RADIATIVE TRANSFER AND STELLAR ATMOSPHERES

Institute for Astronomy
Fall Semester 2007

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Outline

- Introduction: Modern astronomy and the power of quantitative spectroscopy
- Basic assumptions for “classic” stellar atmospheres: geometry, hydrostatic equilibrium, conservation of momentum-mass-energy, LTE (Planck, Maxwell)
- Radiative transfer: definitions, opacity, emissivity, optical depth, exact and approximate solutions, moments of intensity, Lambda operator, diffusion (Eddington) approximation, limb darkening, grey atmosphere, solar models
- Energy transport: Radiative equilibrium and convection, grey atmospheres, numerical solutions for model atmospheres
- Atomic radiation processes: Einstein coefficients, line broadening, continuous processes and scattering (Thomson, Rayleigh)
- Excitation and ionization (Boltzmann, Saha), partition function
- Example: Stellar spectral types
- Non-LTE: basic concept and examples
- 2-level atom, formation of spectral lines, curves growth
- Recombination theory in stellar envelopes and gaseous nebulae
- Stellar winds: introduction to line transfer with velocity fields, hydrodynamics of radiation driven winds
1. Introduction

Astrophysics is based on the collection of photons from cosmic objects from the whole electromagnetic spectrum.

The majority of these photons originates in stellar objects (photospheres or envelopes), constituents of galaxies.

The quantitative analysis of spectra is necessary for the physical understanding of most astronomical objects in the universe.
Spectroscopists do it better
The birthplace of stellar spectroscopy
Joseph von Frauenhofer
1820

Spectrum of the sun

Spectrum of Arcturus, α CrB

Lamont, 1836
Munich solar eclipse, 1999
Munich University Observatory
solar eclipse, 1999
Examples of spectra

The visible solar spectrum

NOAO/AURA/NSF
Examples of spectra
Examples of spectra

$O_4$ supergiant $\zeta$ Puppis

Pauldrach, Puls, Kudritzki et al. 1994, SSRev, 66, 105

UV spectrum
Stellar winds
Spectral diagnostics of massive stars

diagnostic problem:

- high luminosity $\rightarrow$ enormous energy and momentum density of radiation field

$\Psi = \frac{\partial}{\partial r} \left( I_v(r, \mu) \right) + \frac{1}{r(1 - \mu^2)} \frac{\partial}{\partial \mu} \left( I_v(r, \mu) \right) = \eta_v(r) - \chi_v(r) I_v(r, \mu)$

$R_{ji} = 4\pi \left( \frac{c}{\nu_j} \right)^3 \int \frac{\partial}{\partial \nu} \left( \frac{\nu^3}{c^2} + J_v \right) \exp(-\frac{\nu}{kT}) d\nu$

$\rightarrow$ Model atmospheres and radiative transfer

- detailed NLTE treatment
- radiation-hydrodynamics of line-driven winds
- spherical extension

NLTE  stellar winds
LTE vs NLTE

**LTE**

- Each volume element separately in thermodynamic equilibrium at temperature $T(r)$
  
1. $f(v) \, dv = \text{Maxwellian with } T = T(r)$
2. Saha: $(n_p \, n_e)/n_1 / T^{3/2} \exp(-\nu_1/kT)$
3. Boltzmann: $n_i / n_1 = g_i / g_1 \exp(-\nu_{1i}/kT)$

However:

- Volume elements not closed systems, interactions by photons
- $\Rightarrow$ LTE non-valid if absorption of photons disrupts equilibrium
NLTE

1. \( f(v) \ dv \) remains Maxwellian

2. Boltzmann - Saha replaced by \( \frac{dn_i}{dt} = 0 \) (statistical equilibrium)
   for a given level \( i \) the rate of transitions out = rate of transitions in

\[
n_i \sum_{j \neq i} P_{ij} = \sum_{j \neq i} n_j P_{ji}
\]

rate out = rate in

rate equations

\( P_{i,j} \) transition probabilities
complex atomic models for O-stars (Pauldrach et al., 2001)
NLTE Atomic Models in modern model atmosphere codes
lines, collisions, ionization, recombination
Essential for occupation numbers, line blocking, line force
Accurate atomic models have been included

26 elements
149 ionization stages
5,000 levels (+ 100,000)
20,000 diel. rec. transitions
4 \(10^6\) b-b line transitions
Auger-ionization

recently improved models are based on Superstructure
Eisner et al., 1974, CPC 8,270
Basic equations

Hydrodyn.

Rate equations

Radiative transfer

energy equation

Non-linear coupling $\rightarrow$ complex iteration !!!
HD 93129A O3Ia

consistent treatment of expanding atmospheres along with spectrum synthesis techniques allow the determination of stellar parameters, wind parameters, and abundances.
Examples of spectra

**Supernovae**
(photospheric phase)


(a) SN 1987N (Ia), $t \sim 1$ week
(b) SN 1987A (II), $\tau \sim 1$ week
(c) SN 1987M (Ic), $t \sim 1$ week
(d) SN 1984L (Ib), $t \sim 1$ week
Examples of spectra

Quasar composite

Examples of spectra

Quasar + Damped Lyman α system

Carlton & Churchill 2000
Examples of spectra

Seyfert 1 & 2

Osterbrock 1978, Physica Scripta, 17, 137
Examples of spectra


HII regions in M83

- disk
- element abundances
- stellar content
- ionizing flux, stellar atmospheres

Hot spot
Examples of spectra

Planetary Nebula

Examples of spectra

Galactic halo star

SEDs of massive stars in star forming regions

- heavy extinction
- IR spectroscopy

- $A_V = 30$ mag

- O-star SED (intrinsic)
- IR-excess stellar wind
- Black Body
Arches cluster in GC
Galactic Center Arches cluster: quantitative IR spectroscopy

Quantitative stellar spectroscopy of individual stars in galaxies beyond the Local Group

Properties of stellar populations
Evolution of galaxies
Chemical abundance and abundance pattern gradients
Interstellar extinction
Distances
Dark matter content
A supergiants – objects in transition

Brightest normal stars at visual light: $-7 \geq M_V \geq -10$ mag

$t_{ev} \sim 10^3$ yrs
$L, M \sim$ const.

ideal to determine

- chemical compos.
- abundance grad.
- SF history
- extinction
- extinction laws
- distances

of galaxies

NGC 300: spectral classification

Study of metallicities
A supergiants
Metallicity: spectral window
Spectral window 4497-4607Å

NGC300/star21 [Z] = -1.30

\( F_\lambda \) vs \( \lambda \) (Å)

4500 4520 4540 4560 4580 4600
Spectral window 4497-4607Å

\[ \chi^2_i = \frac{2}{S} \frac{1}{n_{pix}} \sum_{j=1}^{n_{pix}} (O_j - C_j)^2 \]
$\chi_i$ spectral window 4497-4607Å

NGC300/star21

$\chi$ vs. $[Z]$
another spectral window
Spectral window 4438-4497Å

NGC300/star21 \([Z]=-1.30\)
$\chi_i$ spectral window 4438-4497Å
$X_i$ all windows $\rightarrow [Z] = -0.4 \pm 0.1$
Wolf-Rayet star in NGC 300

emission line diagnostics: first detailed abundance pattern outside Local Group

NGC 300 WN11 star

non-LTE line-blanketed hydrodynamic model atmospheres with stellar winds

stellar parameters
wind parameters
H, He, CNO, Al, Si, Fe abundances

### NGC 300 WN11 star

<table>
<thead>
<tr>
<th>Species</th>
<th>Relative number fraction</th>
<th>Mass fraction</th>
<th>$X/X_{\odot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1.5 E+00</td>
<td>2.7 E−01</td>
<td>0.4</td>
</tr>
<tr>
<td>He</td>
<td>1.0 E+00</td>
<td>7.2 E−01</td>
<td>2.7</td>
</tr>
<tr>
<td>C</td>
<td>3.6 E−04</td>
<td>7.7 E−04</td>
<td>0.3</td>
</tr>
<tr>
<td>N</td>
<td>2.5 E−03</td>
<td>6.3 E−03</td>
<td>7.7</td>
</tr>
<tr>
<td>O</td>
<td>5.5 E−04</td>
<td>1.6 E−03</td>
<td>0.2</td>
</tr>
<tr>
<td>Al</td>
<td>5.0 E−06</td>
<td>2.4 E−05</td>
<td>0.4</td>
</tr>
<tr>
<td>Si</td>
<td>8.5 E−05</td>
<td>1.7 E−04</td>
<td>0.2</td>
</tr>
<tr>
<td>Fe</td>
<td>1.5 E−04</td>
<td>1.5 E−03</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Stellar metallicity gradient in NGC300

\[ [Z] = -0.03 - 0.08 \frac{d}{\text{kpc}} \]
\[ \rho / \rho_0 = -0.03 - 0.45 \frac{\rho}{\rho_0} \]

\[ \rho_0 = 9.75 \text{ arcmin} \approx 5.7 \text{ kpc} \]

\[ [Z] = \log(\frac{Z}{Z_{\odot}}) \]

AAS 2007

NGC 3621

NGC 3621:

7 Mpc

HST/ACS

Bresolin, Kudritzki, Mendez & Przybilla 2001

~19 blue supergiant candidates (VLT/FORS)

4 analyzed
NGC 3621

~19 blue supergiant candidates (VLT/FORS)


Galactic template

NGC 3621 A0 supergiant

Galactic template

0.2 & 0.5 solar metallicity models

A0 Ia star

$V = 20.5$, $M_V = -9$

Bresolin, Kudritzki, Mendez, Przybilla
Blue supergiants as distance indicators
Flux weighted Gravity - Luminosity Relationship (FGLR)


\[ M \sim g \times R^2 \sim L \times (g/T^4)^x = \text{const.} \]

\[ L, M \sim \text{const.} \]

\[ M \sim g \times R^2 \sim L \times (g/T^4)^x, \ x \sim 3 \]

\[ \Rightarrow L^{1-x} \sim (g/T^4)^x \]

or with \( M_{\text{bol}} \sim -2.5 \log L \)

\[ M_{\text{bol}} = a \log(g/T^4) + b \quad \text{FGLR} \]

\[ a = 2.5 \frac{x}{1-x} \sim 3.75 \]
$M_{bol} = 3.75 \log\left(\frac{g}{T_{eff,4}^4}\right) - 13.73$

$\sigma = 0.24$

Application to TMT (30m telescope)

- WFOS → quantitative spectroscopy possible down to $m_V \sim 24.5$ mag

  → with objects $M_V \leq -8$ mag

$m - M \sim 32.5$ mag $\sim 30$ Mpc possible

chemical evolution studies
SF
ISM, extinction, extinction laws
distances

10 objects per galaxy
  $\Delta(m-M) \sim 0.1$ mag
Mauna Kea Observatories
The best in the world

$1 billion science endeavor
Operating at 14,200 ft.
Site on Mauna Kea Northern Plateau
- below summit
- less visibility
- less cultural and economic impact
- foreseen in year 2000 Master Plan of UH
Planets around other stars

“Brown Dwarf” orbiting a star

Gemini/Keck AO detection by Michael Liu (IfA)

Problem: Planets much fainter than Brown Dwarfs

→ 30m telescope needed !!

→ TMT !!
The power of TMT

TMT will allow for the first time:

- To image giant planets surrounding many hundred stars
- To determine masses and radii
- To analyze atmospheric structure and chemical composition
Exploring other solar systems

Artist conception of planetary system orbiting around 55 Cancri using results of radial velocity Keck observations
55 Cancri - physical characterization by spectroscopy

Sudarsky, Burrows & Lunine, 2003
Predicted spectra of a 5 Gyr Jupiter-like planet

Fig. 3.—Planet-to-star flux ratios vs. wavelength (in μm) from 0.5 to 30 μm for a 1M_J EGP with an age of 5 Gyr orbiting a G2 V main-sequence star similar to the Sun. This figure portrays ratio spectra as a function of orbital distance from 0.2 to 15 AU. Zero eccentricity is assumed and the planet spectra have been phase averaged as described in SBH03. The associated T/P profiles are given in Fig. 1, and Table 1 lists the modal radii for the particles in the water and ammonia clouds. Note that the planet/star flux ratio is most favorable in the mid-infrared. See text for further discussion.


Fig. 4.—Same as Fig. 3, but highlighting the shorter wavelengths and for a subset of distances (0.2, 1, 4, 10 AU). This figure provides a clearer picture of the features shortward of 2.0 μm for each of the represented models. For the 0.2 AU model, the temperatures of the atmosphere are high enough for the Na D doublet around 0.589 μm and the K I doublet near 0.77 μm to be visible. These features are even more prominent for closer in EGPs (SBH03). At greater orbital distances, the atmospheric temperatures are too low for the alkali metals to appear, but the methane features near 0.62, 0.74, 0.81, and 0.89 μm come into their own. Water bands around 0.94, 1.15, 1.6, and 1.85 μm that help to define the Z, J, and H bands are always of importance. For greater distances, the presence of water clouds can smooth the variations in the planetary spectra that would otherwise be large as a result of the strong absorption features of gaseous water vapor. See text for discussion.
Predicted spectra of some interesting planets

**Stellar atmospheres: an overview**

<table>
<thead>
<tr>
<th>Core</th>
<th>Sun</th>
<th>Hot star</th>
<th>SN</th>
<th>Gas nebula</th>
</tr>
</thead>
<tbody>
<tr>
<td>M = $2 \times 10^{33}$ g</td>
<td>50 $M_\odot$</td>
<td>20 $R_\odot$</td>
<td>$10^6 L_\odot$</td>
<td></td>
</tr>
<tr>
<td>R = $7 \times 10^{10}$ cm</td>
<td>20 $R_\odot$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L = $4 \times 10^{33}$ erg/s</td>
<td>$10^6 L_\odot$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta R = 200$ km $\sim 3 \times 10^{-4} R_\odot$</td>
<td>0.1 $R_\odot$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n = $10^{15}$ cm$^{-3}$</td>
<td>$10^{14}$ cm$^{-3}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T = 6000 K</td>
<td>40,000 K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta R = 1000$ km/1 $R_\odot$</td>
<td>100 $R_\odot$</td>
<td>$10^5 R_\odot$</td>
<td>0.1 (PN) 10 (HII) 1,000 (QSO) pc</td>
<td></td>
</tr>
<tr>
<td>n = $10^{12}/10^6$ cm$^{-3}$</td>
<td>$10^{11} \ldots 10^8$ cm$^{-3}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T = $20,000/2 \times 10^6$ K</td>
<td>40,000...15,000 K</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Core**
- Photosphere
- Envelope
- Chromosphere/Corona

**Diagram**
- Core
- Photosphere
- Envelope
- Chromosphere/Corona

v ~ 500 km/s

$\Delta R = 200$ km $\sim 3 \times 10^{-4} R_\odot$

$v \sim 2000$ km/s

$v \sim 20,000$ km/s

$v \sim 20$ km/s (PN)

$\sim 10,000$ km/s (AGN)
Spectral Analysis

- Plasma physics: diagnostics, line broadening
- Atomic physics + quantum mechanics: light-matter interaction (micro)
- Thermodynamics: TE, LTE, non-LTE
- Hydrodynamics: atmospheric structure, velocity fields
- Radiative transfer (macro)

Stellar properties: mass, radius, luminosity, temperature, chemical composition

- Galactic structure
- Stellar and galactic evolution
- Distance scale
Spectral Analysis

- Observed spectrum
- Synthetic spectrum

Theory of stellar atmospheres
- Geometry
- Hydrodynamics
- Thermodynamics
- Radiative transfer
- Atomic physics

Model
Numerical solution of theoretical Equations
L, R, M, chemical composition
Basic equations

\[ \dot{M} = 4\pi r^2 \rho v \]
\[ v \frac{dv}{dr} = -\frac{dp}{dr} \frac{1}{\rho} + g_{\text{rad}} - g \]

\[ g_{\text{rad}} = g_{\text{cont}} + \frac{\text{const}}{\rho} \sum_{\text{lines}} f_{\nu u} g_{\nu u} \left( \frac{n_{\nu}}{g_{\nu}} - \frac{n_{u}}{g_{u}} \right) \int_{0}^{\infty} \int_{-1}^{1} I_{\nu}(\mu) \phi(\nu) \mu d\mu d\nu \]

Hydrodyn.

Rate equations

\[ n_{i} \sum_{j \neq i} (R_{ij} + C_{ij}) + n_{i} (R_{iK} + C_{iK}) = \frac{n_{j} (R_{ji} + C_{ji}) + n_{j}^{+} (R_{Ki} + C_{Ki})}{r (1 - \mu^2)} \]
\[ I_{\nu}(r, \mu) = n_{\nu}(r) - \chi_{\nu}(r) I_{\nu}(r, \mu) \]

Radiative transfer

\[ (S_{\nu} - I_{\nu}) \kappa_{\nu} = \mu \frac{\partial I_{\nu}}{\partial r} + \frac{1 - \mu^2}{r} \frac{\partial I_{\nu}}{\partial \mu} \]

energy equation

\[ v \frac{de}{dr} + pv \frac{d}{dr} \left( \frac{1}{\rho} \right) = \frac{1}{\rho} \cdot \int_{0}^{\infty} 4\pi \kappa_{\nu} (J_{\nu} - S_{\nu}) d\nu \]

Non-linear coupling \( \rightarrow \) complex iteration !!!
complex atomic models for O-stars (Pauldrach et al., 2001)
HD 93129A O3Ia

consistent treatment of expanding atmospheres along with spectrum synthesis techniques allow the determination of stellar parameters, wind parameters, and abundances.
Population synthesis of high-z galaxies

Stellar spectra

Galaxy spectra

Non-LTE atmospheres with winds plus stellar evolution models → Synthetic spectra of galaxies at high z as a function of Z, IMF, SFR
Spectral diagnostics of high-z starbursts

Starburst models - fully synthetic spectra based on model atmospheres

Spectral diagnostics of high-z starbursts

Fully synthetic spectra vs. observation


cB58 @ z=2.7
Starburst99 population synthesis models + UV stellar libraries at ~solar and ~0.25 solar (LMC, SMC) abundance
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Readings

- these notes