Non-LTE line formation for trace elements in stellar atmospheres,
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Departures from LTE in cool stars

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Modelling of the spectra of late-type stars requires quite a different approach.

- Convection is important.

  See *Asplund M.* 2005, ARAA, 43, 481

  for a review of non-LTE and 3D effects.

- The chromosphere is a characteristic of the Sun and probably of most late-type stars.

  E. g., non-LTE + the chromosphere

  explain the formation of the core of solar H_α

  (*Przybilla & Butler*, 2004).

Here, only the lines of a pure photospheric origin are discussed.

Non-LTE line formation
in the atmospheres of cool stars was studied for

H I	He								
Li I	Be II	B I	C I	N I	O I	F	Ne		
Na I	Mg I,II	Al I	Si I	P	S I	Cl	Ar		
K I	Ca I,II	Sc	Ti	V	Cr	Mn I	Fe I,II	Co	Ni
Cu I	Zn I	Ga	Ge	As	Se	Br	Kr		
Rb	Sr II	Y	Zr II	Nb	Mo	Tc	Ru	Rh	Pd

……

Cs Ba II … Eu II

Problems in non-LTE modelling: Fe I

Fe is one of the most important elements in astrophysics.

Fe I/Fe II → log g; the Fe I excitation balance → T_{eff}

Non-LTE studies.

Athay & Lites (1972),
Boyarchuk et al. (1985),
Steenbock (1985),
Takeda (1991),
Holweger (1996),
Shchukina et al. (1997),
Gratton et al. (1999),
Thevenin & Idiart (1999),
Gehren et al. (2001)

The main non-LTE effect for Fe I is overionization.

But there is not a consensus on the magnitude of these effects.

E.g. for [Fe/H] = -3, Δ_{NLTE}(Fe I) varies between ~0 and 0.3 dex.

An adjustment of log g may be up to +0.8 dex!

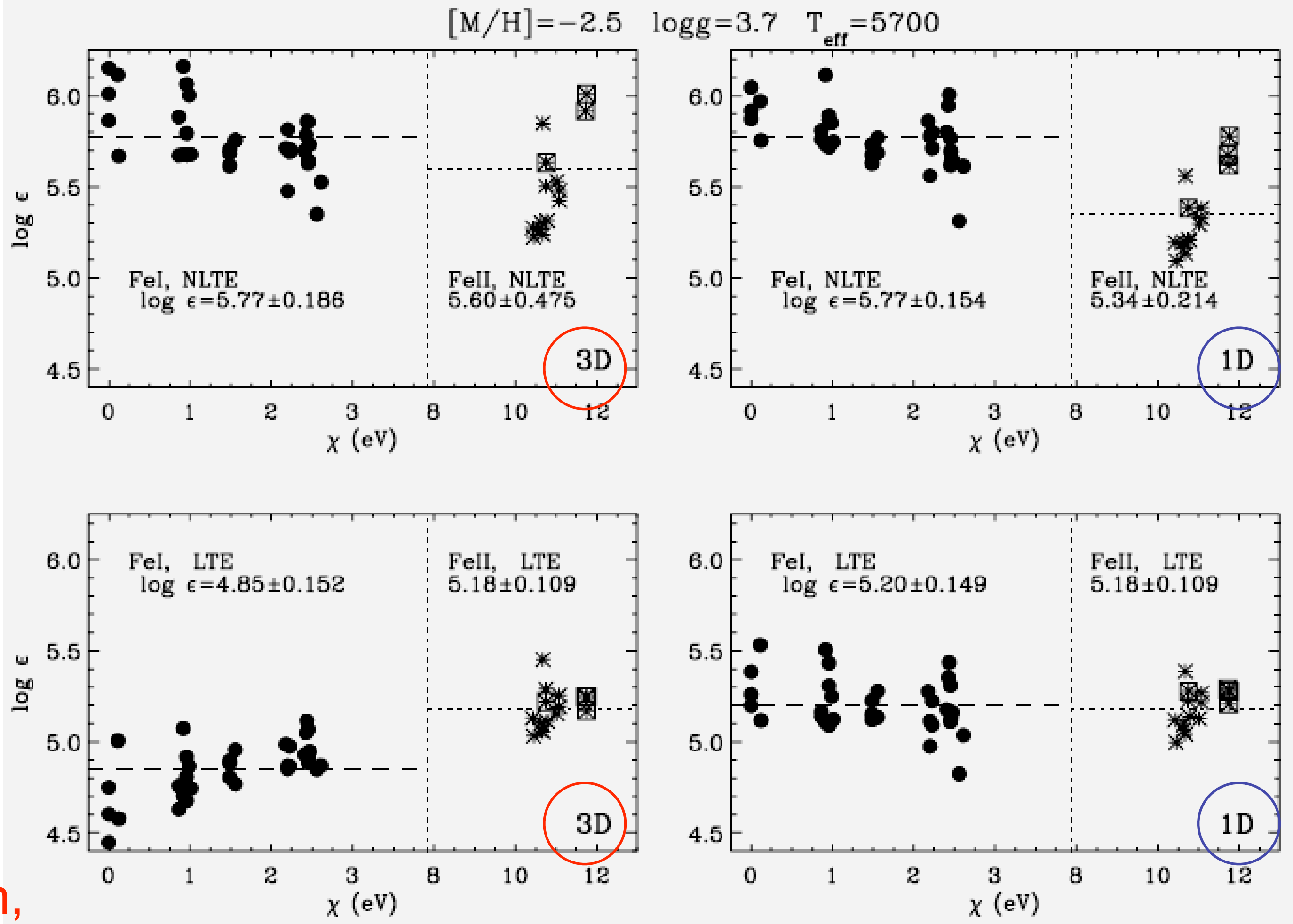
One example of non-LTE calculations in 3D and 1D atmospheres.

HD 140283 *(Shchukina et al. 2005)*

NLTE + 3D:

log ε (Fe I) = 5.77 ± 0.19 (≈30 lines),

log ε (Fe II) = 5.60 ± 0.48 (≈10 lines)



Where do the problems come from?

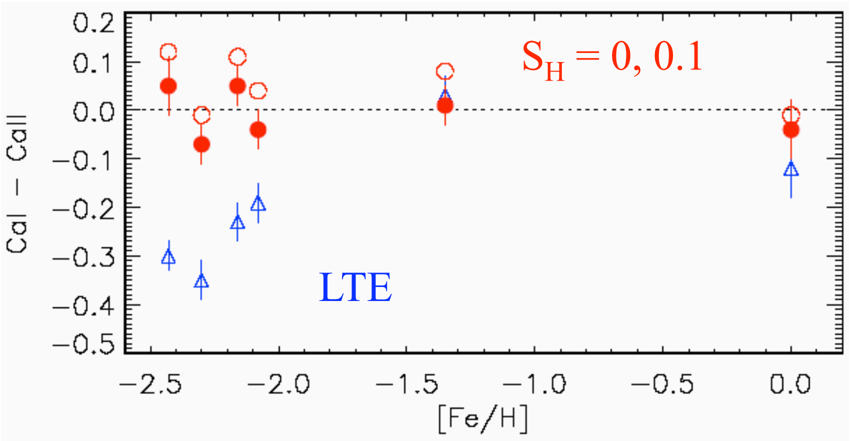
? Incompleteness of the model atom,

? Photoionization cross sections,

? Hydrogenic collisions.

Ca I/II non-LTE line formation

I. CaI/CaII ionization equilibrium in the Sun and 5 selected metal-poor stars *(Mashonkina, Korn, & Przybilla 2007)*

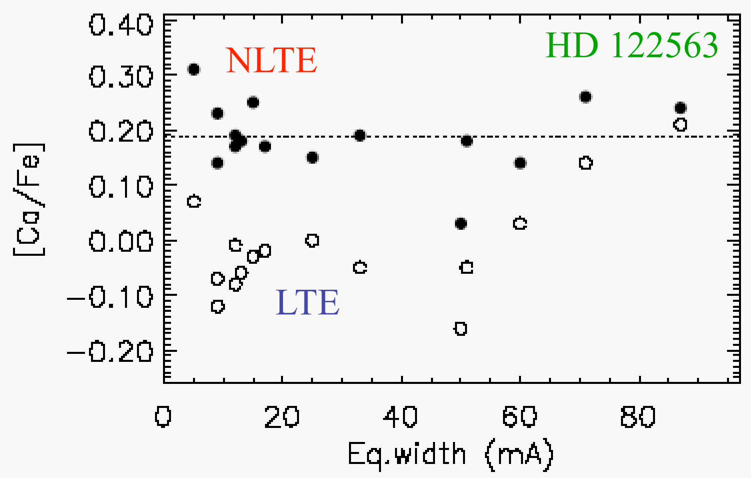


Non-LTE works!
log g *from the* Ca I/II *ionization equilibrium.*

Star	log g (Hip)	$(\text{CaI - CaII})_{LTE}$	log g (Sp)	age
HD 122563 (4600K / -2.51)	1.5±0.2	-0.34	1.5±0.2	
BD +3º 740 (6340K / -2.65)	4.18±0.2	-0.40	3.90±0.15	14.9 Gyr
BD -13º 740 (6390K / -2.66)	-	-0.46	3.88±0.15	13.0 Gyr

(*Mashonkina, Zhao, Gehren, et al.* 2007)

Non-LTE removes the trend of the [Ca/Fe] values with line strength obtained in LTE above W_λ = 60Å.



log g *from the* Ca I/II *ionization equilibrium*.

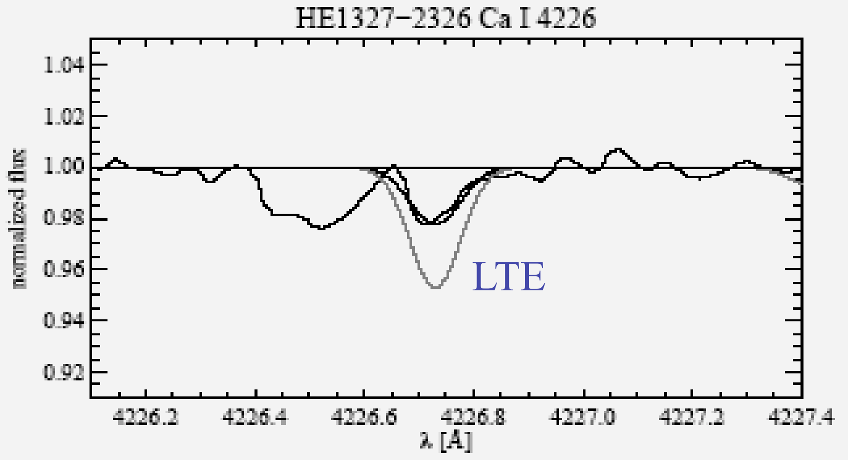
HE1327-2326

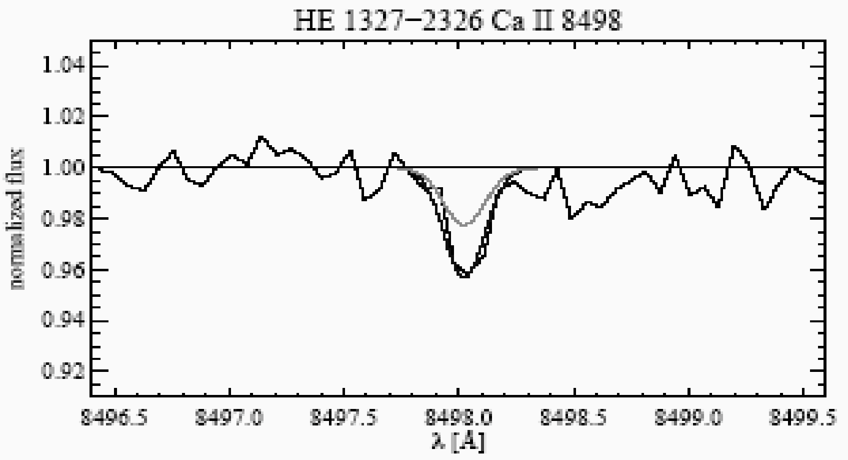
T_{eff} = 6180 K, [Fe/H] = -5.45,

? log g ≈3.7 or ≈4.5,

LTE, (CaII – CaI) > 0.5 dex

(*Aoki, Frebel, Christlieb, et al.* 2006).





log g = 3.7 from

NLTE Ca I(4226) /Ca II(8498)

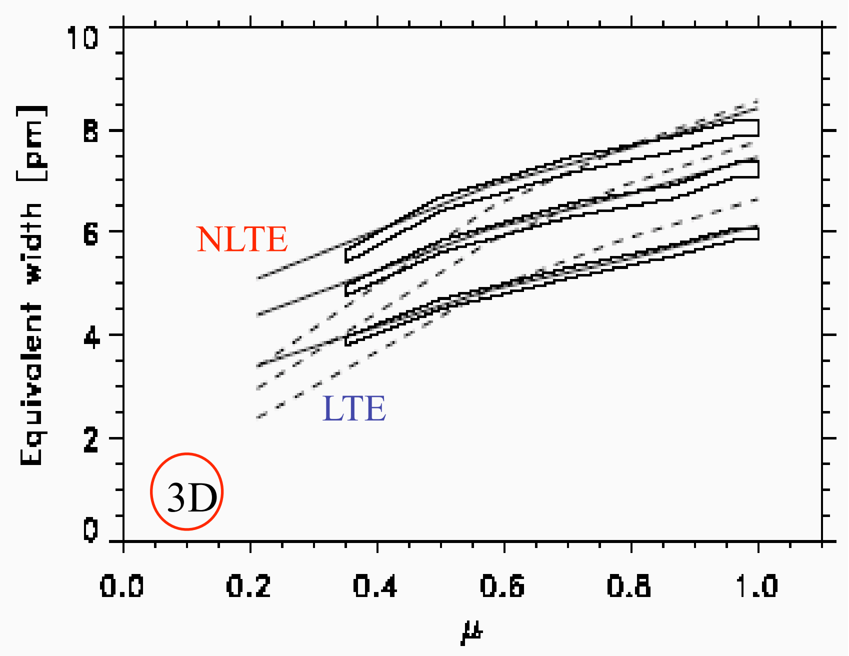
(*Korn, Mashonkina, Richard, et al.* 2007).

Non-LTE predictions for the O I 777 nm triplet

1. The observed center-to-limb variation favors non-LTE line formation (*Kiselman*, 1993).

2. $\Delta_{NLTE} \approx -0.2$ dex,
   log ε_{Sun}(O I 777 nm) ≈ 8.7
   (*Kiselman*, 1993, 1D).

   log ε_{Sun}(O) = 8.72±0.05
   (*Steffen*, 2006, 3D, [O I])



Observations shown as bands are well described in non-LTE.

Δlog ε(3D – 1D) ≈ -0.06 dex.

(*Asplund et al.* 2004)

The effect on stellar abundance determinations

Departures from LTE grow
toward the lower [Fe/H]:

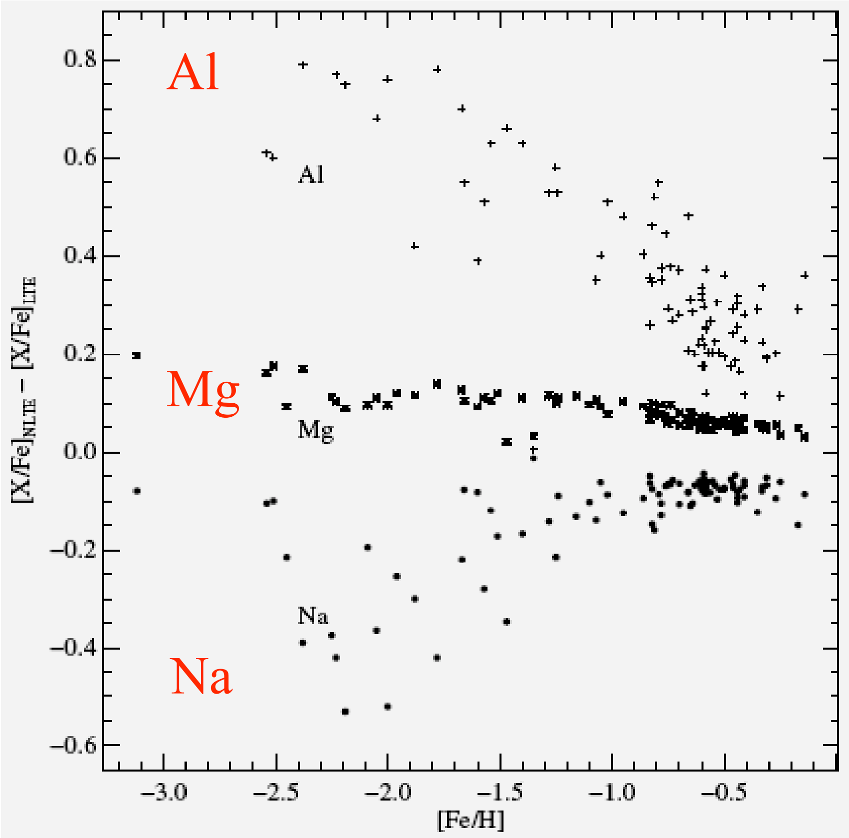
– collision rates decrease,

– photoionization rates increase

NLTE – LTE at [Fe/H] < -2:

≈ +0.6 dex for [Al/Mg],

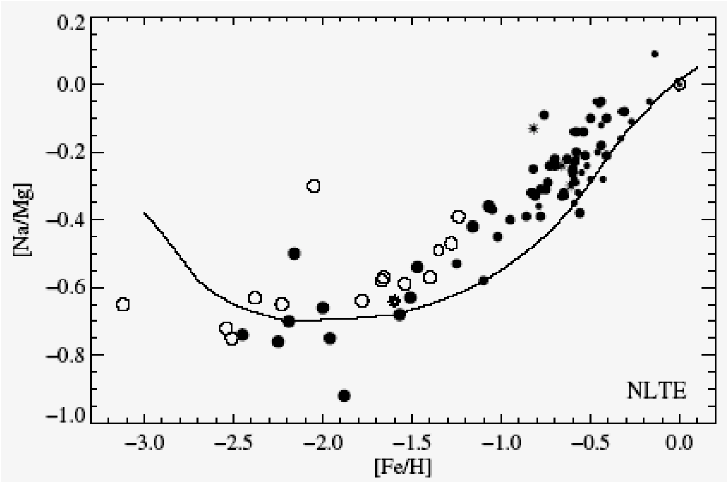
≈ -0.5 dex for [Na/Mg].



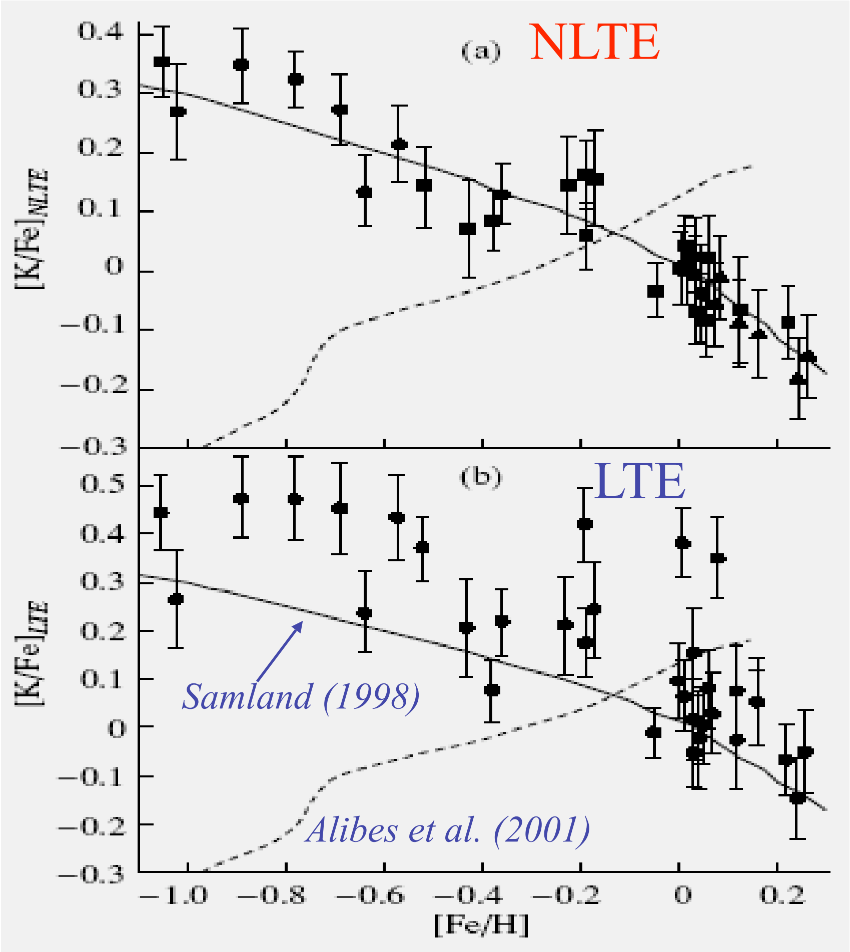
(Gehren et al. 2006)

The effect on stellar abundance determinations

The *odd-Z/even-Z* ratios are important for testing nucleosynthesis models.



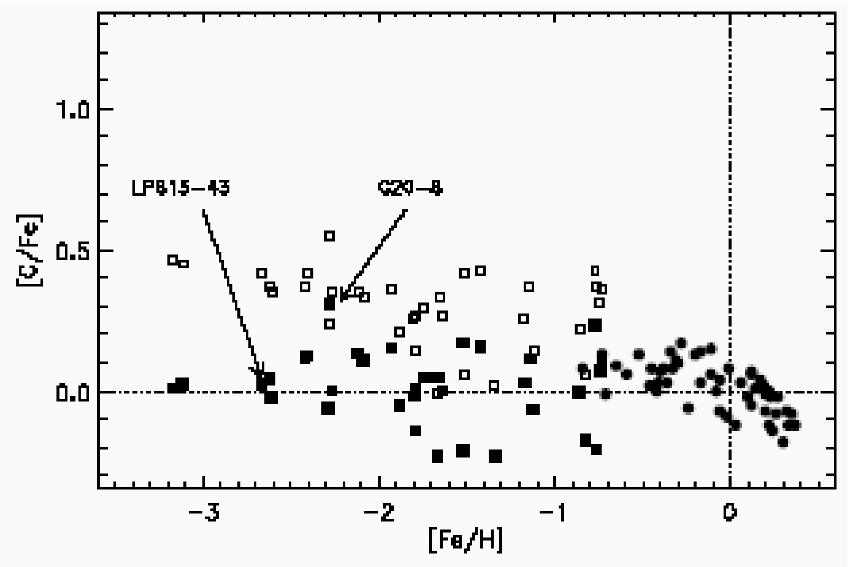
Observed run [Na/Mg] – [Fe/H] compared to the predictions of Timmes et al. (1995).
(*Gehren et al.* 2006)



NLTE leads to less scatter of stellar abundances
(*Shimansky et al.* 2003)

The effect on stellar abundance determinations

Our understanding of
how nucleosynthesis proceeds
throughout the Galaxy history
depends on the accuracy of line formation modelling.



[C/Fe] vs. [Fe/H].
Filled squares show NLTE data,
open squares LTE data.
(Fabbian et al. 2006)