

PROJECT

8

STELLAR SPECTRA: CLASSIFICATION

Objective: The main objective of this project is to learn how to estimate the spectral type of stars from their stellar spectra. At the completion of the project the students should i) understand the process of classifying different spectra by the relative strengths of lines, ii) to be familiar with the sequence of spectral types, iii) to be able to recognize the distinguishing characteristics of different spectral types. This project also introduces the concepts of Equivalent Width and Full Width at Half Maximum of a spectral line and explains how to obtain them.

Observations: In this project the student will make use of already reduced optical spectra of various spectral types. The analysis is carried out with the package SPLOT of IRAF. SPLOT implements graphically all the techniques described in this project. In this way the students can visualize the processes that they are performing and understand their results.

Material: The students will be provided with:

- Low and intermediate resolution spectra of MK standards of various spectral types
- ATLAS and comparison spectra for the identification of spectral lines
- The classification of stars, C. Jaschek & M. Jaschek, 1987, Cambridge University Press
- Particularly useful are the information provided by the Jet Propulsion Laboratory, California Institute of Technology:
<http://nedwww.ipac.caltech.edu/level5/Gray/frames.html>
http://stellar.phys.appstate.edu/Standards/std1_8.html
- For early-type stars (OB type): Walborn & Fitzpatrick (1990 PASP..102..379W)
- For all type of stars: http://stellar.phys.appstate.edu/Standards/std1_8.html

Contents: Stellar Spectra: Classification

1. Stellar Spectra. Spectral types & Luminosity classes
2. Characterization of the spectral line profile
3. Spectral types
4. Spectral Classification
5. Luminosity classes
6. Spectral Classification by cross-correlation with a grid of standard stars

Data used in this project are given in the file "speclass.tar.gz", which is included in the .rar file that you already downloaded.

Stellar Spectra: Classification

1. Stellar Spectra. Spectral types & Luminosity classes

The object of study is the spectrum of electromagnetic radiation radiated from stars. There are three components of a stellar spectrum: *continuum emission (blackbody radiation)*, *emission lines*, and *absorption lines*. The **continuum emission** is caused by an opaque material which emits radiation because of its temperature. The deeper you go into a star, the hotter and denser the gas. The lower layers tend to radiate all the colours rather like a hot solid (black body). However, stellar spectra are not perfect black body emitters. The cooler gas in the outer layers basically absorbs photons coming from the inner layers creating an absorption line. An **absorption line** is characterized by a lack of radiation at specific wavelength. Absorption lines are created by viewing a hot opaque object through a cooler, thin gas. The cool gas in front *absorbs* some of the continuum emission from the background source, and re-emits it in another direction, or at another frequency. Absorption lines are **subtracted** from the continuum emission, so that they appear fainter. The "strength" of an absorption line -- the amount of energy removed from the spectrum -- depends on the amount of the particular chemical element in the star causing the line and on the efficiency of absorption. An **emission line** is characterized by excessive radiation at specific wavelengths. Emission lines are **added** to the continuum emission, so that they appear brighter. Emission lines are seen when the observer sees the gas, but not the original photon source, then the observer will see the photons reemitted in a narrow frequency range.

Spectra can be displayed in different ways. The upper panel of Fig. 1 shows the raw image of a digitally recorded calibration lamp spectrum taken from the 1.3m telescope of the Skinakas Observatory, while the lower panel of Fig. 1 shows the intensity “trace” of the spectrum.

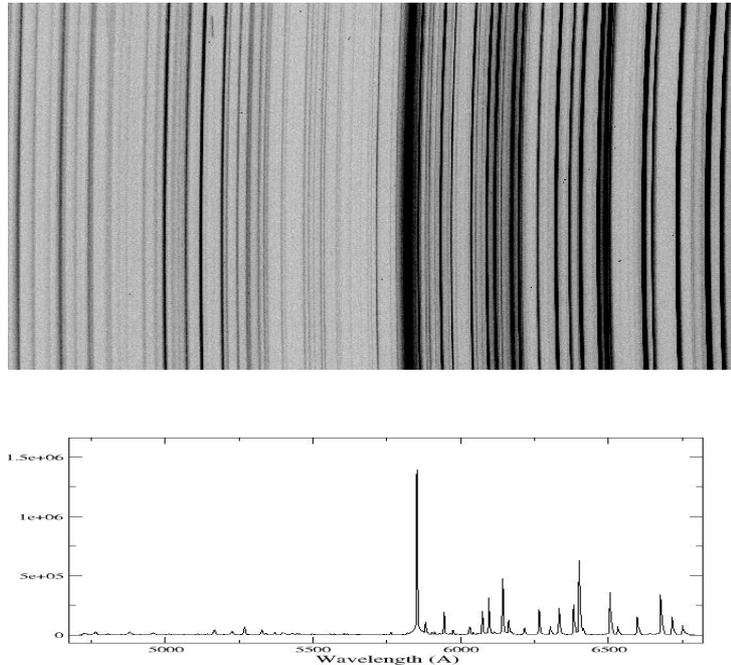


Figure 1: Raw image (above) and intensity trace (below) of a calibration lamp spectrum

2. Characterization of the spectral line profile

Equivalent Width (EW) is defined as the section of a surface counted between the level of the continuum, normalized to unity, and reference zero, having a surface identical to the profile of the line (see figure below). The equivalent width is thus measured in wavelength units (in angstroms for example).

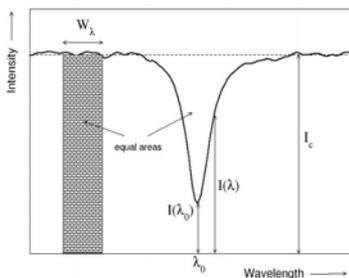


Figure 2: Definition of equivalent width of a spectral line.

Mathematically,

$$W_{\lambda} = \int_{-\infty}^{+\infty} \frac{I_c - I}{I_c} d\lambda$$

where $I(\lambda)$ is the intensity as a function of wavelength, λ , and I_c the intensity of the nearby continuum. The integration need only be done over a relatively short interval (i.e., where the line falls). The equivalent width can be envisaged as the area of a rectangle of unit height and of length W_{λ} . It is therefore the width of the rectangle whose area is equal to the integral of the energy removed by the line from the outgoing radiation.

Full Width at Half Maximum (FWHM) is the width measured at half level between the continuum and the peak of the line. The FWHM is expressed either in wavelength unit or in speed unit when the objective is to measure expansion or disk speeds (if FWHM is in units of wavelength, then the width in km s^{-1} is given by

$$FWHM(\text{km/s}) = c \frac{FWHM(\lambda)}{\lambda_c}$$

where c is the speed of the light ($c=3 \times 10^5 \text{ km/s}$) and λ_c the central wavelength of the line being considered.

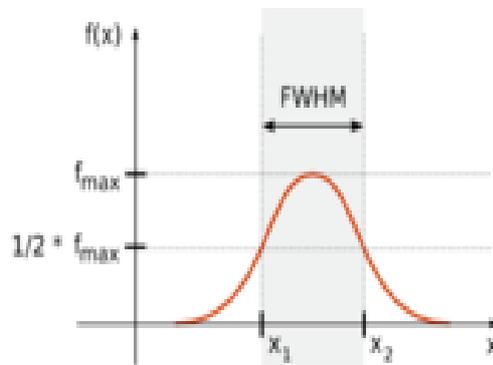


Figure 3: Definition of the Full Width at Half Maximum.

3. Spectral types

The spectral type of a star allows the astronomer to know not only the temperature of the star, but also its luminosity (expressed often as the absolute magnitude of the star) and its color. These properties, in turn, can help in determining the distance, mass, and many other physical quantities associated with the star, its surrounding environment, and its past history. Thus knowledge of spectral classification is fundamental to understanding how we put together a description of the nature and evolution of the stars.

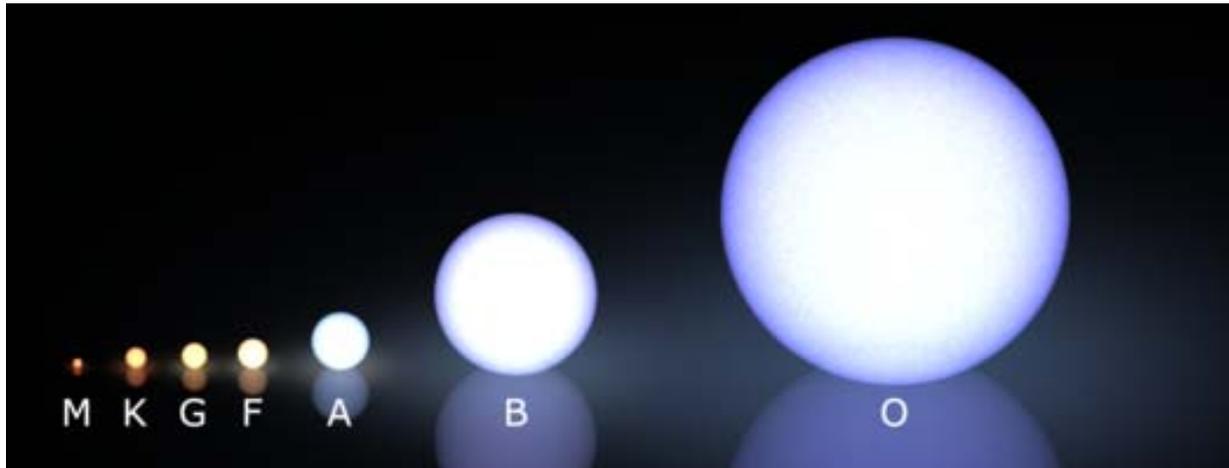


Figure 4: Comparison of the colours and sizes of stars of different spectral types. Picture taken from Wikipedia

Stellar classification is a classification of stars based initially on the photospheric temperature. Stellar spectroscopy offers a way to classify stars according to their absorption lines; particular absorption lines can be observed only for a certain range of temperatures because only in that range is the involved atomic energy levels populated. The Morgan-Keenan (MK) stellar classification is the most commonly used. The common classes are normally listed from hottest to coldest.

Table 1: Mass, radius and luminosity along the spectral sequence compared to the Sun

Class	Temperature	Star colour	Mass	Radius	Luminosity	Hydrogen lines
O	30,000 – 60,000 K	Bluish ("blue")	60	15	1,400,000	Weak
B	10,000 – 30,000 K	Bluish-white ("blue-white")	18	7	20,000	Medium
A	7,500 – 10,000 K	White with bluish tinge ("white")	3.2	2.5	80	Strong
F	6,000 – 7,500 K	White ("yellow-white")	1.7	1.3	6	Medium
G	5,000 – 6,000 K	Light yellow ("yellow")	1.1	1.1	1.2	Weak
K	3,500 – 5,000 K	Light orange ("orange")	0.8	0.9	0.4	Very weak
M	2,000 – 3,500 K	Reddish orange ("red")	0.3	0.4	0.04	Very weak

Spectral classes are further subdivided by Arabic numerals (0–9). For example, A0 denotes the hottest stars in the A class and A9 denotes the coolest ones. The sun is classified as G2.

Exercise 1: Why do O stars and K stars BOTH have weak hydrogen lines?

Absorption lines occur when an electron absorbs energy from the spectrum to move up the energy levels in the atom. Since hydrogen has only one electron, this electron is usually in the ground state. But as the temperature rises, the average electron gains more energy from collisions with other atoms, moving up to the second energy level, then the third, and so on. If the gas is hot enough, the electrons leave the atom entirely, so that it becomes ionized. The Balmer lines are produced only by hydrogen atoms whose electrons are in the second energy level. If the surface of a star is as cool as the surface of the Sun (about 5800 K) or cooler, most of the atoms are in the ground state. This means that, although stars like the Sun have a lot of hydrogen in their atmospheres, very little of their hydrogen atoms have electrons in the second energy level (most electrons are in the first energy level, which is called the ground state). Without electrons in the second level, very little Balmer radiation is produced. So, cool stars have very weak Balmer lines.

In very hot stars (like O stars which have surface temperatures of around 20,000 K), almost all of the hydrogen is either ionized (which means it has lost its electrons completely) or has electrons in only very high energy levels. Again, there are very few hydrogen atoms with electrons in the second energy level, so the Balmer lines of these stars are weak. However, in A stars (surface temperature about 10,000 K), most of the hydrogen atoms have electrons in the second energy level. These stars therefore have very strong hydrogen lines.

In short, O stars do not show many H lines because they have so high temperatures that atoms are ionised. K stars do not show H lines because the temperature is too low to make the electrons to populate higher levels other than the ground state.

4. Spectral classification

The common way of finding the spectral type and luminosity class of a star is the comparison of the unknown spectrum with those of standard stars, known as MK standards. In this project two different methods are explained:

- by visual inspection of the relative strength of certain spectral lines
- by cross-correlating the unknown spectrum with a grid of standard spectra and selecting the best match

- Spectral classification from spectral lines

Exercise 2: Using the information provided in the Table, determine the spectral type of the stars whose spectrum is shown in Fig.5.

Type	Color	Approximate Surface Temperature	Main Characteristics	Examples
O	Blue	> 25,000 K	Singly ionized helium lines either in emission or absorption. Strong ultraviolet continuum.	10 Lacertra
B	Blue	11,000 - 25,000	Neutral helium lines in absorption.	Rigel Spica
A	Blue	7,500 - 11,000	Hydrogen lines at maximum strength for A0 stars, decreasing thereafter.	Sirius Vega
F	Blue to White	6,000 - 7,500	Metallic lines become noticeable.	Canopus Procyon
G	White to Yellow	5,000 - 6,000	Solar-type spectra. Absorption lines of neutral metallic atoms and ions (e.g. once-ionized calcium) grow in strength.	Sun Capella
K	Orange to Red	3,500 - 5,000	Metallic lines dominate. Weak blue continuum.	Arcturus Aldebaran
M	Red	< 3,500	Molecular bands of titanium oxide noticeable.	Betelgeuse Antares

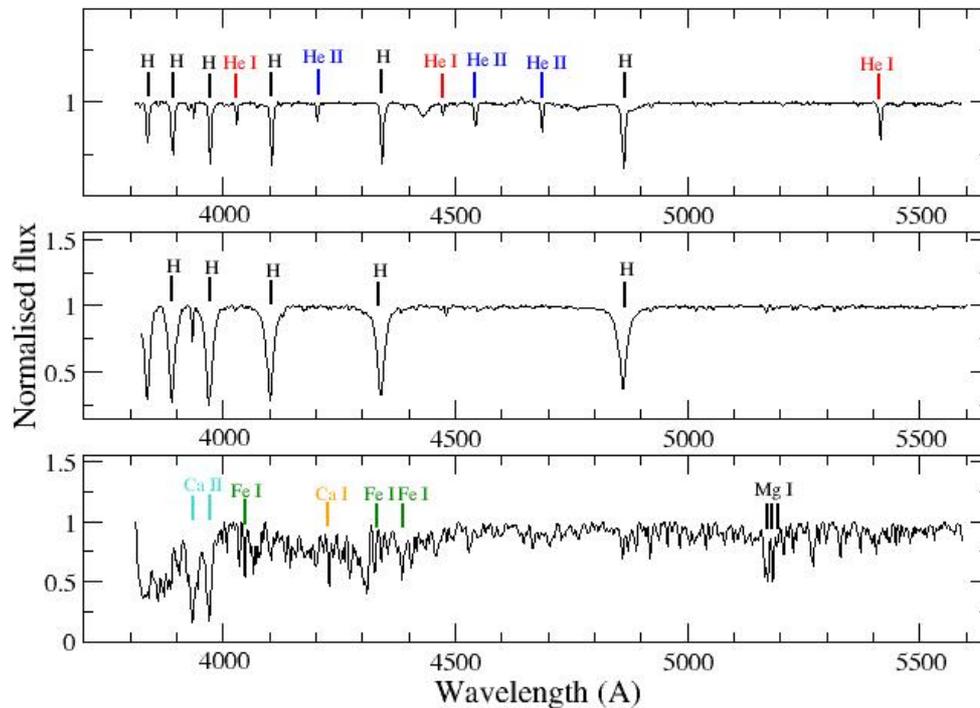


Figure 5: Star spectra. Find out the spectral type.

Exercise 3: Obtain the spectral type and luminosity class of the spectra corresponding to the following files: a) 2s.dat, b) lsi.dat, c) uma.dat and d) her.dat

HINT: classification is done by visual inspection of standard stars. You have to identify the spectral lines (chemical composition) and compare the ratio of some lines with that of the standard. You will find good reference material in

-The classification of stars, C. Jaschek & M. Jaschek, 1987, Cambridge University Press

-<http://nedwww.ipac.caltech.edu/level5/Gray/frames.html>

-A library of stellar spectra

Jacoby, G.H.; Hunter, D.A.; Christian, C.A., 1984, ApJS, 56, 257

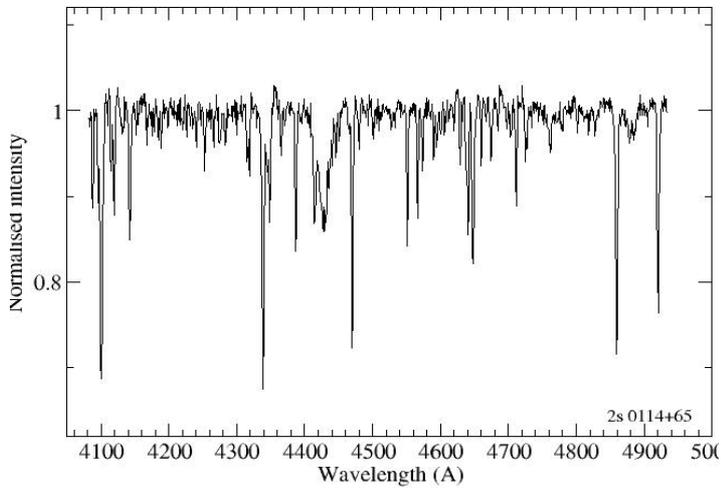
-Contemporary optical spectral classification of the OB stars - A digital atlas

Walborn, Nolan R.; Fitzpatrick, Edward L., 1990, PASP, 102, 379

-http://stellar.phys.appstate.edu/Standards/std1_8.html

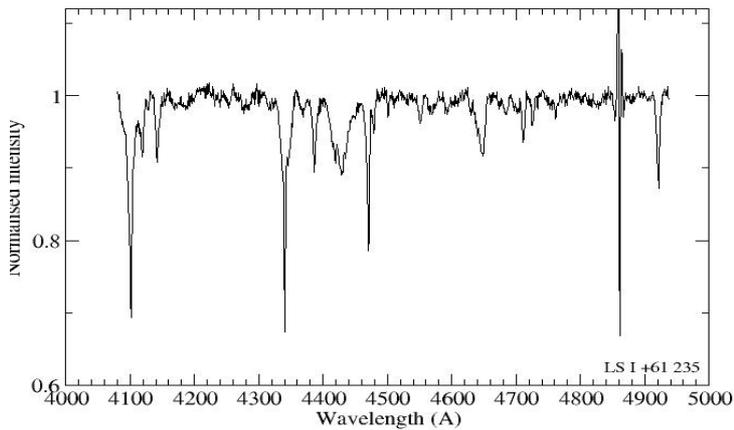
-Montes, D.; Martin, E. L. [1998, A&AS, 128, 485](#)

a) 2s.dat



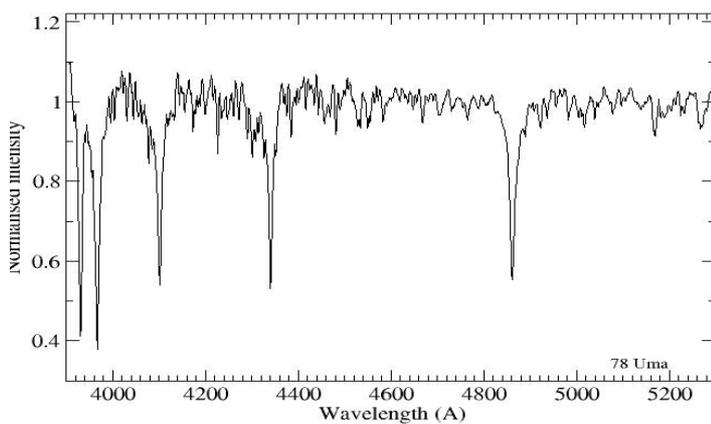
- Look for He I and H lines
- Notice the Si III lines at 4552, 4568, 4575 Å
- Notice the O II lines at 4415, 4640, 4650 Å

b) lsi.dat



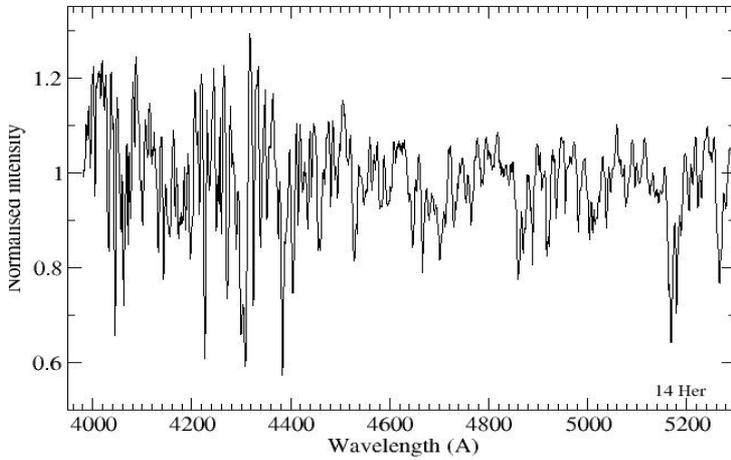
- Look for He I and H lines

c) Uma.dat



- Look for Ca II lines at 3933 Å and Ca I at 4226 Å
- Look for H lines and Fe I lines

d) her.dat



- Look for the Mg I triplet 67-72-83 Å
- Look for Fe II lines (4045 Å)
- Look for molecular lines (CH-G band at 4300 Å)

5. Luminosity classes

The spectral system is based on the **strength** of the spectral lines, which mainly depends on surface temperature. The luminosity classification is based on the **width** of the spectral lines, which mainly depends on the stellar surface gravity which is related to luminosity. In the Yerkes classification scheme, stars are assigned to groups according to the width of their spectral lines. One problem facing early attempts at classifying stellar spectra was the fact that two spectra could have the same lines present, indicating that the stars had the same effective temperature, but the lines in one star's spectrum were broader than in the other.

Luminosity classes	
Designation	Description
Ia	bright supergiants
Ib	supergiants
II	bright giants
III	giants
IV	subgiants
V	main sequence (dwarfs)
VI	subdwarfs
VII	white dwarfs

An important factor that can broaden spectral lines is pressure. Since the radius of a giant star is much larger than a dwarf star while their masses are roughly comparable, the gravity and thus the gas density and pressure on the surface of a giant star are much lower than for a dwarf. These differences manifest themselves in the form of *luminosity effects* which affect both the width and the intensity of spectral lines which can then be measured. Denser stars with higher surface gravity will exhibit greater *pressure broadening* of spectral lines.

Denser stars with higher surface gravity will exhibit greater pressure broadening of spectral lines. With increasing pressure in the stars outer layers more and more atoms will be disturbed during the time when emitting or absorbing a photon. This results in a change of energy of the levels of the atom. Thus the width of a spectral line increases as pressure increases.

The hydrogen lines are quite broad in main sequence (dwarfs) stars as a result of the disturbance of the hydrogen atoms caused by collisions. In the huge distended supergiants, however, lower density leads to lowered collision rates, and as a result the hydrogen lines are narrow.

The equation of state of an ideal gas is

$$P = nkT$$

where P is the pressure, n is the number density of gas particles, k is the Boltzmann constant (1.38066×10^{-23} J/K) and T the temperature of the gas.

The gravitational force is

$$F_{grav} = \frac{GMm}{R^2}$$

where G is the gravitational constant, M and R the mass and radius of the star and m is the mass of the photospheric gas.

The surface gravity of a spherically symmetric star is simply

$$g = \frac{GM}{R^2}$$

Thus,

$$F_{grav} = g\rho H$$

where ρ is the density of the photosphere and H the height of the column of the gas.

In equilibrium the pressure and gravitational force must balance

$$P = g\rho H$$

Two important results can be extracted from the above equations

1. Two stars with the same mass but different sizes have different surface gravities.
2. For stars of comparable temperatures, those with higher surface gravities will have higher pressures and vice-versa. If one compares spectral lines from low pressure gas and high pressure gas, one finds that the high pressure gas produces broader spectral lines.

Let's try to understand this with a couple of exercises.

Exercise 4: Calculate the surface gravities (in solar units) of the following stars:

- **Sirius A: mass = 2.0 solar, radius = 1.7 solar**
- **Sirius B: mass = 1.0 solar, radius = 0.008 solar**
- **Betegeuse: mass ~ 15 solar, radius ~ 600 solar**

HELP: Let's use the Sun as a reference star, and express the surface gravity, mass and radius in solar units. Then we have

$$\frac{g_{star}}{g_{Sun}} = \frac{\frac{GM_{star}}{R_{star}^2}}{\frac{GM_{Sun}}{R_{Sun}^2}} = \frac{M_{star}}{M_{Sun}} \left(\frac{R_{Sun}^2}{R_{star}^2} \right)$$

Both mass and size play a role in determining surface gravity, but size is the more important player because it enters into the calculation of surface gravity as a higher power (squared) than mass (linear) . In addition, the range of stellar sizes (in solar units) is much larger than the range of stellar masses (in solar units).

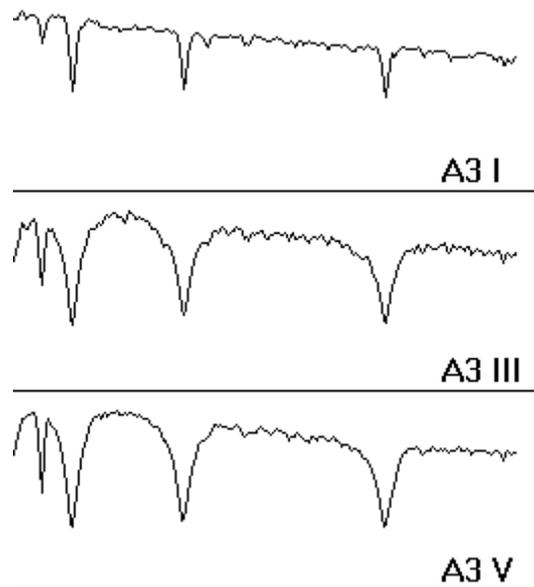


Figure 6: Spectra of stars with the same spectral type and different luminosity class

The spectra shown at Fig. 6 come from stars with the same temperature T but pressure P increasing downwards in the plot. Because the collision rate between atoms is higher for denser gas. When an atom collides with another particle, its energy levels are temporarily shifted making it possible for the atom to absorb slightly redder slightly bluer wavelengths thus making the spectral line appear broader.

Main sequence stars -- have relatively high surface gravities (but not as compared to white dwarfs!)

Giant stars -- have expanded over the size they had while on the main sequence so their surface gravity is lower and their spectral lines are narrower

Supergiant stars -- have expanded the most and so have the thinnest atmospheres and narrowest lines.

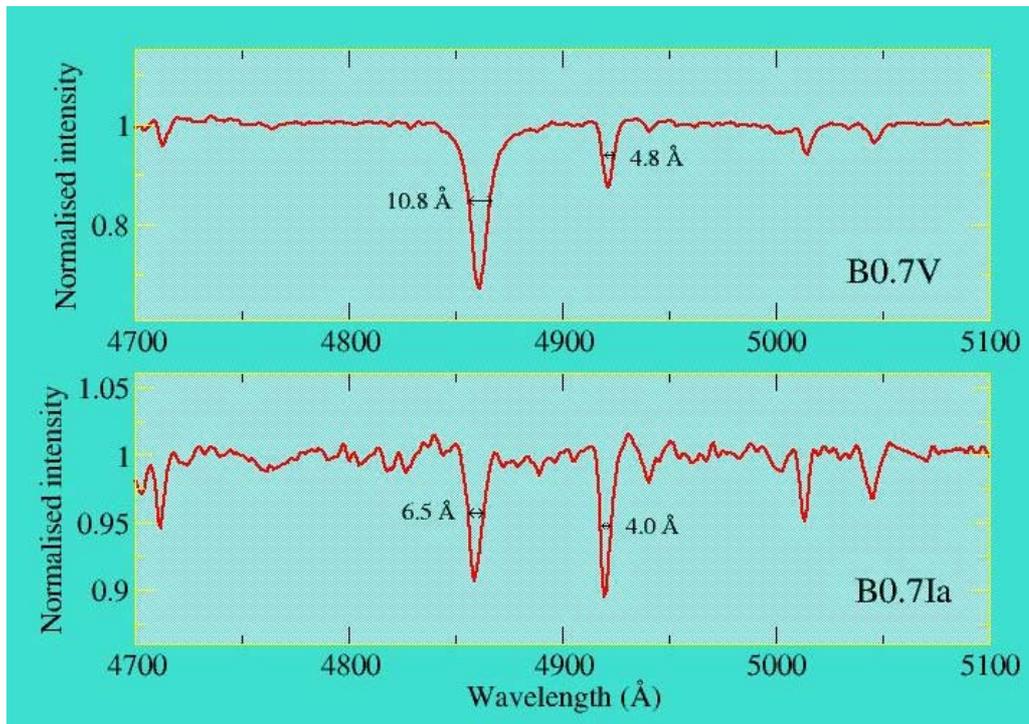


Figure 7: Comparison of a main-sequence star with a supergiant star

Exercise 5: Fit a Gaussian profile to the lines of Fig.7 and obtain the FWHM of these lines. Check if your results coincide with the values given in the figure. The file names for this exercise are *mainseq.fits* and *supergiant.fits*

IRAF help:

1. open terminal xterm (or xgterm) and start IRAF (type cl)
2. move to the directory where you have the spectra
3. run `plot mainseq.fits xmin=4700 xmax=5100` (these numbers represent the lower and upper limits of the displayed wavelength range. Other lines require different values)
4. Normalize to unity: place the mouse on the IRAF terminal and press "t" followed by "/" and "q"
5. Place the mouse on the continuum at the left of the line making sure that you include ~20 angstroms of continuum. Type "k", place the mouse on the continuum at the right of the line and type "k" again.

IRAF will perform a Gaussian fit to the line and the spectral parameters (center, flux, equivalent width and FWHM) will appear.

If you only want to measure the equivalent width you can also use the command key "e". You don't need to normalize the spectrum. Just type "e" at the left and right of the line you want to measure.

NOTE: the flux of an absorption line is negative but its equivalent width is positive. The opposite occurs in an emission line, i.e., negative equivalent width and positive flux. This is just a convention among astronomers.

6. Spectral classification by cross-correlation with a grid of standard stars

This method consists of cross-correlating (comparing) in an automatic way the unknown spectrum with EACH ONE of the spectra of a set of standard stars. This comparison is made with the task *fxcor* of IRAF (a brief user guide to *fxcor* can be found in <http://lanl.arxiv.org/abs/0912.4755>). Each cross-correlation of the unknown object with a standard produces a cross-correlation peak (CCP). The correct spectral type for the object will be the spectral type of the standard that gives the highest value of CCP.

Exercise 6: Obtain the spectral type of the following sources

a) Star 1: file star1.fits

b) Star 2: file star2.fits

c) Star 3: file star3.fits

d) Star 4: file star4.fits

HELP: Use of *fxcor* (rv package)

- 1) open an xterm (xgterm) and start up IRAF by typing "cl"
- 2) load the rv package by typing "rv" in the cl> prompt
- 3) run *fxcor*

```
cl> fxcor objects=star1.fits template=@standard.lis output=crosscor.txt verbose=txtonly  
inter=no
```

where star1.fits is the source with the unknown spectral type, standard.lis is a file that contains the spectra (fits files) of all the standard stars, crosscor.txt is the output filename where the results of the cross correlation will be written (it can be any name). The file standard.lis contains

```
>more standard.lis
```

```
HD188001_O8I.fits
```

```
HD188209_O9.5Iab.fits
```

```
HD886_B2IV.fits
```

```
HD120315_B3V.fits
```

```
HD196867_B9IV.fits
```

HD144206_B9IV.fits

HD130109_A0III.fits

HR262_A3V.fits

.....

.....

and so on

- 4) Open the crosscor.txt file with an editor and extract the value of the CCP (column named as *HGHT*) for each standard star.

Exercise 7: Make a plot of the CCP as a function of the spectral type of the standards.

In order to be able to make such plot we have to assign a numeric value to each spectral type. The easiest way is the following correspondence

O: 0 B: 1 A: 2 F: 3 G: 4 K: 5 M: 6

and treat the subclass as a fraction or decimal. So, for example a G2 star will get the value 4.2, an O9 star will be 0.9, and so on ... However, bear in mind that not all subclasses exist!. For example the subclasses for the G type are G0, G2, G5, and G8. Another example, K5 and M0 are only one subtype apart. So the above correspondence may not produce smooth curves when creating plots.