Stellar Spectroscopy Workshop Prerequisites

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About

This document provides a list of short descriptions of topics which are required for the Spectroscopy Workshop. The description is also accompanied by references to websites and books for a further read on the topic. Most of the topics for this workshop are covered in great detail in the book, David Gray, The Observation and Analysis of Stellar Photospheres. All participants are highly suggested to check the contents of this book. This book will be referred to as Gray's book from now on.

Descriptions

2.0.1 Stellar Spectral Classification

Definition - In Astronomy, stars are classified based on their temperatures and luminosity. The standard spectral classification is -

O	>25000K
B	11000 - 25000K
A	7500 - 11000K
F	6000 - 7500K
G	5000 - 6000K
K	3500 - 5000K
M	<3500K

Within two consecutive spectral classes, it can be further divided into ten subclasses, e.g. - F5, A4 or A0. The luminosity classification is -

Ia	Most luminous supergiants
Ib	Less luminous supergiants
II	Luminous giants
III	Normal giants
IV	Subgiants
V	Main sequence stars (dwarfs)

Importance - Spectral classification allows us to approximate the kind of physics involved in that star without knowing its exact temperatures and luminosities.

Reference - Jesse S Allen, Stellar Spectral Classification

2.0.2 Spectral resolution

Definition - The spectral resolution of a spectrograph is a measure of its ability to resolve features in a spectrum between two wavelengths separated by a small amount. It is denoted by - $\frac{\lambda}{\delta\lambda}$.

Importance - The higher the spectral resolution, the finer the features that can be observed. Spectral resolution is important to know before estimating stellar parameters since it affects the width of the observed spectral line.

Reference - Vik Dhillon, Dispersion and spectral resolution; Gray's book(Chapter - Spectroscopic Tools)

2.0.3 Signal to Noise Ratio (SNR)

Definition - SNR is an estimate of how good a signal is, which, in our case, is the spectrum. It is the ratio between the average flux and the standard deviation in the flux. SNR is estimated only when the signal is detrended. In other words, we need to remove any general trends in the signal before estimating the SNR.

Importance - It is a quick estimate of the quality of a spectrum. The higher the SNR, the better the estimates will be. Generally, for high-resolution spectrum, $SNR > 200$ is good.

Reference - Vik Dhillon, Signal to Noise; Gray's book(Chapter - Light Detectors)

2.0.4 Hyperfine Structure

Definition - It is the splitting of degenerate atomic energy levels due to the interaction of the magnetic dipole moment of nucleons with the electrons around them.

Importance - Hyperfine splitting is important to estimate the abundances of a few elements like Lanthanum. This effect is considered only for slowly rotating stars since fast rotations will blend the lines, and the effect of hyperfine splitting will be indistinguishable.

Reference - Griffiths, Introduction to Quantum Mechanics(Chapter - Time Independent Perturbation Theory)

2.0.5 Loggf values

Definition - Spectral lines form due to the atomic transition of electrons from one energy level to another. For each of these transitions, there is a probability associated with the number of atoms which will make that transition. The probability of the transition is quantified by the oscillator strength(f) and the statistical weight(g) is the quantum mechanical corrections to it.

Importance - A correct log(gf) value is essential to correctly estimate abundances and stellar parameters. Since log(gf) changes the probability of a transition happening, it directly affects the strength of an absorption line.

2.0.6 Radiative Transfer

Definition - A mathematical description of how radiation moves through a medium. In stellar physics, it is the motion of radiation from the stellar interiors through the stellar atmosphere.

Importance - Solving the radiative transfer equation helps us understand how the spectrum of a star forms.

Reference - Rybicki and Lightman, Radiative Processes in Astrophysics(Chapter 1); Gray's book(Chapter - Radiative and convective energy transport)

2.0.7 Local Thermodynamic Equilibrium (LTE)

Definition - Any system is said to be in thermodynamic equilibrium when there is no net macroscopic flow of matter or energy; thus, the system's temperature remains constant. Since a star is a dynamic system, physicists have introduced the concept of Local Thermodynamic Equilibrium, which means that although the temperature everywhere will not be constant across the whole star, for a small enough region(hence the term local), we can assume the stellar temperature at the particular position to be a constant.

Importance - The assumption of LTE works as an approximation, reducing the computation time of radiative transfer equations.

Reference - Richmond M., Thermodynamic Equilibrium

2.0.8 Non-Local Thermodynamic Equilibrium (NLTE)

Definition - Although LTE is a good approximation for almost all regions in the stellar atmosphere, the approximation fails at the very top of the atmosphere where the density is too low for efficient energy transfer between the neighbouring atoms/ions. In such cases, the assumptions of thermal equilibrium fail, and we need to consider NLTE effects. Although low density at the upper atmosphere is one example of NLTE effects, there can be other conditions where this effect might arise too.

Importance - NLTE calculations are essential for some elements whose absorption lines are dominated by this effect, e.g., Sodium(Na).

Reference - Non-Local Thermodynamic Equlibrium, GAPT, Spain; Puertas and Taylor, Non-LTE Radiative Transfer in the Atmosphere

2.0.9 Spectral lines and continuum

Definition - Spectral lines are the absorption/emission lines seen in a spectrum. Continuum, on the other hand, is the spectrum without these spectral lines. In other words, a continuum is a smoothly varying function in a spectrum on which the spectral lines are superposed. A blackbody spectrum is a good example of a continuum, although the continuum can differ from it in an actual spectrum due to multiple reasons.

Importance - Both spectral lines and continuum can give information about the star. Whether a continuum can be helpful depends on whether we can remove the effect of the observing instrument, Earth's atmosphere and other sources. For high-resolution spectra, we cannot use the continuum, and thus, we have to use spectral lines for our analysis.

Reference - Gray's book

2.0.10 Balmer Lines

Definition - Balmer lines are spectral lines produced by the atomic transition of electrons from the higher energy levels of Hydrogen to its second energy level. The transitions are named as follows -

$H\alpha$ $(n : 3 \rightarrow n : 2)$

$H\beta$ $(n : 4 \rightarrow n : 2)$

$H\gamma$ $(n : 5 \rightarrow n : 2)$

$H\delta$ $(n : 6 \rightarrow n : 2)$

and so on...

Importance - Since Hydrogen is the most abundant element, its spectral lines are strongest compared to any other line. These lines are used to estimate effective temperature and surface gravity.

2.0.11 Continuum Normalisation

Definition - For a high-resolution spectrum, we cannot use the continuum due to the effects of the observing instrument. To use just the spectral lines from the spectra, we remove the continuum by first finding the function of the continuum and dividing the spectrum by this function to have the spectral lines.

Importance - Continuum normalisation is essential to analyse the spectral lines for estimating stellar parameters and has to be done for all high-resolution spectra.

2.0.12 Model atmospheres

Definition - To solve the radiative transfer equation, we need information on different parameters like temperature, pressure, opacities and others at each atmospheric layer. Since we cannot have infinite layers, the stellar atmosphere is divided into a finite amount of layers, and these parameters are calculated for each layer. The model atmosphere file contains the information of these parameters at each layer.

Importance - This file is essential to perform the radiative transfer calculation.

Reference - Models of Stellar Atmosphere, Vienna U., 2007

2.0.13 Linelists, Vienna Atomic Line Database (VALD)

Definition - Linelists are files that contain information about the spectral lines from different elements in a particular wavelength region and for a particular value of stellar temperature and surface gravity. VALD is one such website where you can get this list. There are other websites like NIST where you can get such linelists too. ZEEMAN code requires VALD linelist.

Importance - This file is used to generate a synthetic spectrum.

Reference - VALD website

2.0.14 Spectral synthesis

Definition - Spectral synthesis is the process of generating a synthetic(calculated) spectrum using the model atmospheres and line list for a particular wavelength range and stellar parameters using either the assumption of LTE or NLTE.

Importance - It is important for estimating stellar parameters by model fitting.

2.0.15 Model fitting

Definition - Model fitting is the process of estimating the stellar parameters by finding the synthetic spectrum that best matches the observed spectrum. One of the ways of quantifying the best match is through chi-square minimisation.

Importance - Used for estimating stellar parameters.

2.0.16 Stellar parameters

Definition - Stellar parameters are the parameters we can determine from the stellar spectra. The list of parameters we can estimate is -

Effective temperature, T_{eff} - Surface temperature of the star

Surface Gravity, logg - Logarithm of the acceleration due to gravity at the surface of the star

Projected rotational velocity, vsini - Rotational velocity of the star projected to our line of sight

Radial velocity, v_r - Velocity of the star moving towards or away from us.

Microturbulence velocity, v_{mic} - Small-scale turbulences in the stellar atmosphere

Macroturbulence, v_{mac} - Large-scale turbulences in the stellar atmosphere

Abundances - Number density of a particular element in the stellar atmosphere with respect to Hydrogen or all elements.

Importance - Stellar parameters help us understand the star and its physics. The kind of physics that can be studied differs based on the interest of the astronomers. For example, studying the chemical peculiarity of a star using abundances for an accreting star gives information about the accreting material, accretion rate and other valuable information.

2.0.17 Chemically Peculiar Stars

Definition - A star is chemically peculiar if the abundances of different elements don't match the general abundances of the stars in the same spectral class. Different kinds of chemical peculiarities can be seen in stars; for example - Am stars show enhancements in an abundance of heavy metals, and Ap stars enhance the abundance of Si, Cr, Sr and Eu.

Importance - These stars allow us to study unique physics not generally found in other stars. For example- the chemical peculiarity in Ap stars is due to strong magnetic fields.

Reference - Gray's book(Chapter - Chemical Analysis)

2.0.18 ZEEMAN and Spectroscopy Made Easy (pySME)

Definition - ZEEMAN and SME are codes for spectral synthesis and model fitting to estimate stellar parameters from the stellar spectrum. ZEEMAN is written in Fortran, and pySME is in Python. ZEEMAN assumes LTE, but pySME can also work with NLTE if configured.

Importance - Useful tools for stellar parameter estimation from spectroscopy.

Reference - pySME Documentation, no documentation for ZEEMAN available currently.

Further Reading

1. David Gray, The Observation and Analysis of Stellar Photospheres
2. Rybicki and Lightman, Radiative Processes in Astrophysics
3. S. Chandrasekhar, Radiative Transfer
4. Puertas and Taylor, Non-LTE Radiative Transfer in the Atmosphere
5. Jeremy Tatum, Stellar Atmosphere(Online material)
6. Vik Dhillon, Stellar Structure and Evolution(Online Material)