NLTE analysis of spectra: OBA stars

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Outline

NLTE analysis of hot stars

- hot stars: spectral types A, B, O
- $T_{\rm eff} \gtrsim 8500\,\mathrm{K}$

common characteristics

- absence of molecular lines
- less atomic lines
- purely radiative atmosphere (no convection)
- NLTE effects more intensive
  influence atmospheric structure

NLTE analysis of hot stars

- hot stars: spectral types A, B, O
- $T_{\text{eff}} \gtrsim 8500\,\text{K}$

specific features

A quiet atmospheres, chemical peculiarities
stratification of the atmospheres

B some stars pulsating (e.g. β Cep), also non-radially
some stars rapidly rotating, with emission

O strong stellar winds

NLTE analysis of hot stars

Two types of NLTE analysis

full NLTE models

NLTE model atmospheres
consistent approach

NLTE for trace elements

model atmosphere (LTE or NLTE) fixed
NLTE for selected atoms
may be close to consistent

NLTE for trace elements

solution in two steps

1. calculation of a model atmosphere

- include opacities important for atmospheric structure (continua of abundant elements, strong lines)
- many weaker lines may be neglected (no effect on the atmospheric structure)
- can be LTE or NLTE model

NLTE for trace elements

solution in two steps

1. calculation of a model atmosphere

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- can be LTE or NLTE model

2. solution of a NLTE problem

- model atmosphere is fixed
- solution of a NLTE problem for a selected element (trace element)
- detailed model atom with many lines and continua

NLTE for trace elements

conditions

- influence of the trace element on the atmospheric structure is negligible
- opacity of the trace element is negligible compared to the opacity of non-trace element
- or NLTE effects on opacities have negligible influence on the atmospheric structure
- not a significant source of free electrons

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- not a significant source of free electrons
- any detailed calculation *must not* influence the rest
  if this happens $\rightarrow$ improve your background model

NLTE for trace elements

LTE model atmosphere

- elastic collisions – maintain equilibrium velocity distribution
- inelastic collisions – maintain thermodynamic equilibrium (TE)
  collisions mostly with electrons
- radiative transitions – depart level populations from TE
- LTE: inelastic collisions $\gg$ radiative transitions
- NLTE: radiative transitions $\gtrsim$ inelastic collisions
- inconsistent approach, if LTE model atmosphere is used

NLTE model atmosphere

preferred

Full NLTE model atmospheres

- may be part of the trace element procedure
- structure different from LTE models

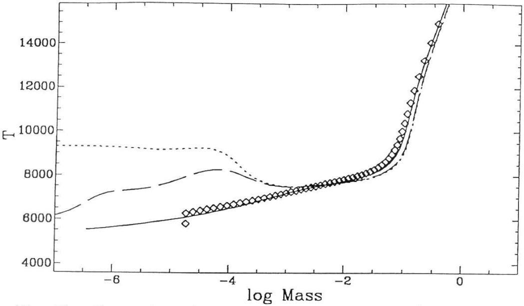

Fig. 5. Comparison of our LTE line blanketed model (full line) and the Kurucz model (diamonds); and two NLTE models: a "classical" NLTE/L hydrogen–carbon model (dotted line), and a NLTE line blanketed model (dashed line).

Hubeny & Lanz, 1993, APSC 44, 98

Solution of a NLTE model atmosphere

equations

- radiative transfer ($I_{\mu\nu}$)
- statistical equilibrium (n_i)
- hydrostatic equilibrium (ρ)
- radiative equilibrium (T)

$$\mu \frac{\mathrm{d}I_{\mu\nu}(z)}{\mathrm{d}z} = \eta_\nu(z) - \chi_\nu(z) I_{\mu\nu}(z)$$

$$n_i \sum_l \left(R_{il} + C_{il}\right) + \sum_l n_l \left(R_{li} + C_{li}\right) = 0$$

$$\frac{\mathrm{d}p}{\mathrm{d}m} = g - \frac{4\pi}{c} \int_0^\infty \frac{\chi_\nu}{\rho} H_\nu \,\mathrm{d}\nu$$

$$4\pi \int_0^\infty \left(\chi_\nu J_\nu - \eta_\nu\right) \mathrm{d}\nu = 0$$

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solution of a nonlinear set of equations

- using Newton-Raphson method (linearization)
- combinaton with accelerated lambda iteration method

Model atmosphere grids

instead of calculating new models (time savings)

LTE model grids

- Kurucz
  grid of LTE line blanketed model atmospheres, practically for all reasonable temperatures and gravities

NLTE model grids

- TLUSTY
  grid of line blanketed NLTE models for O stars and B stars
  (Lanz & Hubeny 2003, ApJS 147, 225; 2007, ApJS 169,83)

using a grid we are fixed to grid parameters ($T_{\rm eff}$, g, $R_\star$, $M_\star$, $L_\star$, abundances, ...)

LTE/NLTE atmosphere modelling

- LTE model calculated within several seconds
- NLTE model calculated within several hours

do we really gain anything?

- more accurate level populations
- more accurate opacities
- more accurate radiation field
- more accurate temperature structure (in models)

is it worth of effort?

Comparison of LTE/NLTE atmosphere modelling

(after Przybilla et al. 2011, J. Phys. Conf. Ser. 328, 012015)

comparison of

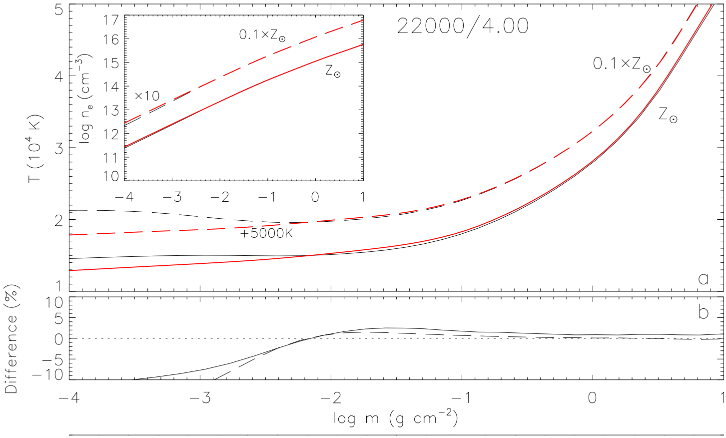
- full LTE analysis (ATLAS9 / SYNTHE)
- full NLTE analysis (TLUSTY / SYNSPEC), grids of models
- hybrid LTE / NLTE analysis (ATLAS9 / DETAIL / SURFACE)

line blanketed models $15\,000\,\mathrm{K} \leq T_{\mathrm{eff}} \leq 35\,000\,\mathrm{K}$

Comparison of LTE/NLTE atmosphere modelling

temperature structure

ATLAS9, TLUSTY



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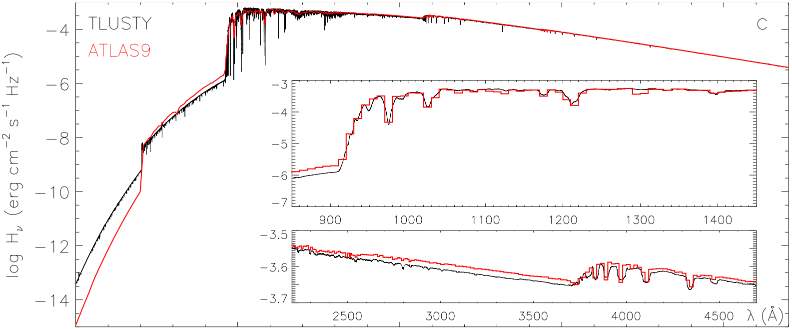
Comparison of LTE/NLTE atmosphere modelling

continuum flux



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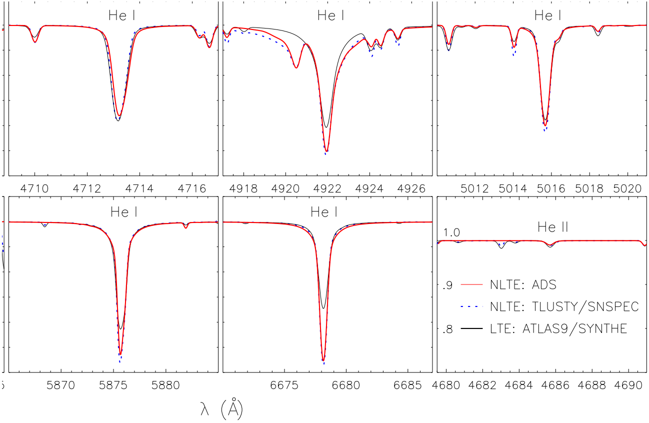
Comparison of LTE/NLTE atmosphere modelling

He I line profiles



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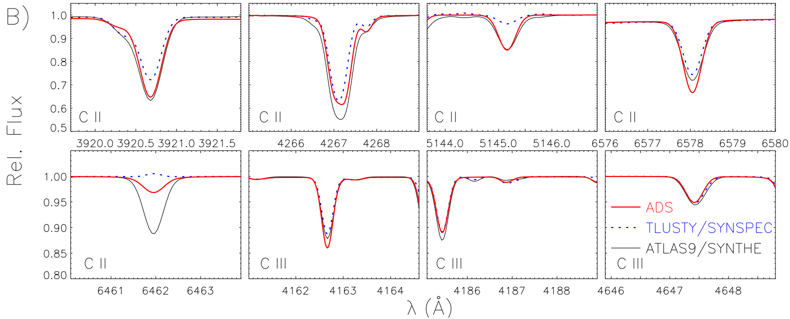
Comparison of LTE/NLTE atmosphere modelling

C II line profiles



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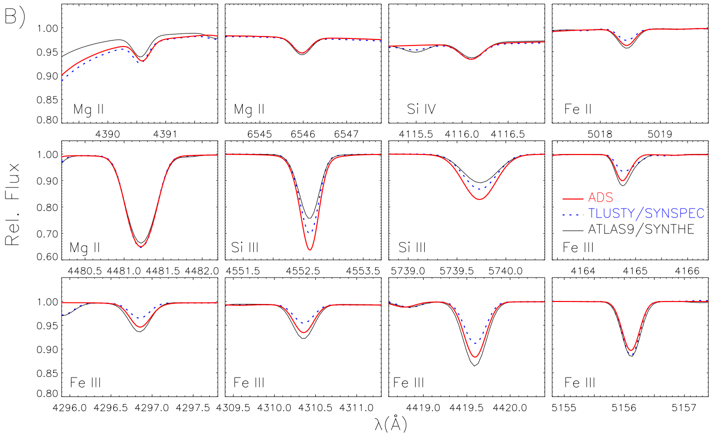
Comparison of LTE/NLTE atmosphere modelling

Mg II, Fe , Si line profiles



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Comparison of LTE/NLTE atmosphere modelling

- line profiles
  - some lines display remarkable differences
    - these lines are known after comparison
    - practically impossible prediction
- temperature structure
  - difference in temperature structures between LTE and NLTE models
  - may result in VERY different line profiles

Comparison of LTE/NLTE atmosphere modelling

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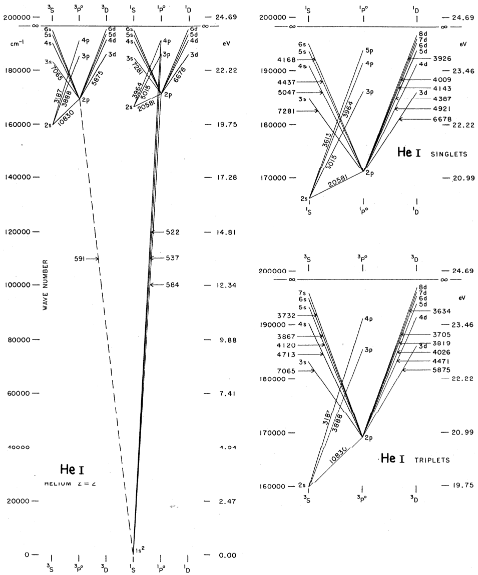
    - practically impossible prediction
- temperature structure
  - difference in temperature structures between LTE and NLTE models
  - may result in VERY different line profiles
- LTE model atmospheres – fast option
- NLTE model atmospheres – more exact option
  - should be preferred

best option

NLTE model atmospheres + NLTE for trace elements

Model atom construction

simple example:
He I
(Grotrian diagram)



Model atom construction

some ions

real number of levels and transitions may be enormous

Model atom construction

Fe II (Hauschildt & Baron, 1995, JQSRT 54, 987)

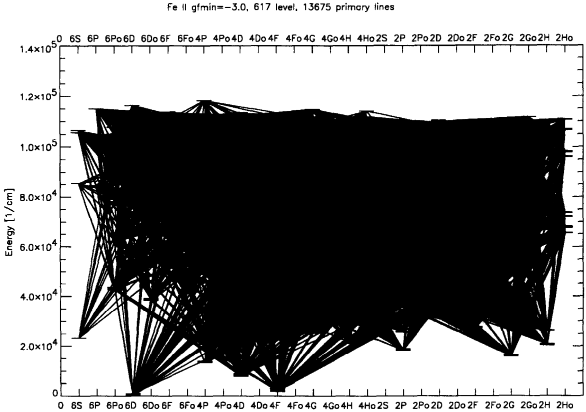


Fig. 1. Grotrian diagram of the Fe II model atom that we use for the calculations presented here. All 617 level and 13,675 b–b transitions which we include in NLTE are shown.

Model atom construction

selecting atomic levels included

- more levels
  - more accurate results
  - more time consuming calculations

Model atom construction

selecting atomic levels included

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- simplifying the atomic structure

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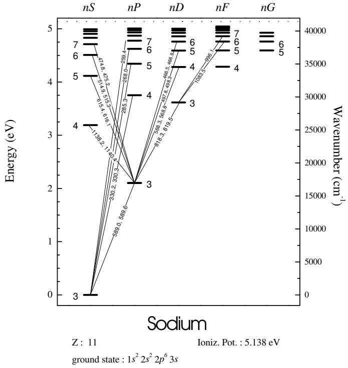
  - neglecting levels with high *n* (which can be close to their LTE values)



Model atom construction

selecting atomic levels included

- more levels
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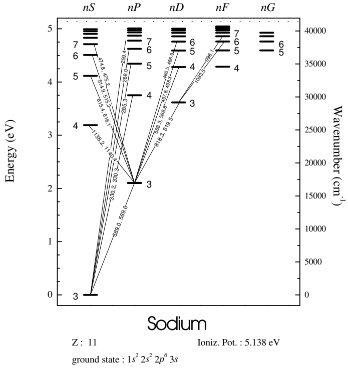
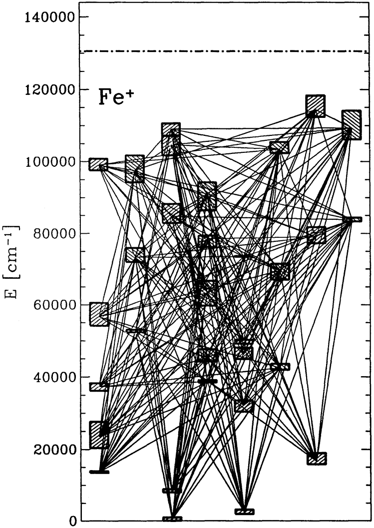
  - more time consuming calculations
- simplifying the atomic structure
  - neglecting levels with high *n* (which can be close to their LTE values)
  - merging levels (e.g. for multiplets)



Model atom construction

selecting atomic levels included

- more levels
  - more accurate results
  - more time consuming calculations
- simplifying the atomic structure
  - neglecting levels with high *n* (which can be close to their LTE values)
  - merging levels (e.g. for multiplets)
  - creating superlevels



Model atom construction

collecting atomic data

- ionization cross sections for all levels
- transition probabilities for allowed radiative transitions
- collisional cross sections for all transitions
- evaluation of values for merged levels

O II model atom

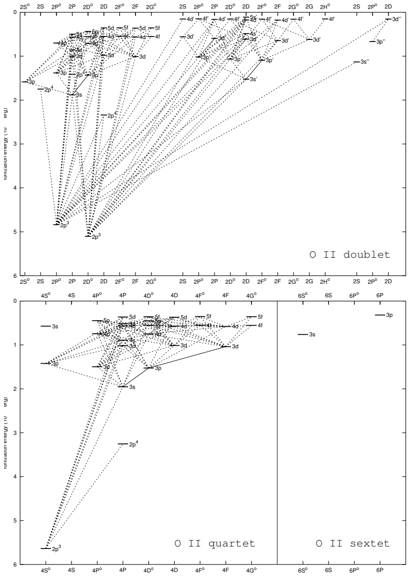
model atom after Becker & Butler (1988, A&A 201, 232)

- O I: 3 levels, only ionization
- O II: 79 levels, all transitions
- O III: 1 level
- O IV: 0 levels, but included in LTE ionization equilibrium

background model atmosphere – NLTE (Kubát)

quartet lines: stronger NLTE effects

(connected with the ground level)



Hot stars with winds

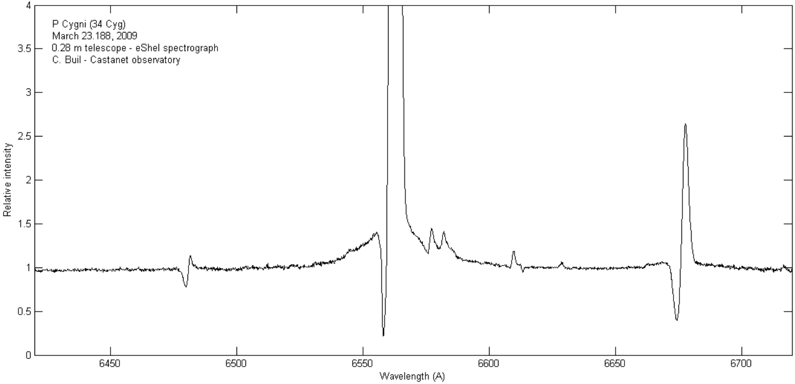
Stellar wind

- outflow of material from the stellar surface
- present for most of massive stars
- mass-loss rate $\frac{dM}{dt}$ up to 10^{-6} $M_{\odot}$ year^{-1}
- terminal velocity v_{∞} up to $\sim 3000\,\mathrm{km\,s^{-1}}$
- outflow driven by radiation
  - continuum (electron scattering + b-f + f-f)
  - line (resonance lines of metals)
  - H, He $\rightarrow$ negligible radiation force
  - momentum transferred by Coulomb collisions
- for brighter stars stronger winds

winds have to be taken into account in analysis

Hot stars with winds

P Cygni profiles



these profiles are formed in a spherical expanding medium (wind)

Hot stars with winds

- large velocity gradients $\Rightarrow$
  radiation can be described using Sobolev approximation
- NLTE effects present
- solution of ESE + RTE is local

Hot stars with winds

core-halo approximation

wind does not influence the photosphere
photospheric flux – lower boundary condition for a wind
analysis done by parts (photosphere, winds)
NLTE line blanketing is a must

- photospheric lines are selected (lines expected not to be influenced by wind)
- these lines serve for T_{eff} determination (used as for static models)
- then the wind line profiles are calculated for given $v(r)$ and $\rho(r)$ – determination of mass-loss rate
- wind modelling – NLTE for trace elements

Summary

- for hot stars NLTE analysis necessary
- LTE/NLTE model atmospheres + NLTE for trace elements
- model atoms have to be carefully constructed
- NLTE model atmospheres should be preferred (more exact)
- model grids may save computing time
- systematic influence of stellar wind