Radiative Transfer and Stellar Atmospheres

4 lectures within the first IMPRS advanced course

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Contents

- quantitative spectroscopy: the astrophysical tool to measure stellar and interstellar properties
- the radiation field: specific and mean intensity, radiative flux and pressure, Planck function
- coupling with matter: opacity, emissivity and the equation of radiative transfer (incl. angular moments)
- radiative transfer: simple solutions, spectral lines and limb darkening
- stellar atmospheres: basic assumptions, hydrostatic, radiative and local thermodynamic equilibrium, temperature stratification and convection
- microscopic theory
  - opacities and emissivities
    - line transitions: Einstein-coefficients, line-broadening and curve of growth
    - continuous processes and scattering
  - atomic level population
    - ionization and excitation in LTE: Saha- and Boltzmann-equation
- non-LTE: motivation and introduction
- stellar winds: brief introduction into pressure and radiation driven winds
- quantitative spectroscopy: stellar/atmospheric parameters and how to determine them, for the exemplaric case of hot stars
(3rd edition - together with I. Hubeny - in press)


Shu, F.H., "The physics of astrophysics, Volume I: radiation", University science books,
Mill Valley, 1991


Osterbrock, D.E., "Astrophysics of Gaseous Nebulae and Active Galactic Nuclei",
University science books, Mill Valley, 1989

Springer, 1987

Kudritzki, R.-P., Hummer, D.G., "Quantitative spectroscopy of hot stars", Annual Review

Kudritzki, R.-P., Puls, J., "Winds from hot stars", Annual Review of Astronomy and Astrophysics,
Vol. 38, p. 613, 2000
Experiment in astrophysics = Collecting photons from cosmic objects

hydrogen Lyman edge

$1 \text{ Å} = 10^{-8} \text{ cm} = 10^{-4} \mu \text{ (micron)}; \quad 1 \text{ nm} = 10 \text{ Å}$

Collecting: earthbound and via satellites!

Note: Most of these photons originate from the atmospheres of stellar(-like) objects.

Even galaxies consist of stars!
AN ATLAS OF STELLAR SPECTRA
WITH AN OUTLINE OF SPECTRAL CLASSIFICATION

Morgan, Keenan, Kellman
Empirical system

$\Rightarrow$

Physical system
spectral lines formed in (quasi-)hydrostatic atmospheres

ESO 3.6m CASPEC

$\Delta \lambda \approx 0.5\text{Å}
S/N 30...70

(Walborn et al.,1995)
P-Cygni lines formed in hydrodynamic atmospheres

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<th>Si IV</th>
<th>C IV</th>
<th>He II</th>
<th>N IV</th>
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HST-FOS

SMC

LMC

SMC
UV spectrum of the O4I(f) supergiant $\zeta$ Pup

montage of Copernicus ($\lambda < 1500$ Å, high res. mode, $\Delta \lambda \approx 0.05$ Å, Morton & Underhill 1977) and IUE ($\Delta \lambda \approx 0.1$ Å) observations
Supernova Type II in different phases

photospheric phase

transition to nebular phase

figure prepared by Mark M. Phillips, reproduced from McCray & Li (1988)
Spectrum of Planetary Nebula

pure emission line spectrum with forbidden lines of O III

H\textsubscript{\alpha}

H\textsubscript{\beta}

H\textsubscript{\gamma}

[O\textsc{iii}] 5007, 4959\textsc{\AA} ratio 3:1

Quasar spectrum in rest frame of quasar

\[ \frac{\Delta \lambda}{\lambda} = z, \text{ cosmological redshift} \]
galaxy at $z = 2.72$

local starburst galaxy, wavelengths shifted

From Steidel et al. (1997)
Quantitative spectroscopy gives insight into and understanding of our cosmos

- requires
  - plasma physics, plasma is "normal" state of atmospheres and interstellar matter (plasma diagnostics, line broadening, influence of magnetic fields,...)
  - atomic physics/quantum mechanics, interaction light/matter (micro quantities)
  - radiative transfer, interaction light/matter (macroscopic description)
  - thermodynamics, thermodynamic equilibria: TE, LTE (local), NLTE (non-local)
  - hydrodynamics, atmospheric structure, velocity fields, shockwaves,...

- provides
  - stellar properties, mass, radius, luminosity, energy production, chemical composition, properties of outflows
  - properties of (inter) stellar plasmas, temperature, density, excitation, chemical comp., magnetic fields

- INPUT for stellar, galactic and cosmologic evolution and for stellar and galactic structure
atomic levels and allowed transitions ("Grotrian-diagram") in OIV

\[ \log gf > 0 \]
\[ 0 > \log gf > -1 \]
\[ -1 > \log gf \]

gf oscillator strength, measures "strength" of transition (cf. Chap 5)
sites of X-ray emission in hot stars:

shell collisions

hydrodynamical simulations of instable hot star winds, from A. Feldmeier, by permission
Stellar Atmospheres - An Overview

- **Core**
  - $M_0 = 2 \times 10^{23} \text{g}$
  - $R_0 = 7 \times 10^{10} \text{cm}$
  - $L_0 = 4 \times 10^{33} \text{erg/s}$

- **Photosphere**
  - $\Delta R = 200 \text{Km}$
  - $n = 10^{15} \text{cm}^{-3}$
  - $T = 6000 \text{K}$

- **Envelope Chromo Corona**
  - $\Delta R = 1000 \text{Km}$
  - $n = 10^{22} \text{cm}^{-3}$
  - $T = 20,000 \text{K}$

- **Hot Star**
  - $V = 500 \text{Km/s}$
  - Wind $v > 2000 \text{Km/s}$

- **Supernova**
  - Expl./Core
  - $V = 20,000 \text{Km/s}$
  - "Photosphere" Remnant

- **Gaseous Nebula**
  - Central Object
  - Optically Thin Nebula
  - $V = 20 \text{Km/s}$
  - $10,000 \text{Km/s}$

- **PN - HII - AGN**
  - $L = 10^4 \ldots 10^6 \ldots 10^{12} \text{L}_\odot$
  - $R = 0.1 \text{pc} \ldots 10 \text{pc} \ldots 10^3 \text{pc}$
Concept of Spectral Analysis

- observed spectrum
  - detector
  - spectrograph
  - telescope
  - theory of atmospheres
    - physical concept
      - hydro-/thermodynamics
      - atomic physics
      - radiative transfer
  - approximations for specific objects
    - geometry, symmetry, homogeneity, stationarity

- comparison

- synthetic spectrum
  - model calculations (simulation)
    - numerical solution of theoretical equations
    - INPUT of L, M, R, chemical composition