NLTE analysis of spectra: OBA stars

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11 April 2013
Outline

NLTE analysis of hot stars

Trace elements

Full NLTE model atmospheres

Comparison of LTE and NLTE modelling

Model atom construction

Stars with winds

Summary
NLTE analysis of hot stars

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

Specific features

A. quiet atmospheres, chemical peculiarities
   stratification of the atmospheres

B. some stars pulsating (e.g. $\beta$ 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
   • 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

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
NLTE for trace elements

conditions

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• or NLTE effects on opacities have negligible influence on the atmospheric structure

• not a significant source of free electrons

• any detailed calculation must not influence the rest if this happens → 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 ($\rho$)
- radiative equilibrium ($T$)

\[
\frac{dI_{\mu\nu}(z)}{dz} = \eta_\nu(z) - \chi_\nu(z)I_{\mu\nu}(z)
\]

\[
n_i \sum_l (R_{il} + C_{il}) + \sum_l n_l (R_{li} + C_{li}) = 0
\]

\[
\frac{d\rho}{dm} = g - \frac{4\pi}{c} \int_0^\infty \frac{\chi_\nu}{\rho} H_\nu \, d\nu
\]

\[
4\pi \int_0^\infty (\chi_\nu J_\nu - \eta_\nu) \, d\nu = 0
\]
Solution of a NLTE model atmosphere

equations

- radiative transfer ($I_{\mu\nu}$)
- statistical equilibrium ($n_i$)
- hydrostatic equilibrium ($\rho$)
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\]
\[
4\pi \int_0^{\infty} (\chi_{\nu} J_{\nu} - \eta_{\nu}) \, d\nu = 0
\]

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 ($T_{\text{eff}}$, $g$, $R_\star$, $M_\star$, $L_\star$, 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 $15\,000\,K \leq T_{\text{eff}} \leq 35\,000\,K$
Comparison of LTE/NLTE atmosphere modelling

temperature structure

(after Przybilla et al. 2011, J. Phys. Conf. Ser. 328, 012015)
Comparison of LTE/NLTE atmosphere modelling

continuum flux

(after Przybilla et al. 2011, J. Phys. Conf. Ser. 328, 012015)
Comparison of LTE/NLTE atmosphere modelling

He I line profiles

(after Przybilla et al. 2011, J. Phys. Conf. Ser. 328, 012015)
Comparison of LTE/NLTE atmosphere modelling

C II line profiles

(after Przybilla et al. 2011, J. Phys. Conf. Ser. 328, 012015)
Comparison of LTE/NLTE atmosphere modelling

Mg II, Fe, Si line profiles

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

- 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
- LTE model atmospheres – fast option
- NLTE model atmospheres – more exact option
  - should be preferred

best option

NLTE model atmospheres + NLTE for trace elements
simple example:
He I
(Grotrian diagram)
Model atom construction

Some ions

Real number of levels and transitions may be enormous
2. MODEL ATOM

2.1. Kurucz data

We have taken our model atom from the long term project of R. L. Kurucz, to provide accurate atomic data for modeling stellar atmospheres, an invaluable service to the scientific community. For our current model atom we have kept terms to 2H, which corresponds to the first 29 terms of Fe II. Within these terms we treat all observed levels that have observed "primary" transitions with loggf > -3.0, where g is the statistical weight of the lower level and f is the oscillator strength of the transition. This leads to a model atom with 617 levels and 13,675 "primary" transitions which we treat in detailed NLTE; we solve the full rate equations for all these levels including all radiative rates for the primary lines. In addition we treat the opacity and emissivity for the remaining nearly 1.2 million "secondary" transitions in NLTE.

2.2. Photo-ionization rates

Detailed photo-ionization rates for Fe II have yet to be published, although this is one of the goals of the iron project. Thus, we have taken the results of the Hartree Slater central field calculations of Reilman and Manson to scale the ground state photo-ionization rate and have then used a hydrogenic approximation for the energy variation of the cross section. Although these rates are only very rough approximations, they are useful for initial calculations. In the conditions of the test cases we will consider in this paper, the exact values of the b-f cross sections are not important for the opacities themselves (which are dominated by known b-b transitions of Fe II and other species), but they have an influence on the actual b-f rates. This is, of course, unimportant for the computational method which we use and the b-f cross sections can be changed once better data become available.

2.3. Collisional rates

For collisional rates we have had to make rather rough approximations and, therefore, have...
Model atom construction

selecting atomic levels included

- more levels
  - more accurate results
  - more time consuming calculations
Model atom construction

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- simplifying the atomic structure
Model atom construction

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- simplifying the atomic structure
  - neglecting levels with high $n$
    (which can be close to their LTE values)
Model atom construction

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

**Sodium**

- Z: 11
- Ioniz. Pot.: 5.138 eV
- ground state: $1s^2 2s^2 2p^6 3s$

![Energy vs. Wavenumber diagram for Sodium](image)
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 $10^{-6} \, M_\odot \, \text{year}^{-1}$
- terminal velocity $v_\infty$ up to $\sim 3000 \, \text{km s}^{-1}$
- 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 $T_{\text{eff}}$ 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