**Stellar Atmospheres: Literature**

- **Dimitri Mihalas**  
  - Stellar Atmospheres, W.H. Freeman, San Francisco
- **Albrecht Unsöld**  
  - Physik der Sternatmosphären, Springer Verlag (in German)
- **Rob Rutten**  
  - Lecture Notes Radiative Transfer in Stellar Atmospheres  
    http://www.fys.ruu.nl/~rutten/node20.html

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**Why physics of stellar atmospheres?**

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<th>Astronomy</th>
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<td>Spectral analysis of stars</td>
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<td>Plasma-, atomic-, and molecular physics, hydrodynamics, thermodynamics</td>
<td>Structure and evolution of stars</td>
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<td>Basic research</td>
<td>Galaxy evolution</td>
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<td>Technical application</td>
<td>Evolution of the Universe</td>
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Magnetic fields in white dwarfs and neutron stars

Shift of spectral lines with increasing field strength

Hertzsprung Russell Diagram
Chemical evolution of the Galaxy

Carretta et al.
2002, AJ 124, 481
Stellar Atmospheres: Motivation

SN movie

SN Ia

Stellar Atmospheres: Motivation
Stellar Atmospheres: Motivation

SN Ia cosmology

\[ \Omega_M, \Omega_\Lambda \]

0, 1

0.5, 0.5

1, 0

1.5, -0.5

Redshift z

\[ \frac{H_0}{\sqrt{\Omega_M + \Omega_\Lambda}} = 15 \text{ Gyr} \]

14.3 Gyr

11.9 Gyr

9.5 Gyr

7.6 Gyr
Stellar Atmospheres: Motivation

Uranium-Thorium clock

Stellar atmosphere – definition

- From outside visible, observable layers of the star
- Layers from which radiation can escape into space
  - Dimension
- Not stellar interior (optically thick)
- No nebula, ISM, IGM, etc. (optically thin)
- But: chromospheres, coronae, stellar winds, accretion disks and planetary atmospheres are closely related topics
Stellar Atmospheres: Motivation

Fraunhofer lines
Stellar Atmospheres: Motivation

**Spectrum - schematically**

![Spectrum graph](image)

**Spectrum formation**

![Spectrum formation diagram](image)
Formation of absorption lines

Line formation / stellar spectral types
Stellar Atmospheres: Motivation

The spectral types on the main sequence:

O        B       A       F       G       K       M

O5       B4      O7      B6       A1      A5      A8      A9

Die Spektraltypen der Hauptreihe:

O        B       A       F       G       K       M

F6       G2      G5      G8      A7      F3      G6      G9

A7       F3      F8      G2      G5      G8      K5
Stellar Atmospheres: Motivation

Classification scheme

T dwarfs
Stellar Atmospheres: Motivation

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Optical telescopes

Calar Alto (Spain)
3.5m telescope
Stellar Atmospheres: Motivation

**Optical telescopes**

ESO/VLT

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Stellar Atmospheres: Motivation

**UV / EUV observations**

**Why is it important?**

![Graph](image)

- $T_{\text{eff}} = 110,000$ K
- $T_{\text{eff}} = 5,500$ K

(Both graphs showing emission flux vs. wavelength, with peaks at different temperatures)
Stellar Atmospheres:  

**UV/optical telescopes**

HST

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**X-ray telescopes**

XMM
Stellar Atmospheres: Motivation

**Gamma-ray telescopes**

![INTEGRAL](image)

**Infrared observatories**

![ISO](image)  

![JWST](image)
Stellar Atmospheres: Motivation

**Sub-mm telescopes**

![Artist's impression of ALMA (Atacama Large Millimetre Array)](image)

**Radio telescopes**

100m dish at Effelsberg
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Planetary nebula spectrum

PG 2131+066 HST-GHRS Cycle 5 data (smoothed 0.5Å)

$T_{\text{eff}}/\text{K} = 95000$

$\log (g/\text{cm}^2) = 7.5$

+ ISM
Stellar Atmospheres: Motivation

Quasar + IGM spectrum

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Stellar Atmospheres: Motivation

Stellar wind spectrum

Eta Carinae - HST

Stellar wind spectrum
Formation of wind spectrum (P Cygni line profiles)

Stellar winds – P Cyg profiles

Blueshift

Redshift

continuum

1538 1542 1546 1550 1554 1558

km/s

-2000 -1000 0 1000
Accretion disks

AM CVn disk spectrum

- $R_{\text{out}} = 1.4 \, R_\odot$, $R_{\text{in}} = 11.3 \, R_\odot$
- $\dot{M} = 3 \times 10^{-6} \, M_\odot/\text{yr}$
- Inklination $i = 30^\circ$
Temperature structure of an accretion disk

Planetary atmospheres

HST detects additional sodium absorption due to light passing through planetary atmosphere as planet transits across star.
Quantitative spectral analyses – what can we learn?

**Shape of line profile:**
- Temperature
- Density
- Abundance
- Rotation
- Turbulence
- Magnetic field

**Temporal variation:**
- Companion
- Surface structure
- Spots
- Pulsation

**Line position:**
- Chemical composition
- Velocities
- Redshift

Zeeman effect
Magnetic fields

Spectrum of a white dwarf (PG 1658+440) with field strength of about 5 MG

White dwarf Grw+70 8247
B=300MG
Extrasolar planets

![Graph showing velocity fields and wavelength](image)

**51 Pegasi**

- Mass = 0.45 \( M_{\text{Jup}} / \sin i \)
- \( P = 4.233 \) day
- \( v = 25.84 \) m/s
- \( e = 0.04 \)

**Distance / 1000 km**

- \( \sim 0.01 \) Å

**Solar disk**

- Distance / 1000 km
- Time / min
Non-radial pulsation modes

Time resolved spectroscopy
Stellar Atmospheres: Motivation

**Time dependent line profiles**

- **Doppler tomography**
Summary – stellar atmospheres theory

The atmosphere of a star contains less than one billionth of its total mass, so, why do we care at all?

• The atmosphere of a star is that what we can see, measure, and analyze.
• The stellar atmosphere is therefore the source of information in order to put a star from the color-magnitude diagram (e.g. B-V, m_V) of the observer into the HRD (L, T_{eff}) of the theoretician and, hence, to drive the theory of stellar evolution.
• Atmosphere analyses reveal element abundances and show us results of cosmo-chemistry, starting from the earliest moments of the formation of the Universe.
• Hence, working with stellar atmospheres enables a test for big-bang theory.
• Stars are the building blocks of galaxies. Our understanding of the most distant (hence most early emerged) galaxies, which cannot be resolved in single stars, is not possible without knowledge of processes in atmospheres of single stars.
• Work on stellar atmospheres is a big challenge. The atmosphere is that region, where the transition between the thermodynamic equilibrium of the stellar interior into the empty blackness of space occurs. It is a region of extreme non-equilibrium states.

Summary – stellar atmospheres theory

Important source of information for many disciplines in astrophysics
— research for pure knowledge, contribution to our culture
— ambivalent applications (e.g. nuclear weapons)

Application of diverse disciplines
— physics
— numerical methods

Still a very active field of research, many unsolved problems
— e.g. dynamical processes