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Non-LTE line formation for Pb I and Th II in cool stars

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Outline of this talk

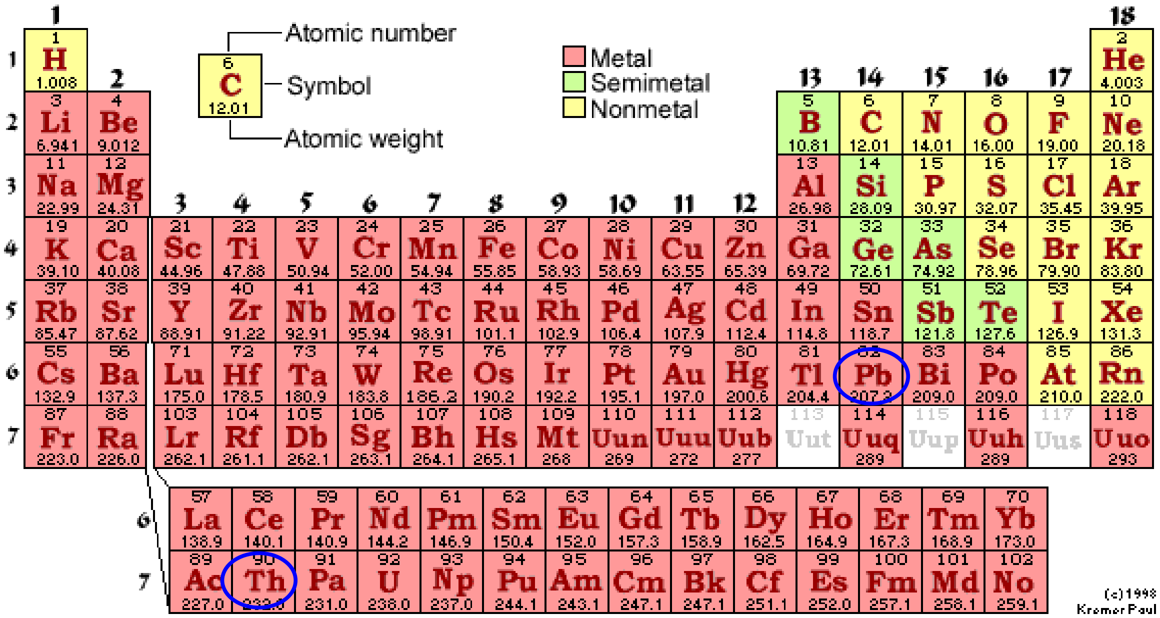
- ✶ Introduction.
  - Why to study Pb and Th in metal-poor stars?
  - What is non-LTE?
- ✶ Non-LTE modelling for Th II.
- ✶ Non-LTE modelling for Pb I.
- ✶ Solar Pb abundance.
- ✶ Pb abundances of metal-poor stars.

Cool star: $T_{\mathrm{eff}} = T_{Sun} \pm 1000$ K, low-mass, long-lived,
preserves on its surface initial chemical composition,
[Fe/H] = +0.5 to -5.5.

$[X/Y] = \lg n(X)/n(Y) - \lg n(X)/n(Y)^{\mathrm{sun}}$

Metal-poor star: [Fe/H] < -1,
old, age ≥ 10 Gyr (*Freeman & Bland-Hawthorn*, 2002).

Why to study Pb and Th in metal-poor stars?



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc 98.91	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	71 Lu 175.0	72 Hf 178.5	73 Ta 180.9	74 W 183.8	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po 209.0	85 At 210.0	86 Rn 222.0
7	87 Fr 223.0	88 Ra 226.0	103 Lr 262.1	104 Rf 261.1	105 Db 262.1	106 Sg 263.1	107 Bh 264.1	108 Hs 265.1	109 Mt 268	110 Uun 269	111 Uuu 272	112 Uub 277	113 Uut	114 Uuq 289	115 Uup	116 Uuh 289	117 Uus	118 Uuo 293

6	57 La 138.9	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm 146.9	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0
7	89 Ac 227.0	90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np 237.0	94 Pu 244.1	95 Am 243.1	96 Cm 247.1	97 Bk 247.1	98 Cf 251.1	99 Es 252.0	100 Fm 257.1	101 Md 258.1	102 No 259.1

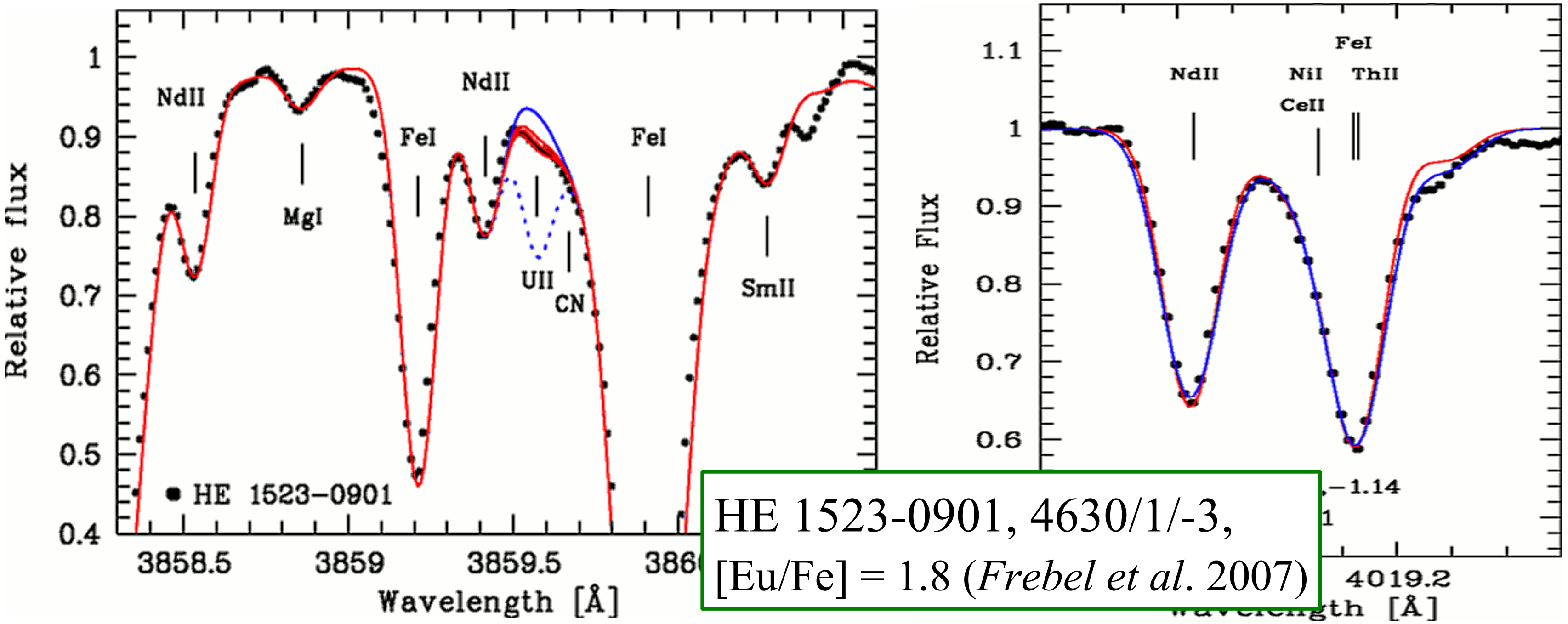
Pb, Z = 82
Th, Z = 90
U, Z = 92

} Heaviest elements observed in MP stars.

Bi: in one MP star,

Po-Pu: radioactive, halflives < 1 Gyr except Th and U.

Nucleocosmochronometry with Th and U



HE 1523-0901, 4630/1/-3,
[Eu/Fe] = 1.8 (*Frebel et al*. 2007)

- U abundance was measured in only 3 stars.

Star age from abundances of Th and stable element (r) produced together with Th in r-process:

$$\Delta t = 46.78 \{ \log (\mathrm{Th/r})_{\mathrm{initial}} - \log \varepsilon(\mathrm{Th/r})_{\mathrm{now}} \} \text{ Gyr}$$

$\Delta \log \varepsilon(\mathrm{Th}) = 0.05$ dex → uncertainty of 2.3 Gyr
for the star age !

- Pb in MP stars as indicator of the onset of the s-process in AGB stars.

Solar Pb
s : r = (91-62) : (9-38), most s-nuclei originate from AGB stars with [Fe/H] = -1
(*Gallino et al.* 1998; *Travaglio et al.* 2001).

- Pb in VMP r-II stars tell about initial Th and U (?)

r-II stars: [Eu/Fe] > 1, [Ba/Eu] < 0 (*Beers & Christlieb,* 2005)

r-II star: present day Pb	=	Initial Pb: β^-, β and α decays of short-lived $A \geq 206$ nuclei	+	Accumulated Pb: decays from long-lived Th and U nuclei
Waiting-point r-process (*Roederer et al.* 2009)		82 %		18 % (13 Gyr)

This study aims

- ✓ to evaluate systematic abundance errors connected with simplified line formation treatment for Th II and Pb I,

- ✓ to improve observational data for testing nucleosynthesis theories.

What is meant by *non-local thermodynamic equilibrium* (non-LTE) ?

- Maxwellian velocity distribution, $T_\mathrm{e} = T_\mathrm{A} = T_\mathrm{i}$,
- n_i from balance between various population and de-population processes:
    - photoexcitation, ▪ photoionization and their inverse,
    - inelastic collisions with electrons, atoms, molecules,
    - dielectronic recombination, ▪ charge exchange.

$$\boxed{dn_i/dt = 0}$$

$$\left\{\begin{aligned} & n_i \sum_{j \neq i} (R_{ij} + C_{ij}) = \sum_{j \neq i} n_j (R_{ji} + C_{ji}) \qquad i = 1, \ldots, NL. \\ & \mu \frac{dI_\nu(z,\mu)}{dz} = -\chi_\nu(z) I_\nu(z,\mu) + \eta_\nu(z) \end{aligned}\right.$$

Statistical equilibrium equations for *NL* levels in model atom.

Radiation transfer equations at frequencies of all transitions

Radiative rate $R_{ij}(J_\nu)$, collisional rate $C_{ij}(T,N_e)$.

	Non-LTE:	LTE:
at any depth point	$\boxed{n_i = F(T_1,p_1,T_2,p_2, \ldots, T_{ND},p_{ND})}$	$\boxed{n_i = f(T, p),}$
calculations	☹ bulky (combined SE + RT equations),	☺ simple (Saha-Boltzmann equations),
atomic data	☹ a lot, ☹ missing data,	☺ for single line.
validity	☺ correct description of line formation.	☹ not fulfilled in line formation layers.

Non-LTE modelling for Th II

Th II is a majority species

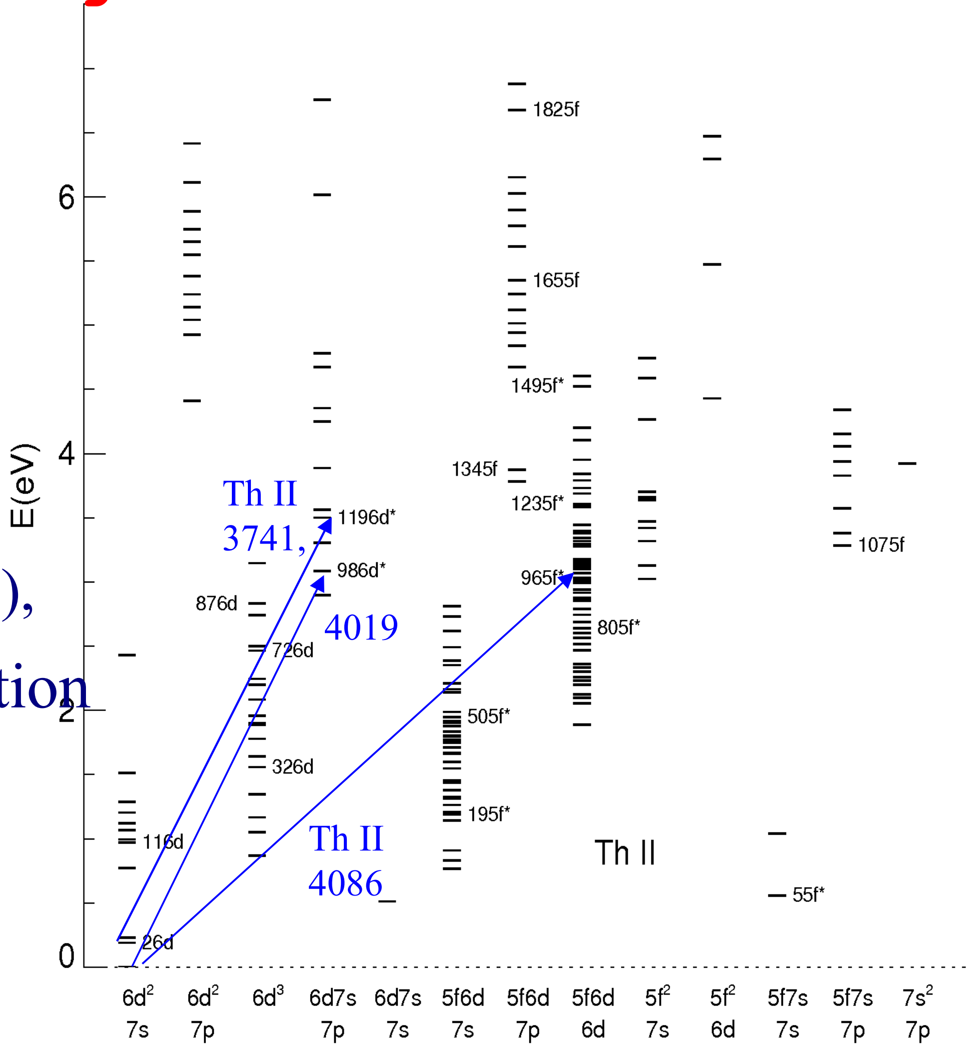
at $T_{\mathrm{eff}} = 4500 - 6000$ K.

Input atomic data

- transition probabilities:
  measured (*Nilsson et al.* 2002),
  calculated (*Kurucz & Bell*, 1995),
- collision excitation and ionization
  by electrons and H atoms,
- hydrogenic photoionization
  cross-sections.

Code DETAIL

(*Butler & Giddings* 1985, updated)

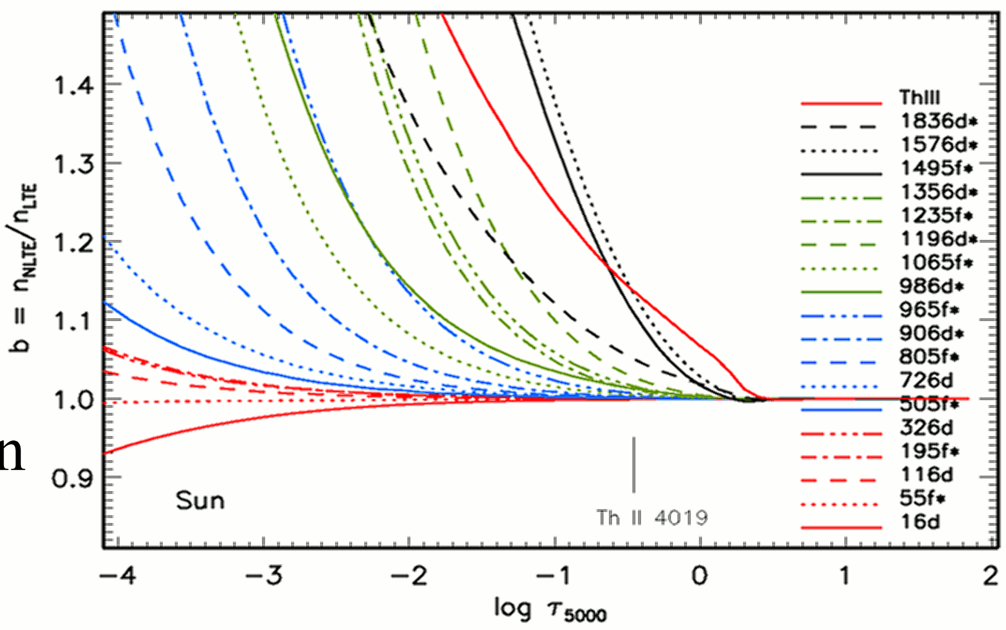


- Model atom of Th II based on 416 levels from *Blaise & Wyart* (1992)

Departure coefficients for Th II in solar and 4500/1/-3 models.

- b(E_{exc} = 0-2.5 eV) = 1,
- b(E_{exc} > 2.5 eV) > 1

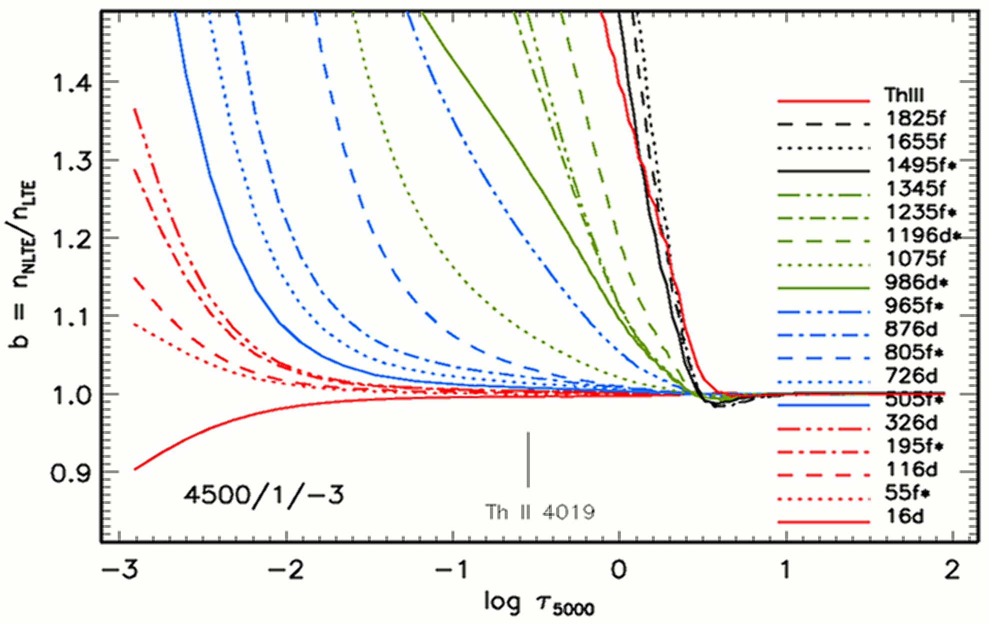
due to enhanced photoexcitation from the E_{exc} = 0-1 eV levels.



Th II lines:

- b(*low*) = 1,
- b(*up*)/b(*low*) > 1 → $S_\nu > B_\nu(T)$

NLTE leads to weaker Th II lines and positive abundance corrections.



Non-LTE abundance correction, $\Delta_{NLTE} = \log \varepsilon_{NLTE} - \log \varepsilon_{LTE}$ $\leq$ 0.15 dex for Th II lines when inelastic collisions with H atoms are included.

Δ_{NLTE}(Th II 4019)

	$S_H = 0$	0.1	1
5780/4.44/0	0.06	0.01	0.0
4500/1.0/-2		0.12	
4500/1.5/-2		0.07	
4500/1.0/-3	0.52	0.12	0.03
4500/1.5/-3		0.07	

S_H - scaling factor to Drawin formula,

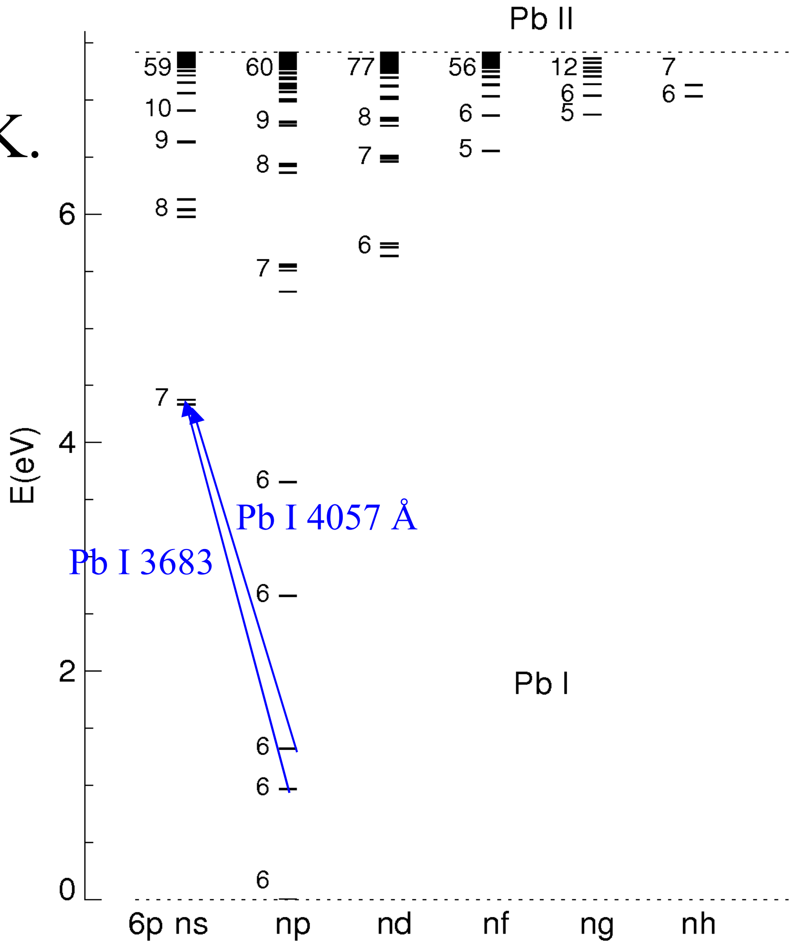
$S_H = 0$ – pure electronic collisions

Non-LTE modelling for Pb I

Pb I is minority species at $T_{\mathrm{eff}} \geq 4500$ K.

Input data

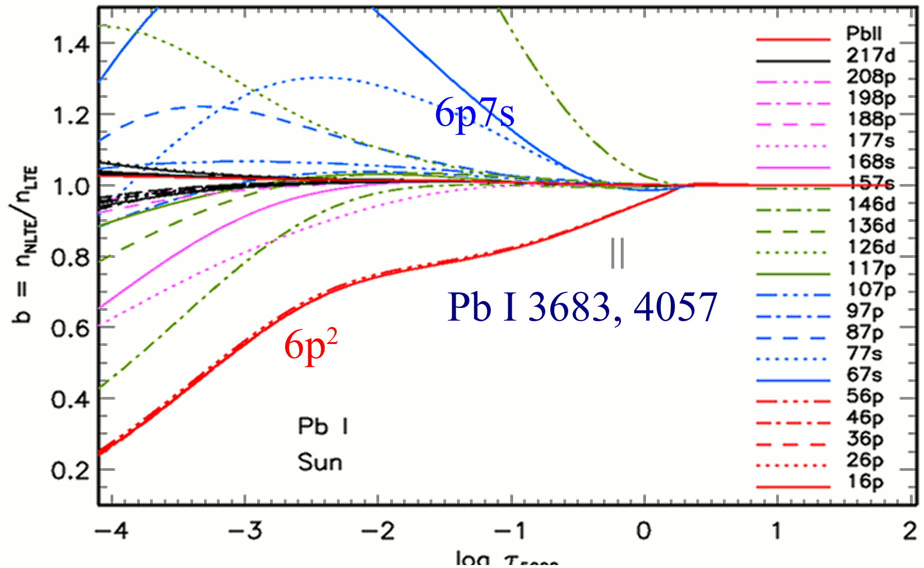
- model atom: 97 levels of Pb I + Pb II,
- photoionization cross-sections:
  measured (the ground state) and
  hydrogenic approximation,
- transition probabilities:
  measured (*Biemont et al.* 2000) and
  calculated (*A. Ryabtsev*, 2010),
- collisional excitation and ionization
  by electrons and H atoms.



Energy levels of Pb I
(*Wood & Andrew*, 1968;
Brown et al. 1977,
Hasegawa & Suzuki, 1996)

Departure coefficients for Pb I in solar and 4500/1/-3 models:

- 6p^2 leves: b < 1 due to UV overionization.
- b(6p7s) > b(6p^2) due to radiative pumping.



6p7s

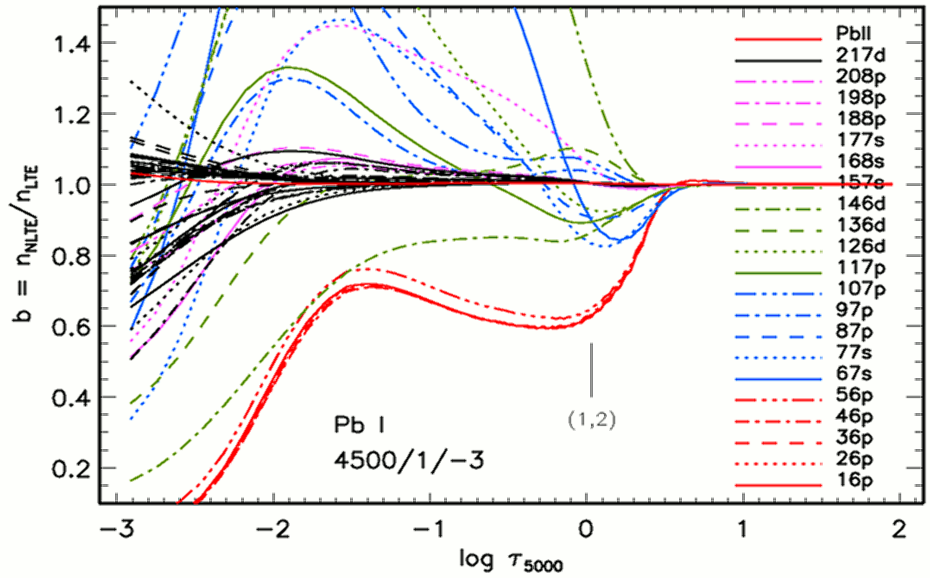
Pb I 3683, 4057

6p^2

Pb I 3683, 4057 Å

- b(*low*) < 1,
- b(*up*)/b(*low*) > 1

$$\rightarrow\ S_\nu > B_\nu(T)$$



Non-LTE leads to weaker Pb I spectral lines and positive abundance corrections.

$\lg \varepsilon(X) = \lg n(X)/n(H) + 12$

Solar Pb abundance

$T_{\rm eff}/\log g$ = 5780/4.44, *MARCS model*, ξ_t = 0.9 km/s

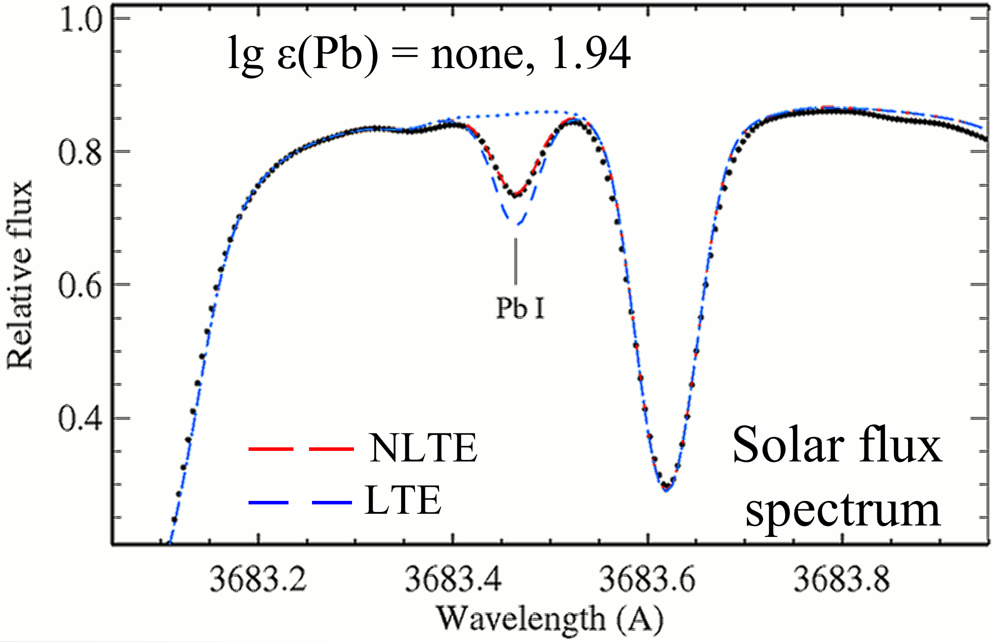
log ε(Pb I 3683 Å) =

NLTE, $S_H = 0$ 1.99,

NLTE, $S_H = 0.1$ 1.94,

$S_H = 1$ 1.87,

LTE 1.78.



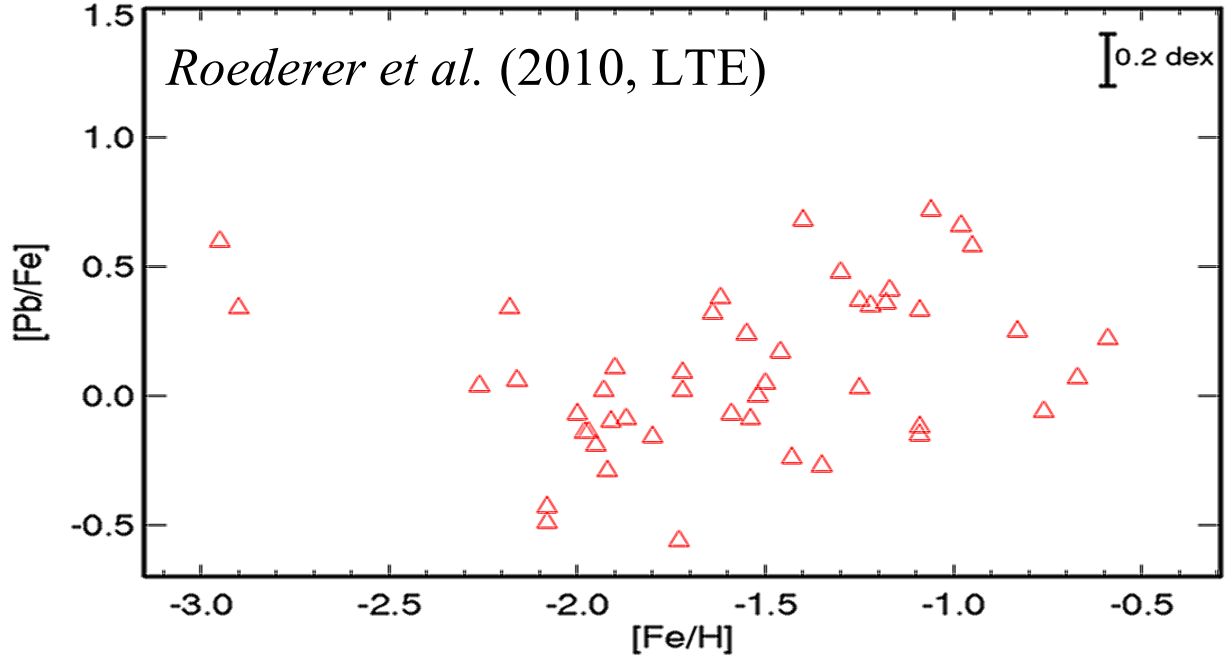
Other studies, LTE, Pb I 3683: 1.75±0.10 (*Asplund et al*. 2009),

2.00±0.06 (*Lodders et al*. 2009)

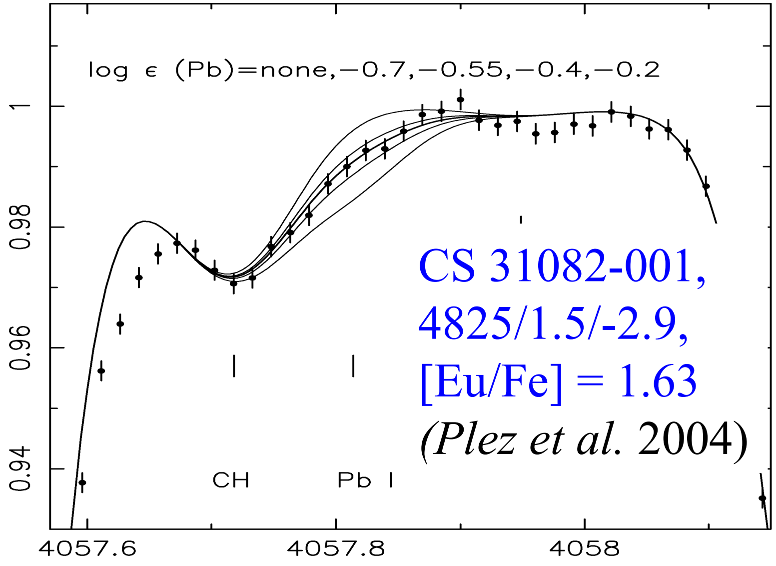
Meteoritic Pb: 2.06±0.03 (*Lodders et al*. 2009)

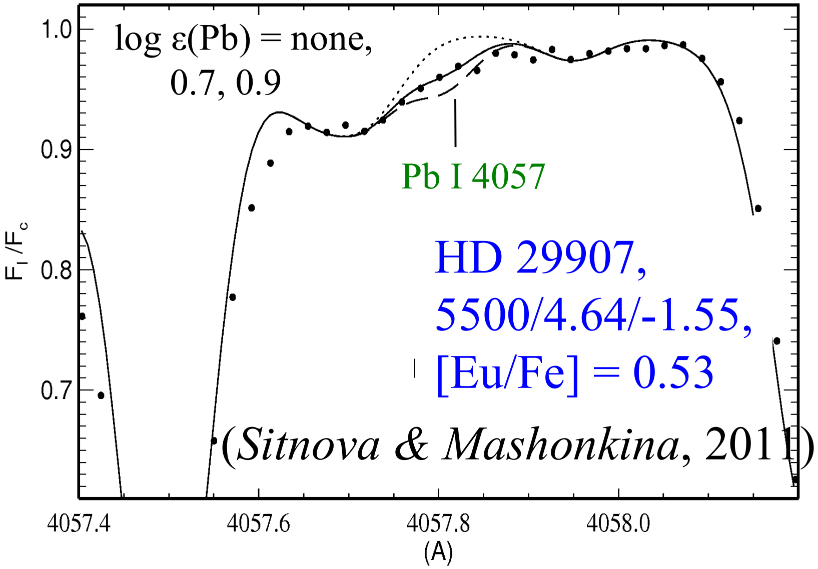
Non-LTE reduces discrepancy between solar and meteoritic Pb abundances

Stellar Pb abundances



Scatter of data -
  real cosmic?
  observational errors?
  stellar parameters?



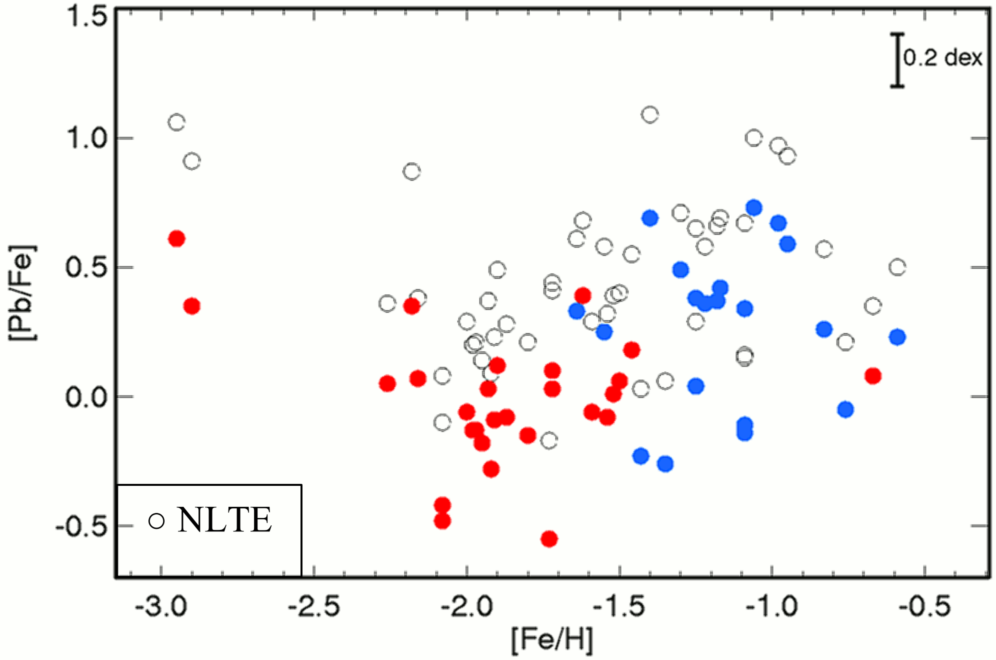


Non-LTE effects on stellar Pb abundances

Non-LTE correction
grows toward lower [Fe/H],
lower lg g,
higher $T_{\rm eff}$

$\Delta_{\rm NLTE}$(Pb I 4057, $S_{\rm H}$ = 0.1) =

+0.16	5500/4.5/0
+0.33	5500/4.5/-1.5
+0.31	4500/1.0/-2
+0.41	4500/1.0/-3



LTE [Pb/Fe] - [Fe/H] from
Roederer et al. (2010):
● lg g < 3,
● lg g > 3.
Non-LTE: less steep upward
trend at [Fe/H] > -2.3.

Empirical constraining a pure r-process Pb/Eu ratio ?

Roederer et al. (2010), LTE

- ✓ -2.3 < [Fe/H] < -1.4: Pb/Eu shows no upward trend, *no production* of Pb by AGB stars.
- ✓ [Fe/H] > -1.4: Pb/Eu grows, s-process is *at work*.

Non-LTE

- ✓ -2.3 < [Fe/H] < -1.4: log Pb/Eu = 1.26±0.25,
- ✓ two r-II stars, log Pb/Eu = 0.67.

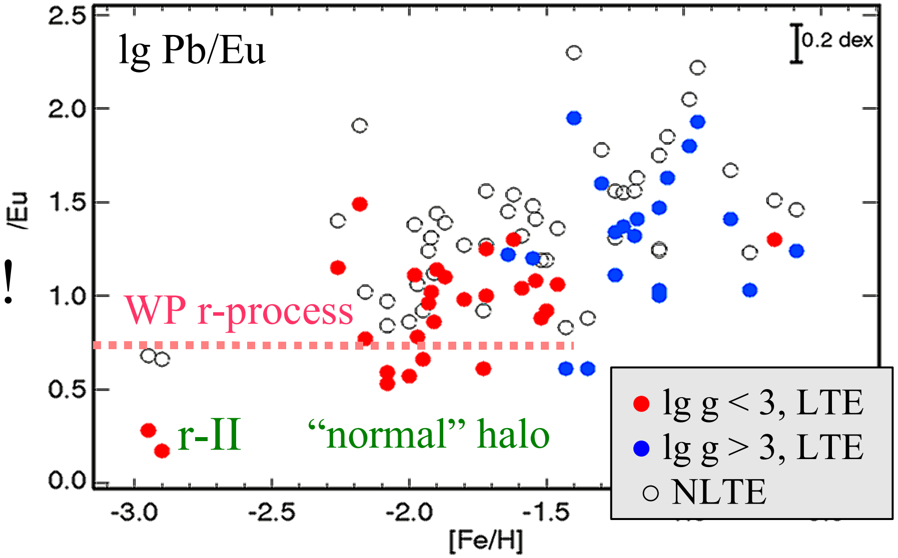
Non-LTE for
Eu II according
to *Mashonkina*
(2000, updated)

Waiting-point r-process:
log Pb/Eu = 0.61 - 0.7
(*Roederer et al.* 2009)

Δ("normal" halo - r-II) = 0.6 dex!

? s-nuclei of Pb at [Fe/H] < -2

? multiple r-processes



Conclusions

Non-LTE leads to

- weaker Pb I spectral lines and positive abundance corrections,

  $\Delta_{\mathrm{NLTE}}(\mathrm{Pb\ I}\ 4057,\ S_{\mathrm{H}} = 0.1) = 0.16 – 0.56$ dex

  depending on stellar parameters,
- consistent solar and meteoritic Pb abundance,
- weaker Th II spectral lines and positive abundance corrections, $\Delta_{\mathrm{NLTE}}(\mathrm{Th\ II}\ 4019,\ S_H = 0.1) = 0.01 - 0.15$ dex.
- Non-LTE Pb/Eu in two r-II stars support the WP r-process predictions of K.-L. Kratz (in *Roederer et al.* 2009).

? What is the source of discrepancy (0.6 dex!) in Pb/Eu between r-II and “normal” halo stars?