Current status of NLTE analysis and perspectives for future

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Outline

Importance of radiation

NLTE model atmosphere codes

NLTE wind models

Coupling of hydrodynamics and radiation

Generalized equations of statistical equilibrium

Summary

Importance of radiation

radiation is not only an information source

interaction with matter

- transfer of momentum
  - $\frac{h\nu}{c}$
- transfer of energy
  - ionization $\rightarrow h\nu_{\text{ion}} + \frac{1}{2}m_{\text{e}}v_{\text{e}}^2$
  - excitation $\rightarrow h\nu_{\text{exc}}$
  - free-free $\rightarrow \frac{1}{2}m_{\text{e}}\Delta v_{\text{e}}^2$

transfer to kinetic electron energy $\rightarrow$ heating (cooling)
transfer to atomic internal energy $\rightarrow$ changes in excitation and ionization balance
if radiation changes dominate $\rightarrow$ NLTE

Importance of radiation

effect of radiation on temperature

- transfer of energy by interaction with matter (absorption, emission)
- heating and cooling by radiation

effect of radiation on motion

- transfer of momentum from radiation by interaction with matter (absorption, emission, scattering)
- acceleration by radiation

effect of radiation on population numbers

NLTE stands for “take into account influence of radiation on population numbers”

NLTE modelling options

equations of statistical equilibrium (n_i) solved with

- radiative transfer ($I_{\mu\nu}$)
  - fixed parameters $[T(\vec{r}), \rho(\vec{r}), \vec{v}(\vec{r})]$
  - basic NLTE solution

NLTE modelling options

equations of statistical equilibrium (n_i) solved with

- radiative transfer ($I_{\mu\nu}$)
  - fixed parameters [$\vec{v}(\vec{r})$]
- radiative equilibrium (T)
- hydrostatic equilibrium (ρ)

NLTE modelling options

equations of statistical equilibrium (n_i) solved with

- radiative transfer ($I_{\mu\nu}$)
- radiative equilibrium (T)
- continuity equation (ρ)
- equation of motion ($\vec{v}$)

NLTE modelling options

equations of statistical equilibrium (n_i) solved with

- radiative transfer ($I_{\mu\nu}$)

- continuity equation (ρ)
- equation of motion ($\vec{v}$)
- energy equation (T)

different codes solve different combination of equations

NLTE model atmosphere codes

(Sakhibullin 1996, APSC 108, 207)

NLTE problem for given structure

PANDORA (Eugene Avrett & Rudolf Loeser), since 1966
1-D RTE + ETLA
`http://www.cfa.harvard.edu/~avrett/pandora.html`

LINEAR (Auer, Heasley, Milkey 1972)
use complete linearization method

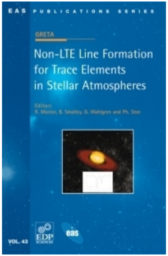
MULTI : Multi-level Non-LTE Problems in Moving or Static Atmospheres
solution of RTE + ESE
`http://folk.uio.no/matsc/mul22/`

MALI (Auer, Fabiani Bendicho, Trujillo Bueno)
2-D RTE + NLTE

- ...

NLTE Line Formation for Trace Elements in Stellar Atmospheres

R. Monier, B. Smalley, G. Wahlgren, Ph. Stee
eds., EAS Publ. Ser. 43
contributions by K. Butler, L. Chevallier, I. Kamp,
J. Kubát, L. Mashonkina, N. Przybilla,
G. Wahlgren



DETAIL (J. R. Giddings, Keith Butler)
RTE + ESE using accelerated lamda iteration (ALI)
SURFACE calculates synthetic spectrum

Kiel code (Hartmut Holweger)
RTE + ESE

`http://www.astro.rug.nl/~kamp/overview_NLTE.html`

NLTE model atmosphere codes

Static NLTE model atmospheres

- – (Mihalas, Heasley, Auer, 1975)
  uses complete linearization
  plane-parallel NLTE model atmospheres
- – (Kudritzki 1975)
  independent code, also complete linearization
  plane-parallel NLTE model atmospheres

TLUSTY – static NLTE line-blanketed model atmospheres
includes also convection
option for NLTE problem for a given structure
uses hybrid complete linearization + ALI method
`http://nova.astro.umd.edu/index.html`
SYNSPEC - synthetic spectra

NLTE model atmosphere codes

Static NLTE model atmospheres

TMAP – Tübingen NLTE Model-Atmosphere Package
static NLTE line-blanketed model atmospheres, focus on white dwarfs
accelerated lambda iteration method
PRO2 models, LINE2 NLTE line formation
`http://astro.uni-tuebingen.de/~TMAP/`

PHOENIX – accelerated lambda iteration (operator splitting)
line blanketing
for novae, supernovae, cool stars, substellar objects
`http://www.hs.uni-hamburg.de/EN/For/ThA/phoenix/`
access to manual restricted
for cool stars: `http://perso.ens-lyon.fr/france.allard/`

NLTE model atmosphere codes

Static NLTE model atmospheres

- – Mihalas & Hummer 1974
  spherically symmetric NLTE model atmospheres
  complete linearization
- – Gruschinske 1978
  independent code for spherically symmetric NLTE model atmospheres

ATA – static spherically symmetric NLTE model atmospheres
mode for trace elements calculation
uses accelerated lambda iteration

http://www.asu.cas.cz/~kubat/ATA/

NLTE wind model codes

FASTWIND – ESE + RTE in comoving frame, Sobolev
given $v(r)$ and $\rho(r)$
T may be iterated

Joachim Puls et al.

WM-basic line blocked and blanketed NLTE model
stationary hydrodynamic stratification
Adalbert Pauldrach

`http://www.usm.uni-muenchen.de/people/adi/adi.html`

ISA-WIND – ESE+RTE in comoving frame, Sobolev
given $v(r), \rho(r), T(r)$

Alex de Koter

NLTE wind model codes

CMFGEN – RTE + ESE in comoving frame
given $v(r)$ (β-law) and $\rho(r)$
T may be iterated
a grid of models available for dowloading
D. John Hillier

`http://kookaburra.phyast.pitt.edu/hillier/web/CMFGEN.htm`

PoWR – The Potsdam Wolf-Rayet Models
RTE + ESE in comoving frame
given $v(r)$ and $\rho(r)$
possibility of hydrodynamic solution
designed for Wolf-Rayet stars
Wolf-Rainer Hamann

`http://www.astro.physik.uni-potsdam.de/~wrh/PoWR/`

NLTE wind model codes

- – (Peter Höflich)
  successive use of radiation hydrodynamics,
  radiative transfer, and NLTE
  for supernovae

  http://amida.physics.fsu.edu/~pah/scheme.gif
- – (Kromer & Sim 2009)
  NLTE Monte Carlo radiative transfer in supernovae

HDUST – NLTE Monte Carlo radiative transfer in circumstellar disks
(Carciofi & Bjorkman)

Hydrodynamic models with NLTE

- – hydrodynamic equations for a stellar wind radiative force calculated using ESE
  (Krtička & Kubát, 2004, A&A 417, 1003)
- – Monte Carlo calculation of a radiative force, NLTE radiative transfer using ISA-WIND
  (Vink, de Koter, Lamers, 1999, A&A 350, 181)

Additional processes in ESE

Auger ionization

- X-rays or collisions expell an inner-shell electron
- followed by fluorescence or ionization

$$-n_i \sum_{j \neq i} \left(R_{ij} + C_{ij}\right) - n_i \sum_{i<j} R_{ij}^{\text{Auger}} + \sum_{j \neq i} n_j \left(R_{ji} + C_{ji}\right) = 0$$

- two-electron ionization process
- states with inner-shell vacancy not included in ESE

Generalized equations of statistical equilibrium

equations of statistical equilibrium

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \vec{v}) = \sum_{j \neq i} \left(n_j P_{ji} - n_i P_{ij} \right)$$

left hand side usually neglected

advection term $\nabla \cdot (n_i \vec{v})$

- for static atmospheres $\vec{v} = 0$
- hydrodynamics of solar convection
  radiative hydrodynamic simulations – (Leenaarts et al. 2007, A&A 473, 625)
- radiative transfer in supernovae

Time-dependent equations of statistical equilibrium

if relaxation timescale is longer than dynamic timescales
examples:

solar chromosphere dynamic ionization
(Carlsson & Stein 2002)

supernovae rapidly expanding atmospheres (Utrobin & Chugai 2005)

Non-Maxwellian velocity distribution

nothermal electrons

- non-thermal electron velocity distribution

$$-n_i \sum_{j \neq i} \left(R_{ij} + C_{ij} + C_{ij}^{\mathrm{nt}} \right) + \sum_{j \neq i} n_j \left(R_{ji} + C_{ji} \right) = 0$$

electron beams in solar flares

kinetic equation for electrons

Polarization

- radiation described by Stokes vector

$$\vec{I} = (I, Q, U, V)^{\mathsf{T}}$$

- transfer equation

$$\frac{\mathrm{d}\vec{I}}{\mathrm{d}s} = \vec{\eta} - \mathbf{K}\vec{I}$$

- equations of statistical equilibrium
  $\rightarrow$ equation for evolution of the density matrix

$$\frac{\mathrm{d}\rho^K}{\mathrm{d}t} = 0$$

Summary

- NLTE is a consequence of radiation-matter interaction
- number of codes, always distinguish:
    - codes for model atmosphere calculations
    - codes for restricted NLTE problem (radiative transfer + statistical equilibrium)
    - codes for calculation of synthetic spectrum
    - codes for making this work easier
- NLTE as is popular now is not the end of research