sun},
- weak component ($A < 90$), He burning core of $M > 10\ M_{sun}$,

✓ rapid (*r*-) process: SNeII, neutron star mergers ??

Solar System matter, Ba and Eu isotopes

	Lodders2009 (%)	*s*-process (%) A99	*s*-process (%) B11		Lodders2009 (%)	*s*-process A99	*s*-process B11
^{134}Ba	2.4	100	100	^{151}Eu	47.8	6	6
^{135}Ba	6.6	26	30	^{153}Eu	52.2	5	6
^{136}Ba	7.9	100	100				
^{137}Ba	11.2	66	67				
^{138}Ba	71.7	86	94				
Total Ba:		81	88.7	Total Eu		6	6

Significant discrepancy!

Why is Ba/Eu important?

81 to 89% of solar Ba are of *s*-process origin.
94% of solar Eu are of *r*-process origin.

- Solar system matter: log Ba/Eu = 1.66
- Solar system *r*-process (SSr):

r-residuals = SS abundance – *s*-contribution

$\log(\mathrm{Ba/Eu})_r = 0.96$ (**A99**),
0.74 (**B11**).

A99: s-process calculations of *Arlandini et al.* (1999),
B11: *Bisterzo et al.* (2011).

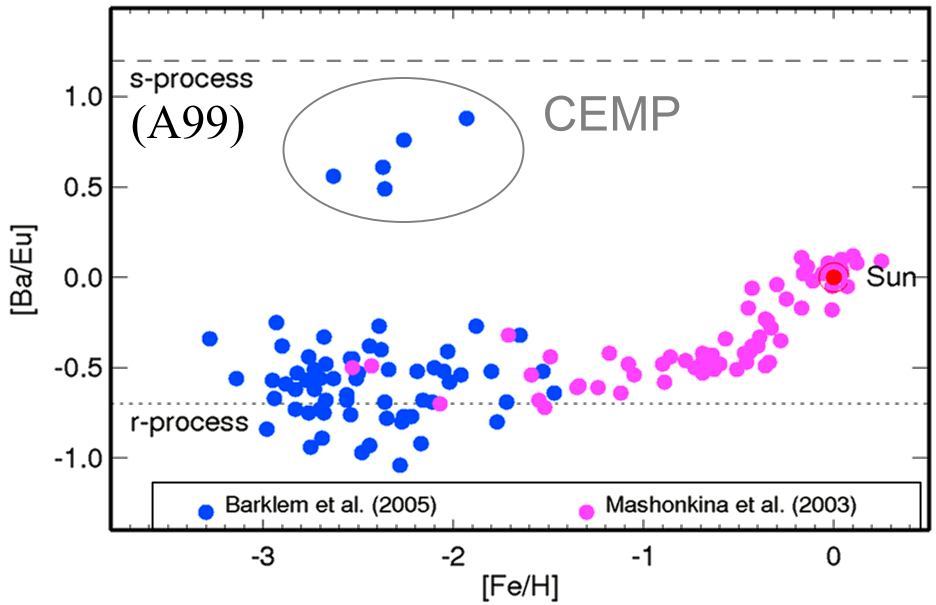
- *r*-process models

$\log(\mathrm{Ba/Eu})_r \approx 1$, WP approximation (*Kratz et al.* 2007),
0.8, HEW (*Farouqi et al.* 2010)

Ba/Eu is sensitive to whether s- or r-process dominated heavy element production

Most MP stars are enriched in Eu

Spite & Spite (1978),
McWilliam (1998), *Mashonkina&Gehren* (2000),
Barklem et al. (2005), *Francois et al.* (2007).



- -3.2 < [Fe/H] < -1 stars form plateau at [Ba/Eu] ≈ -0.6.

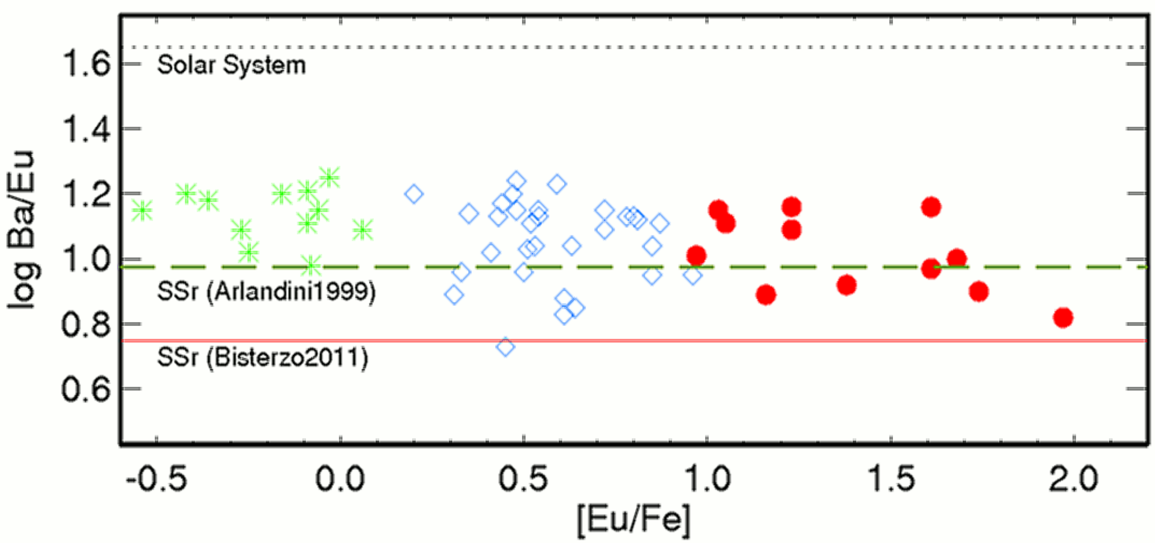
r-process dominated heavy element synthesis

- [Ba/Eu] grows at [Fe/H] > -1.

s-process contribution to Ba

Ba/Eu in [Fe/H] < -1.5 stars with [Ba/Eu] < -0.4

(based on literature data, in total, 14 sources)



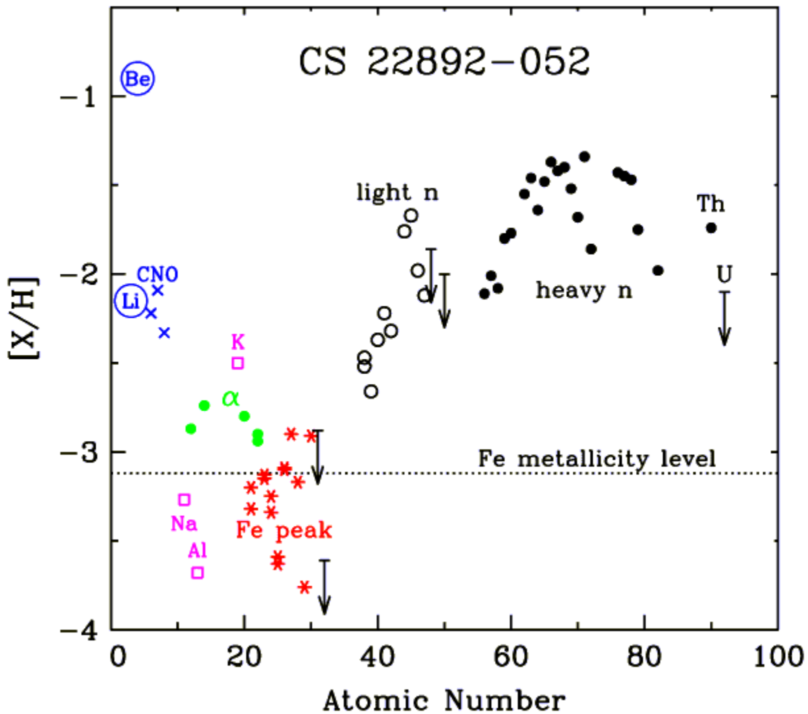
log Ba/Eu ≈ 1,
independent of [Eu/Fe]

●	[Eu/Fe] > 1	r-II	(*Christlieb et al.*, 2004)
◊	[Eu/Fe] = 0.3 – 1	r-I	
*	[Eu/Fe] < 0	Eu-poor	

Is there problem with theoretical predictions
or stellar observed Ba/Eu?

r-II stars are best candidates for learning about *r*-process

✓ First discovery: CS 22892-052
[Fe/H] = -3.1, [Eu/Fe] = 1.63.



30 elements from Sr to Th
were measured

(*Sneden et al.* 1994, 1996, 2003)

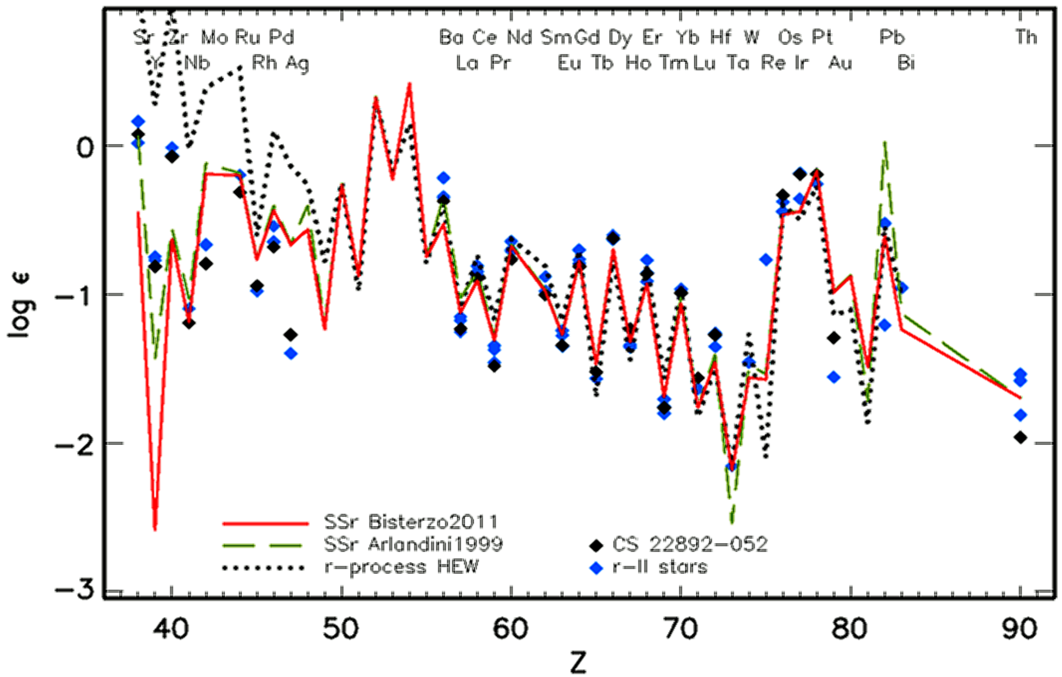
✓ CS 31082-001
2001: detection of U (*Cayrel*, 2001)
2013: 37 elements in Ge-U range
(*Siqueira Mello et al.*, 2013)

✓ r-II: ~ 5 % of stars at [Fe/H] < -2.5
(*Barklem et al.* 2005)

✓ 12 r-II stars were discovered:
-3.4 ≤ [Fe/H] ≤ -2.8,
[Eu/Fe] = 1.0 to 1.9

✓ n-capture element abundances of r-II stars are dominated by influence of single (few) r-process event(s).

Element abundance patterns of r-II stars and SSr



CS 22892-052 (*Sneden*03)
CS 31082-001(*Siqueira Mello*13)
HE 1523-091 (*Frebel*07)
HE 1219-0312 (*Hayek*2009),

they all have [Eu/Fe] > 1.5.

- r-II stars: similar element patterns for Sr-Pt,
  common origin of Sr-Pt in classical r-process.
- SSr: Arlandini99 vs. Bisterzo11
  large differences in Sr, Y due to dominant contribution of s-process,
  notable differences in Ba, La, Ta, Pb.
- r-II stars vs. SSr: similar element patterns for Ba-Hf,
  universal r-process.

Ba and Eu abundances of the r-II stars

need to be revised because

- different papers used different Ba isotope mixture,

- most papers did not take the departures from LTE for Ba II and Eu II into account.

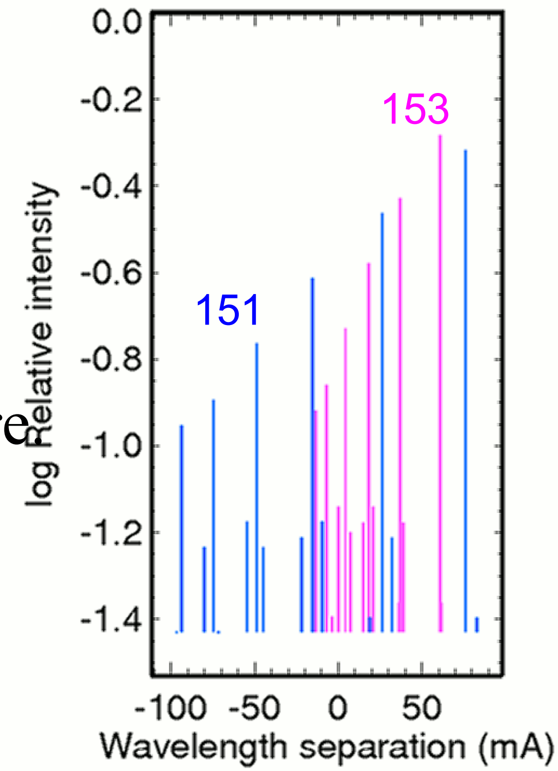
- In odd-atomic mass isotopes, nucleon-electron spin interactions lead to hyper-fine splitting (HFS) of the energy levels.

- Each line of Ba II and Eu II consists of isotopic (IS) and HFS components. They make the line broader resulting in larger absorbed energy.

- HFS and IS effects depend on isotope mixture.

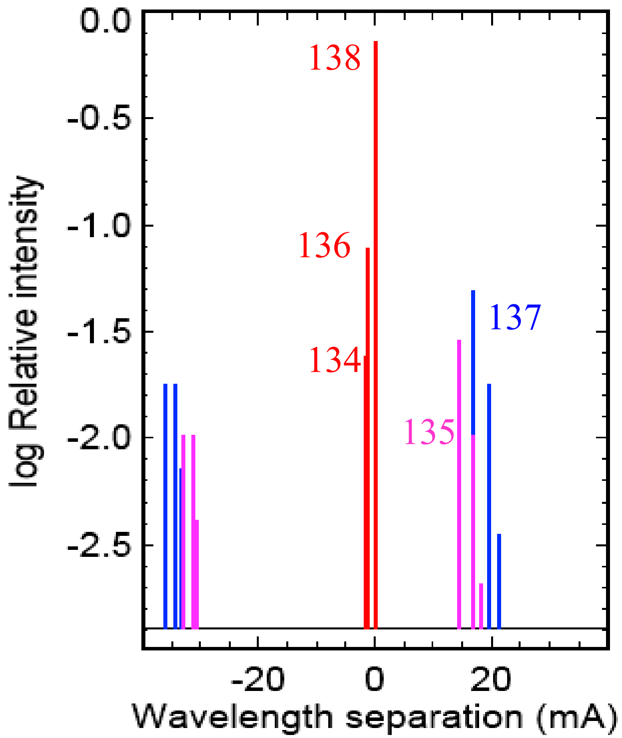
- Eu, two odd-A isotopes.
  SS: ^{151}Eu:^{153}Eu = 48:52,
  r-process: 39:61.
  Minor change in derived abundances between using two isotope mixtures.

- Ba: isotope mixture is different for SS matter and r-process.

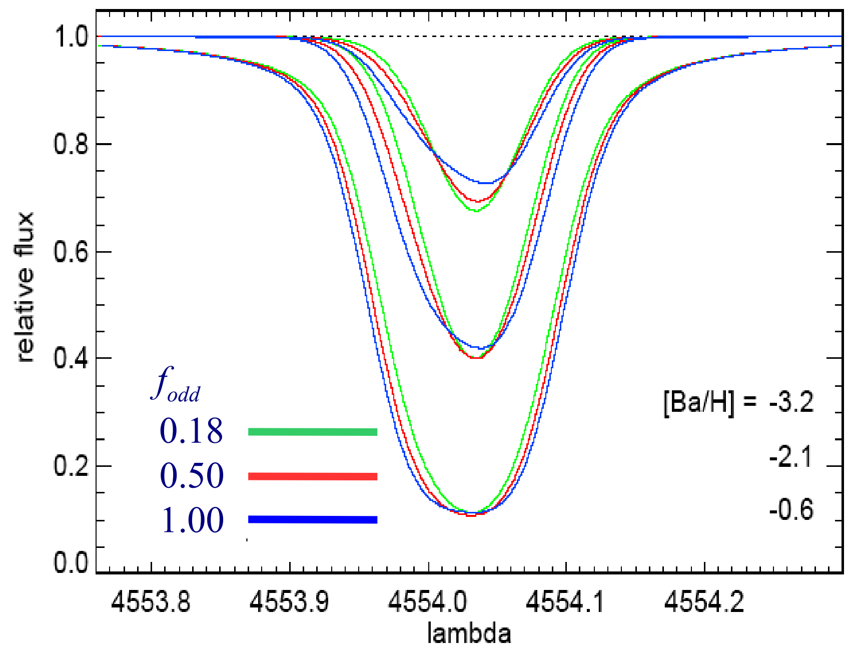


Eu II 4129: isotopic and HFS components. Relative intensities correspond to ^{151}Eu:^{153}Eu = 48:52

HFS and IS effects on derived Ba and Eu abundances



Ba II 4554 Å:
IS and HFS components.
Relative intensities correspond to
SS Ba isotope mixture,
$f_{odd} = 0.18$.



- ✓ The greater f_{odd}, the stronger Ba II 4554 is. Ba abundances derived from resonance lines depend on adopted f_{odd}
- ✓ HFS is negligible for subordinate lines of Ba II.

Effect of using different Ba isotope mixtures for CS 22892-052, 4800/1.5/-3.1

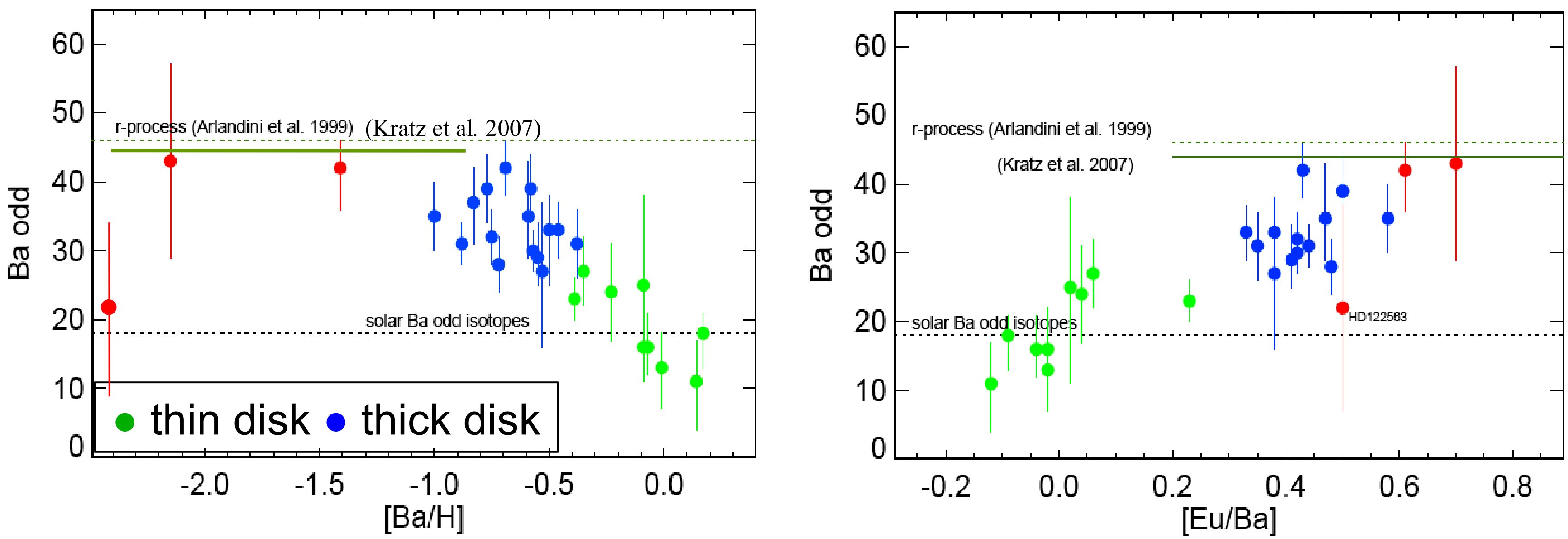
Mean non-LTE abundance (Ba II 4554, 4934 Å)	f_{odd}	
0.03	0.18	(Solar System)
-0.18 ± 0.01	0.46	(A99)
-0.28 ± 0.03	0.66	(B11)
-0.30	0.72	(*McWilliam*, 1998)
-0.20	0.52	(*Sneden et al.* 1996)
(Ba II subordinate lines)		
-0.15 ± 0.02		

Ba abundances of Sneden star favor higher $f_{odd} \approx 0.5$ than solar value.

Stellar f_{odd} can be evaluated from requirement

ε(Ba II resonance lines) = ε(Ba II subordinate lines)

Stellar fractional abundance of odd-A isotopes of Ba



thin disk
thick disk

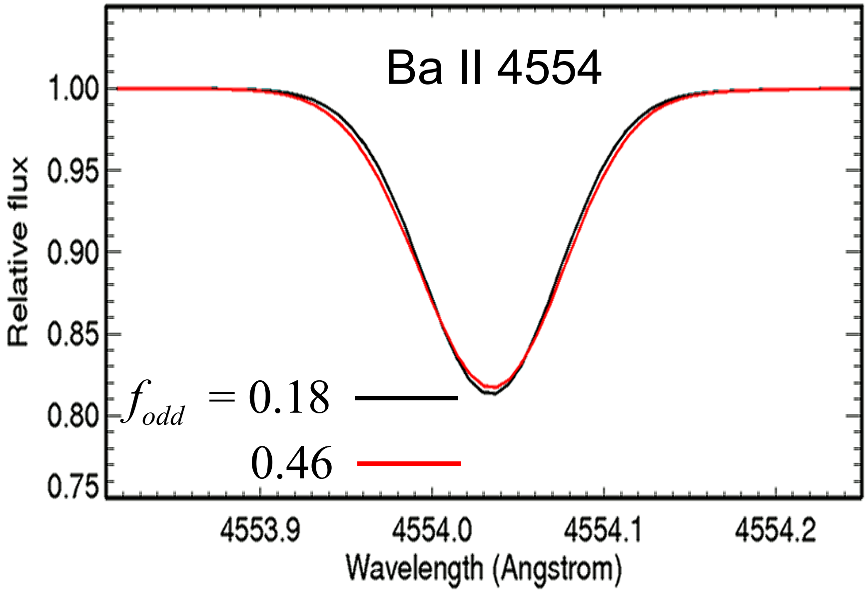
} f_{odd} grows toward lower Ba and higher Eu/Ba

Halo stars:	[Fe/H]	f_{odd}	[Eu/Fe]	[Eu/Ba]	
HD 84937	-2.08	0.43	0.70	0.70	r-I stars
HD 103095	-1.35	0.42	0.56	0.62	r-I stars
HD 122563	-2.54	0.22	-0.51	0.50	Eu-poor

Mashonkina et al. (2006,2008)

Different method is based on
measuring the broadening of Ba II *resonance lines,*
needs very high-quality stellar spectra: $R > 100\,000$, $S/N = 180$ to 1100.

HD 140283: V = 7.2^m, $T_{eff} = 5750$ K, log g = 3.7, [Fe/H] = -2.5



$f_{odd} = 0.08$ (*Magain*, 1995)
0.30±0.21 (*Lambert & Allende Prieto* 2002)
0.15±0.12 (*Collet et al.* 2009)
0.02±0.06 (*Gallagher et al.* 2010)

f_{odd} = 0.18±0.08, 0.08±0.08, -0.02±0.09, -0.05±0.11, -0.12±0.07
for different 5 halo stars (*Gallagher et al.* 2012)

Stellar fractional abundance of odd-A isotopes of Ba

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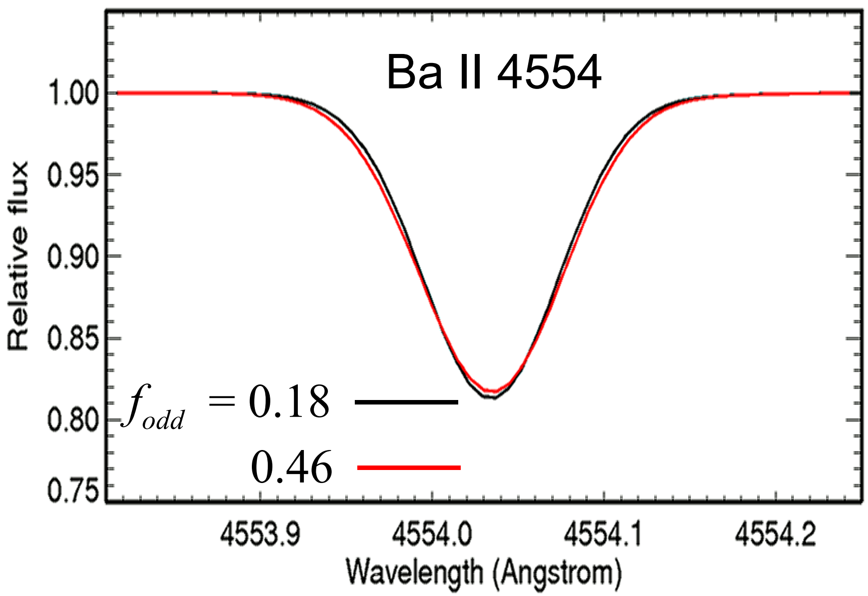


f_{odd} = 0.08 (*Magain*, 1995)

0.30±0.21 (*Lambert & Allende Prieto* 2002)

0.15±0.12 (*Co*

0.02±0.06 (*Ga*

Pure *s*-process:
f_{odd} = 0.11
(*Arlandini*99)

f_{odd} = 0.18±0.08, 0.08±0.08, -0.02±0.09, -0.05±0.11, -0.12±0.07
for different 5 halo stars (*Gallagher et al.* 2012)

Problems and pitfals of f_{odd} determinations

1st approach: Ba II subordinate vs. resonance lines

Precise determination of abundance from individual lines:

- ✓ accurate T_{eff}, log g, microturbulence velocity,
- ✓ non-LTE effects,
- ✓ 3D effects on *abundances* are predicted to be small.

2nd approach: broadening of Ba II resonance lines

Precise measurement of line broadening:

- ✓ accurate star's rotation and macroturbulence velocity, instrumental profile,
- ✓ 3D effects on *line shape* can be significant.

Stellar fractional abundance of odd-A isotopes of Ba

We suspect that f_{odd} is related to
the r-process abundances of the star.

All the r-process enhanced stars,
HD103095, HD 84937, and the selected thick disk stars,
with [Eu/Fe] = 0.24 to 0.70,
reveal high f_{odd}

HD122563 and HD 140283 are Eu-poor,
with [Eu/Fe] = -0.51 and < -0.2,
and reveal low fractions of odd-A isotopes of Ba.

Revision of Ba and Eu abundances of r-II stars

Sources of observational data (spectra, EWs, LTE abundances):

Sneden et al. (1996); *Christlieb et al.* (2004); *Honda et al.* (2004); *Andrievsky et al.* (2009); *Aoki et al.* (2010); *Mashonkina et al.* (2010).

Ba non-LTE abundances:

- Ba II subordinate lines that are nearly free of HFS
  (CS 22892-052, HE 1219-0312, HE 2327-5642, SDSS J2357),
- if only resonance lines are available, two f_{odd} = 0.46 and 0.66
  (CS 22183-031, CS 29497-004),
- from *Andrievsky et al.* (2009)
  (CS 31082-001, CS 22953-003, subordinate and resonance lines, f_{odd} = 0.5).

Eu non-LTE abundances:

- 4 to 10 lines of Eu II in 8 stars.

Non-LTE effects depend on stellar parameters and the line

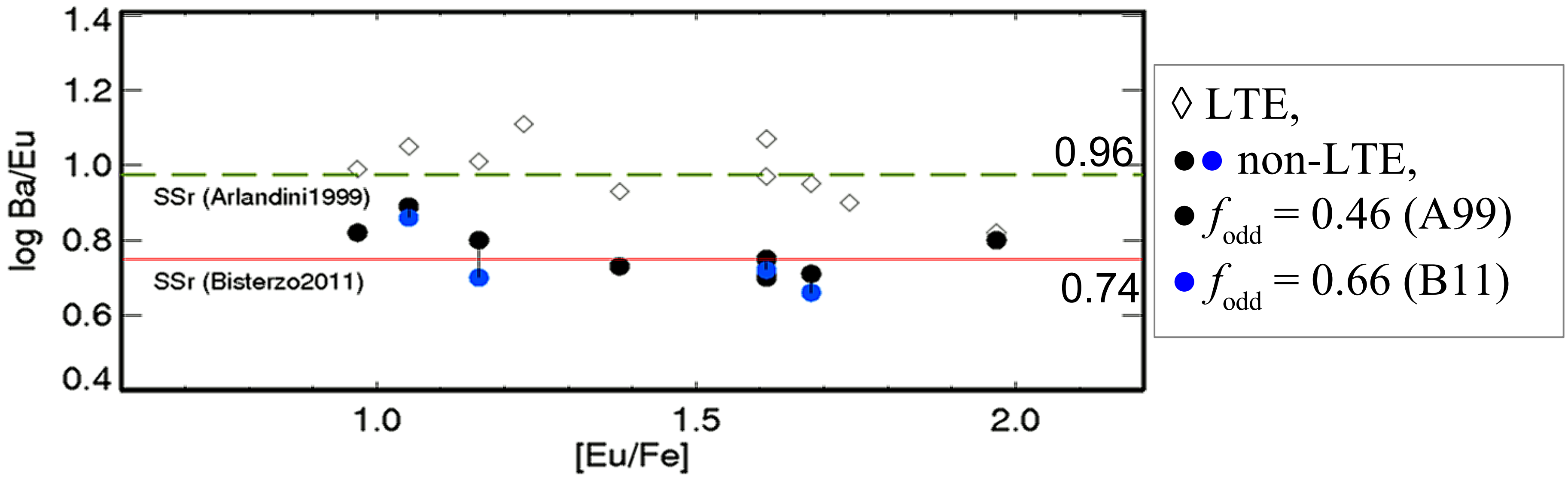
$$\Delta_{NLTE} = \log \varepsilon_{NLTE} - \log \varepsilon_{LTE}$$

T_{eff}/log g/[Fe/H]/[Ba/Fe]		Ba II 4554	5853	6497	[Eu/Fe]	Eu II 4129
4800/1.5/-3/	1.1	-0.13	-0.14	-0.35	1.8	0.06
4800/1.5/-3/	0.7	-0.14	-0.02	-0.22	1.6	0.08
5050/2.3/-3/	0.7	-0.15	0.02	-0.11	1.5	0.10
5010/4.8/-3/	0.7	-0.01	0.01	0.01	1.5	0.03

✓ r-II stars are mostly VMP cool giants.
Non-LTE leads to *lower* Ba, but *higher* Eu abundance.

✓ Exception is VMP dwarf with [Eu/Fe] = 1.9 (*Aoki et al*. 2010).
Non-LTE effects are minor.

Ba/Eu of r-II stars



LTE, mean log Ba/Eu = 0.99 (10 stars)

non-LTE, $f_{odd} = 0.46$ 0.78 (8 stars)

non-LTE, $f_{odd} = 0.66$ 0.75

For 4 stars, Ba abundances depend on used Ba isotope mixture.

Ba/Eu non-LTE ratios of the r-II stars support

- ✓ updated solar r-process log $(Ba/Eu)_r = 0.74$ (*Bisterzo et al.* 2011)
- ✓ HEW r-process model log $(Ba/Eu)_r = 0.8$ (*Farouqi et al.* 2010)

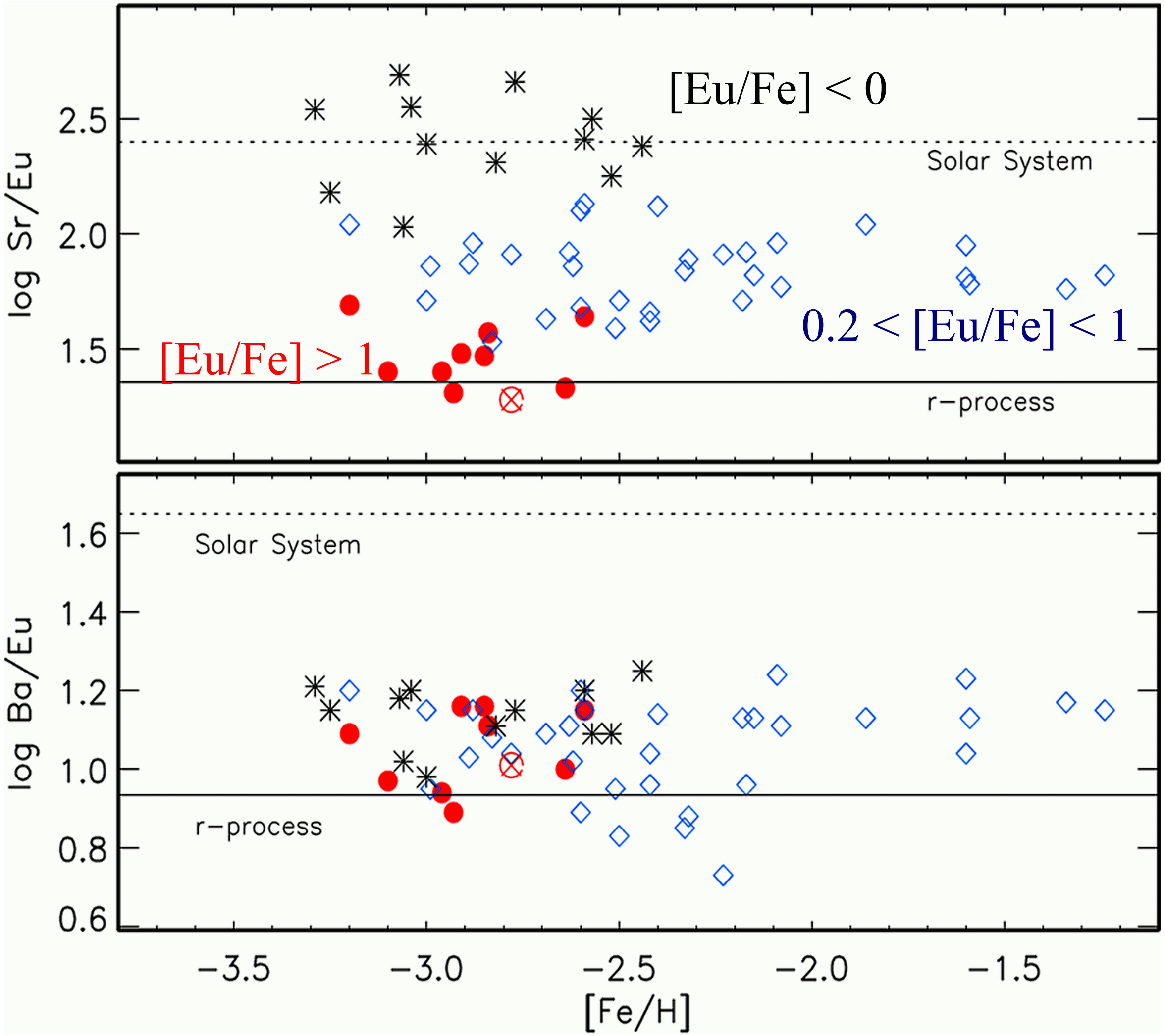
Mashonkina & Christlieb (2014, A&A, submitted)

Concluding remarks

- When deriving element abundances,
  take care of high-quality star's spectrum,
  accurate stellar parameters,
  adequate atmosphere and line-formation modelling.

- Revised Ba/Eu abundance ratios of the r-II stars favor chemical evolution calculations of *Bisterzo et al.* (2011) and HEW r-process model by *Farouqi et al.* (2010).

- For constraining r-process models, it would be important to determine fraction of the odd isotopes of Ba in the r-II stars.



Sr/Eu

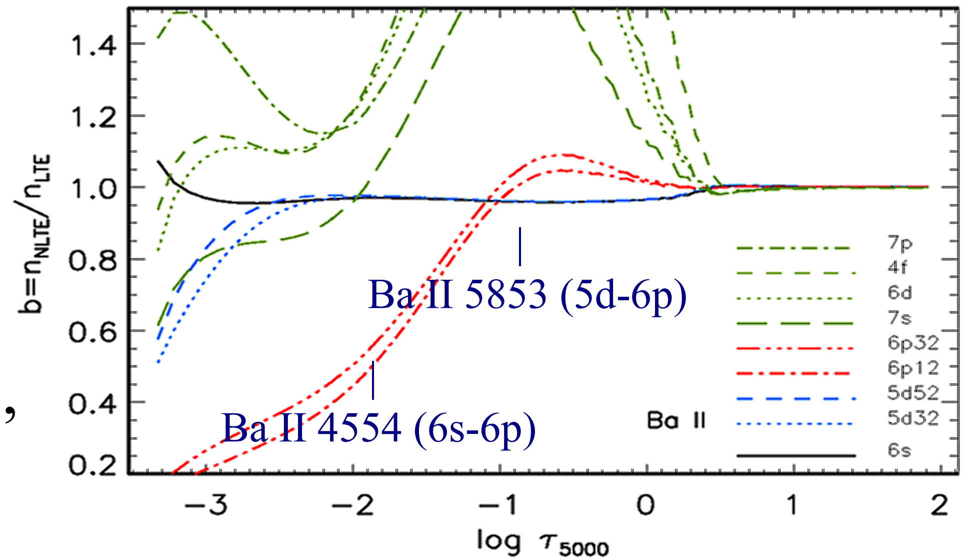
and

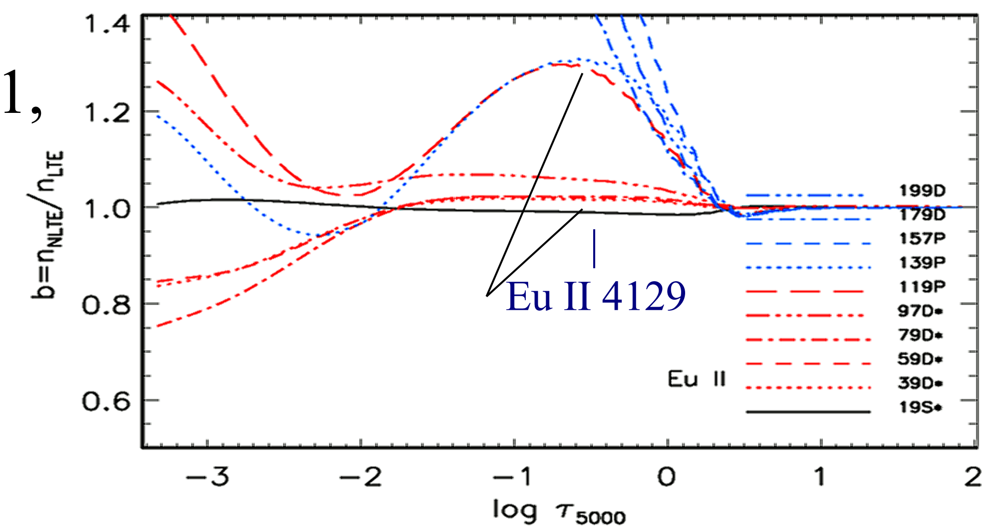
Ba/Eu
in metal-poor stars

Mashonkina et al. (2010)

Departure coefficients
$b = n_{NLTE}/n_{LTE}$
for Ba II and Eu II
in 4800/1.5/-3 model

- Ba II 4554: b(6s) ≈ 1, b(6p) < 1, line is strengthened, with non-LTE abundance correction Δ_{NLTE} = -0.14 dex.
- Ba II 5853: b(5d) ≈ 1, b(6p) ≈ 1, Δ_{NLTE} = -0.03 dex.
- Eu II 4129: b_{low} ≈ 1, b_{up} > 1 line is weakened, Δ_{NLTE} = +0.10 dex.





Mashonkina et al. (2013, in prep)

Method of calculations

- Non-LTE populations for Ba II and Eu II:
  - model atoms and atomic data from *Mashonkina et al.* (1999), *Mashonkina* (2000, updated)
  - code DETAIL by *Butler & Giddings* (1985) with updated opacity package.
- Spectral line synthesis: code SIU by *Reetz* (1991).
- Model atmospheres: MARCS (*Gustafsson et al.* 2008)