ASTR545:
STELLAR ATMOSPHERES

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Motto:

One picture is worth 1000 words, but one spectrum is worth 1000 pictures!

Introduction

1. Outline
    - What is a stellar atmosphere?
    - Basic properties and morphology
    - Why study stellar atmospheres?
    - Stellar Atmospheres in the global astronomical and physical context
2. Observational Foundations
    - Spectral Classification
    - Colors, color-magnitude diagrams

What is a stellar atmosphere?

- generally, any material connected physically to a star, from which the photons escape to the surrounding space

- that is, the region where the radiation, observable by a distant observer, originates

- usually, a very thin layer on the surface of a star

- solar type stars: photosphere, chromosphere, corona

- early-type stars: photosphere, expanding regions - wind

Physical conditions

TEMPERATURE (T)

• Main sequence stars	• $T \sim 2000 - 60{,}000$ K; typ. 10^4 K
• Brown dwarfs, giant planets	• $T \sim 50 - 2000$ K
• Hot, degenerate objects	• $T \sim 10^4 - 10^8$ K
– White dwarfs	– $T < 100{,}000$ K
– Pre-WD (PG 1159 stars)	– $T < 300{,}000$ K
– Super-soft sources	– $T \sim 10^5 - 10^7$ K
– Neutron stars	– $T \sim 10^7$ K
– Accreting NS	– $T \sim 10^7 - 10^8$ (10^9) K

DENSITY (or number density, N)

• MS	• $N \sim 10^{10} - 10^{15}$ cm^{-3}
• Outer layers	• $N \sim 10^5 - 10^{10}$
• WD	• $N \sim 10^{14} - 10^{18}$
• NS	• $N \sim 10^{16} - 10^{22}$

Under these conditions:

- Non-equilibrium statistical mechanics
- Randomly distributed particles --> no collective effects
- Radiation described via photons
- Wave phenomena (e.g. refraction) usually negligible (because the mean interparticle distance > wavelength

WHY STUDY STELLAR ATMOSPHERES?

Salpeter's question (to Dimitri Mihalas, some 40 years ago)

"Why in the world would *anyone* want to study stellar atmospheres? They contain only 10^{-10} of the mass of a typical star! Surely such a negligible fraction of a star's mass cannot possibly affect its overall structure and evolution."

THREE GROUPS OF ANSWERS

- A) Importance of atmospheres in the context of stars
- B) Importance of stars in the Big Picture
- C) Methodological importance

Importance of atmospheres in the context of stars

- Atmospheres are all we see (with a few exceptions) ==> we want to use this information in the fullest
- Determination of basic stellar parameters (*M, R, L*)
- Determination of chemical composition
- Determination of secondary parameters (turbulence, rotation, etc.)
- Determination of the detailed physical state
- Outer boundary for the stellar structure/evolution models
- Atmospheres do influence the evolution after all (via mass loss from the atmosphere; or for strongly irradiated objects - EGP)
- Predicting otherwise unobservable radiation (EUV)

FUNDAMENTAL STELLAR PARAMETERS

- From the viewpoint of stellar evolution
  - mass
  - chemical composition
  - age
- From the instantaneous point of view
  - mass - M
  - radius - R
  - luminosity - L
  - chemical composition
- From the viewpoint of stellar atmospheres
  - effective temperature - T_{eff}, where $L = 4\pi R^2 \sigma T_{eff}^4$
  - surface gravity, $\log g$, where $g = GM/R^2$
  - chemical composition

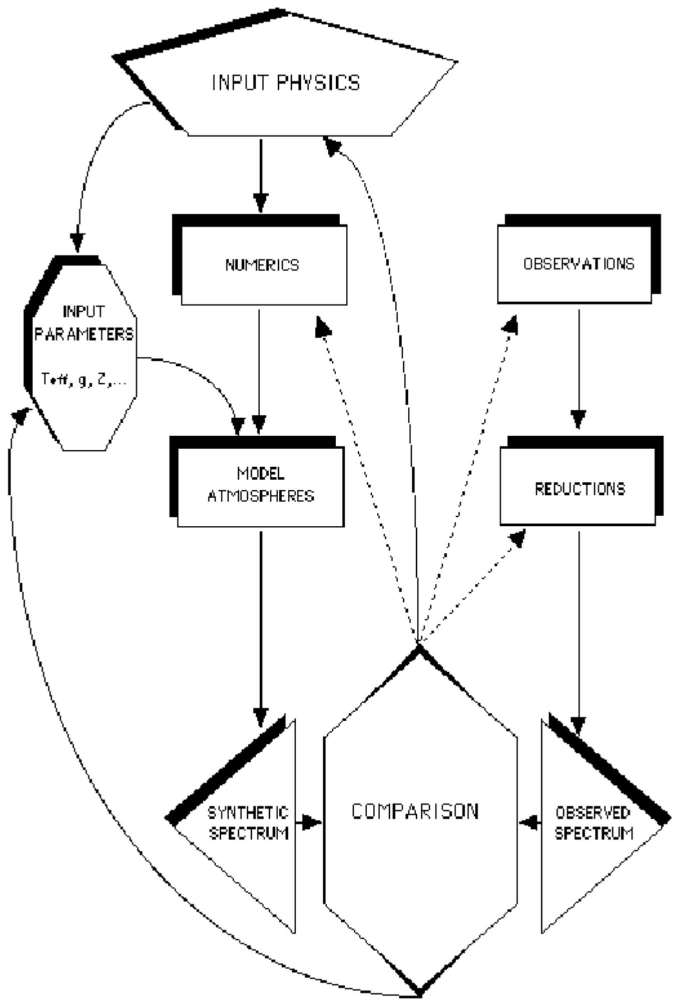
Importance of stars in the global context

- Stars are fundamental building blocks of galaxies
- They thus directly contribute to population synthesis of galaxies
- Ionization of ISM
- Important sources of photons in the Universe
- First stars - re-ionization of the Universe (?)
- Engines for making chemical species
- Precursors of supernovae (through SNe they thus influence the distance ladder ==> most of modern cosmology partly hinges on them)

Methodological importance

- Radiation is not only a *probe*, but an important *energy (and momentum) balance agent*
- Radiation thus *determines* the physical structure, yet the structure is probed only by the radiation
- Sophisticated modeling approach needed ==> stellar atmospheres are thus *guides* for modeling other astronomical objects, such as:
  - Accretion disks
    - AGN, quasars (around supermassive black holes)
    - X-ray binaries (around solar-mass black holes or neutron stars)
    - Cataclysmic Variables (CV) (around white dwarfs)
  - H II regions, planetary nebulae, ISM
  - planetary atmospheres (in particular, extrasolar planets)
  - also, for instance, neutrino transport in core-collapse SNe

Astrophysical spectroscopic diagnostics



Global outline

- 1. Introduction
- 2. Phenomenological Description of Radiation
- 3. Physics of Radiation-Matter Interaction
- 4. Radiation Transport
- 5. Model Atmospheres and Spectral Analysis
- 6. Beyond Classical Models

Introduction

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Phenomenological Description of Radiation

3. Radiation
   - Specific intensity
   - Mean energy and energy density
   - Radiation flux and pressure tensor
   - Thermal radiation: Planck function
4. Interaction of radiation with matter
   - Absorption, emission, and scattering of radiation
   - Phenomenological absorption and emission coefficients
   - Stimulated emission
   - Emission by scattering
5. Radiative transfer equation
   - Derivation
   - Transport equation in various geometries
   - Moments of the transport equation
   - Optical depth and the source function
   - Probabilistic interpretation
   - Diffusion approximation
6. Approximate treatments of line formation
   - Eddington-Barbier relation
   - Classical Milne-Eddington and Schuster-Schwarzschild models
   - Optically thick and thin regimes
   - Escape probability
   - Flux-limited diffusion
   - Some astrophysical applications

Physics of Radiation-Matter Interaction

7. Kinetic equilibrium; LTE and NLTE
   - Fundamentals of statistical mechanics
   - Local Thermodynamic Equilibrium (LTE)
   - Microscopic requirements of LTE
   - Departures from LTE: non-LTE (or NLTE) effects
   - NLTE rate equations
8. Quantitative description of radiation-matter interactions
   - Semi-classical calculation of transition probabilities
   - Einstein relations for bound-bound transitions
   - Einstein-Milne relations for the continuum
   - Continuum absorption and scattering cross-sections
   - Thomson and Compton scattering
9. Spectral lines: broadening and redistribution
   - Overview of line broadening mechanisms
   - Natural damping
   - Collision (pressure) broadening
   - Frequency redistribution in lines
   - Redistribution functions

Radiation Transport

10. Formal solution of the transfer equation
    - Basic strategies; discretization
    - Integral methods: short characteristics
    - Finite elements methods; discontinuous finite element
    - Second-order differential methods: Feautrier algorithm
    - Comparison of methods
11. Radiative transfer with scattering
    - Nature of the problem
    - Lambda iteration and its failure
    - Direct algorithms
    - Iterative methods
12. Accelerated Lambda iteration
    - Aside on linear algebra: iterative solutions of large sparse linear systems
    - Astrophysical implementation
    - Construction of the approximate operator
13. NLTE line transfer
    - Two-level atom
    - Equivalent 2-level atom approach
    - Multi-level atom: coupling of many transitions and levels
    - Modern numerical approaches

Model Atmospheres and Spectral Analysis

14. Basic physics and equations of stellar atmospheres
    - Overview of Equations
    - Overview of approximations; basic types of models
    - Energy balance: radiative and convective equilibrium

15. Model stellar atmospheres: LTE-gray models
    - Formulation
    - Mean opacities
    - LTE-gray model: a key to understand the temperature structure of a stellar atmosphere
    - Generalizations of the gray model: two-step gray; multi-group

16. LTE model atmospheres
    - Temperature correction schemes
    - Treatment of convection: Mixing-length theory
    - Line blanketing
    - Treatment of molecules
    - Results: LTE temperature structure and emergent energy distribution
    - Existing grids of LTE model atmospheres: Kurucz models

17. NLTE stellar atmospheres: Methods
    - Early approximate models: Detailed radiative balance in lines
    - Complete Linearization
    - Modern numerical methods: application of ALI
    - NLTE line blanketing: superlevels and superlines
    - TLUSTY code
18. NLTE stellar atmospheres: Results; grids
    - NLTE temperature structure
    - Effects of NLTE line blanketing
    - NLTE emergent spectral energy distribution
    - Overview of existing computer programs and model grids
19. Use of model atmosphere for determining basic stellar parameters
    - Classical methods: curve of growth, abundances
    - Micro- and macro-turbulence, rotation
    - Detailed spectrum synthesis
    - Fit diagrams
    - NLTE abundance determination
    - Overview of spectrum synthesis codes

Beyond Classical Models

20. Radiative transfer in expanding atmospheres
    - Transfer equation in the observer's (Eulerian) frame
    - Transfer equation in the comoving (Lagrangian) frame
    - Sobolev approximation
    - Numerical methods
21. Stellar winds
    - Equations of radiation hydrodynamics
    - Radiation (line)-driven winds
    - Other types of stellar winds
    - Wind diagnostics
22. Atmospheres of substellar mass objects
    - Exatrasolar giant planets and brown dwarfs: Similarities and differences
    - Chemical equilibrium and departures from it
    - Grains and cloud formation
    - Models atmospheres of substellar mass objects
    - Theory precedes observations: models spectra of yet undiscovered Y dwarfs
    - Some applications
23. Accretion disks
    - Basic physics of accretion disks
    - Atmospheres and disks: similarities and differences
    - Accretion disk models
    - Applications: quasars and AGNs, X-ray binaries; cataclysmic variables
24. Advanced radiative transfer
    - Multi-dimensional transport
    - Time-dependent radiation transport
    - Neutrino transport; core-collapse supernovae
    - Radiation Hydrodynamics

Literature

- D.Mihalas and I. Hubeny, 2008: *Stellar Atmospheres*, 3rd Ed. (so far unpublished - draft version of selected chapters)
- I. Hubeny, 1997: *Stellar Atmospheres Theory: An Introduction*, in "Stellar Atmospheres: Theory and Observations", ed. by J.P. De Greve, R. Blomme, and H. Hensberge, Lecture Notes in Physics, Springer, Berlin Heidelberg (available electronically)
- D.Mihalas, 1978: *Stellar Atmospheres*, 2nd Ed., Freeman, San Francisco