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Spectroscopy of Bright Stars

1. Introduction

In AST203, you learned that stars are, to first order, black-body radiators (see e.g. Kutner 2003). The black-body description has immediate predictions for the *spectral energy distribution* (SED) of stars: with increasing temperature, the luminosity increases, and the peak of the emission shifts to shorter wavelengths, rendering the color of hotter stars "blue" (Fig. 1). This is the main reason why main-sequence stars largely populate a one-dimensional locus in the Hertzsprung-Russel diagram (HRD), given by their effective temperature.

To second order, however, we have to take into account that the ions, atoms and molecules that make up the photosphere of a star absorb a fraction of light at specific wavelengths that correspond to certain energy transitions of the particles. For example, if there is atomic hydrogen in the star's atmosphere, the spectrum will display Hydrogen Balmer lines (Hα, Hβ, ...). The SED of a star therefore also depends on the chemical composition of its atmosphere. Fig. 1 shows example spectra of stars of a range of temperature; note that these spectra have been normalized so that the continuum is set to 1.

Moreover, the strength of an absorption line depends on how many particles are in the required state. For example, the Hydrogen Balmer lines describe transitions starting from $n = 2$, i.e. the first excited state of

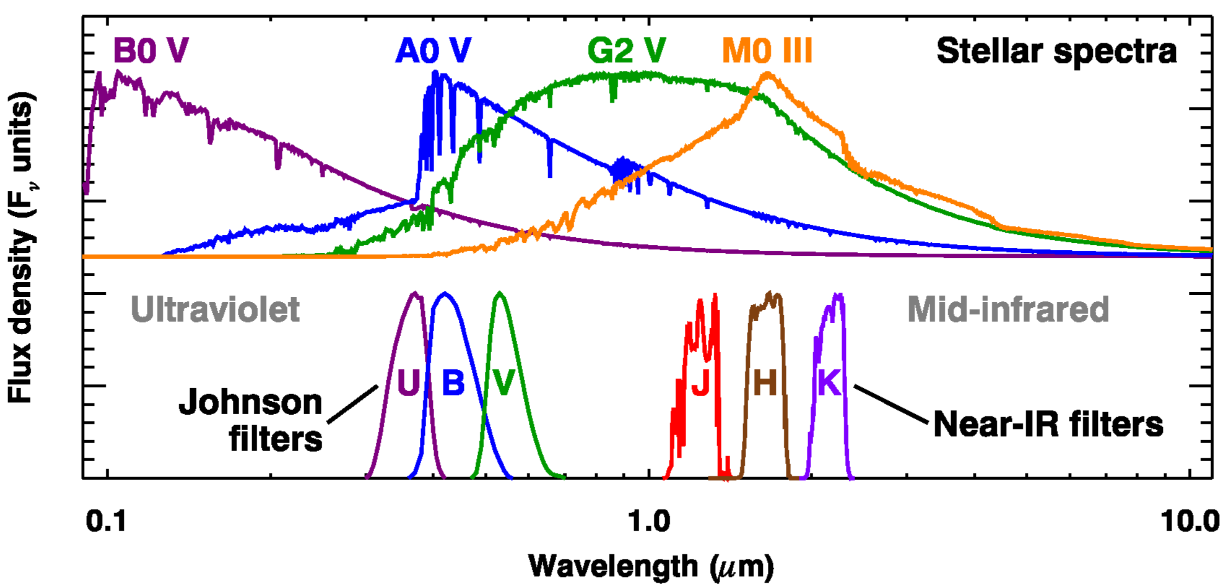

Figure 1. Top panel: model spectra for four stars with different temperatures / spectral types. The hottest stars (B0V and A0V) is the bluest, meaning that the flux ratio between the B and V filters is much higher than for cooler stars. Note that the wavelength range shown here is much wider than what we can observe with our equipment. Figure from `https://users.physics.unc.edu/~gcsloan/research/spectra.html`.

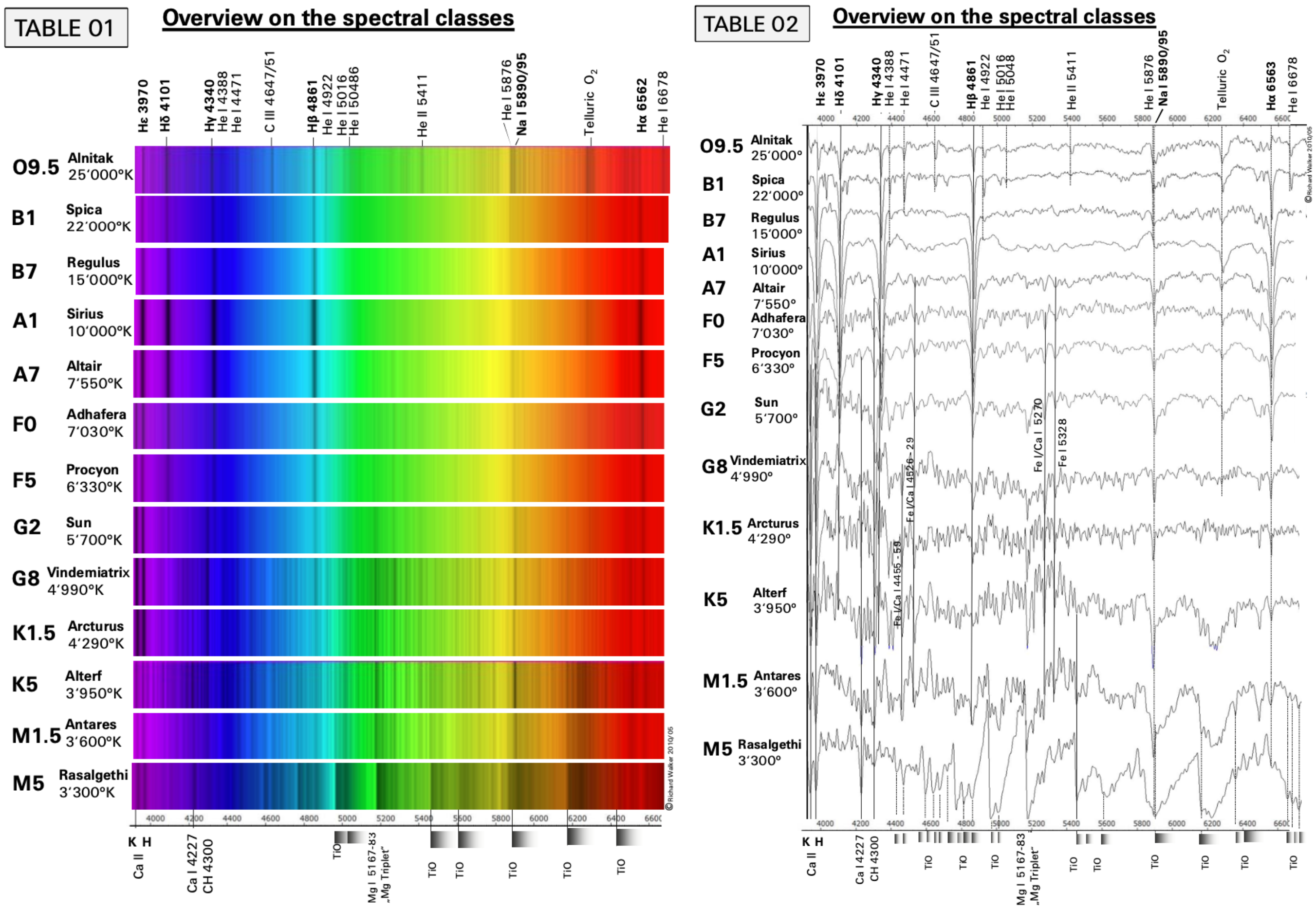

Figure 2. Example spectra of stars over a wide range of temperatures. Note that the spectra have been normalized; i.e. the continuum has been set to 1 by dividing the spectra by the continuum flux. It is clearly evident that the strength of absorption lines varies with stellar temperature. Figure from Walker (2017).

the Hyrogen atom. Hα is the transition from $n = 2$ to $n = 3$, Hβ from $n = 2$ to $n = 4$, and so forth. If the star is too cold, very few Hydrogen atoms are in the first excited state, and the Balmer lines are weak. If the star is very hot, the population ratio between two state of energy levels approaches a limit given by the ratio of their statistical weights. The population ratio can be calculated from a *Boltzmann distribution.*

However, with increasing temperature, more atoms become ionized. For Hydrogen atoms, ionization means that the atoms no longer produce any discrete line transitions. Therefore, the Balmer lines are also weak in very hot stars. The population ratio between two ionization states is given by the *Saha equation*.

For Hydrogen, we expect the Balmer lines to be most prominent in A stars, and weaker in both colder stars (since fewer atoms in the $n = 2$ state) and hotter stars (since more atoms are ionized). Similar calculations can be done for other line transitions commonly found in stellar spectra, see Fig. 1.

This lab has two goals:

1. Measure the strengths of several absorption lines in stars of a range of temperatures (similar to Fig. 1).

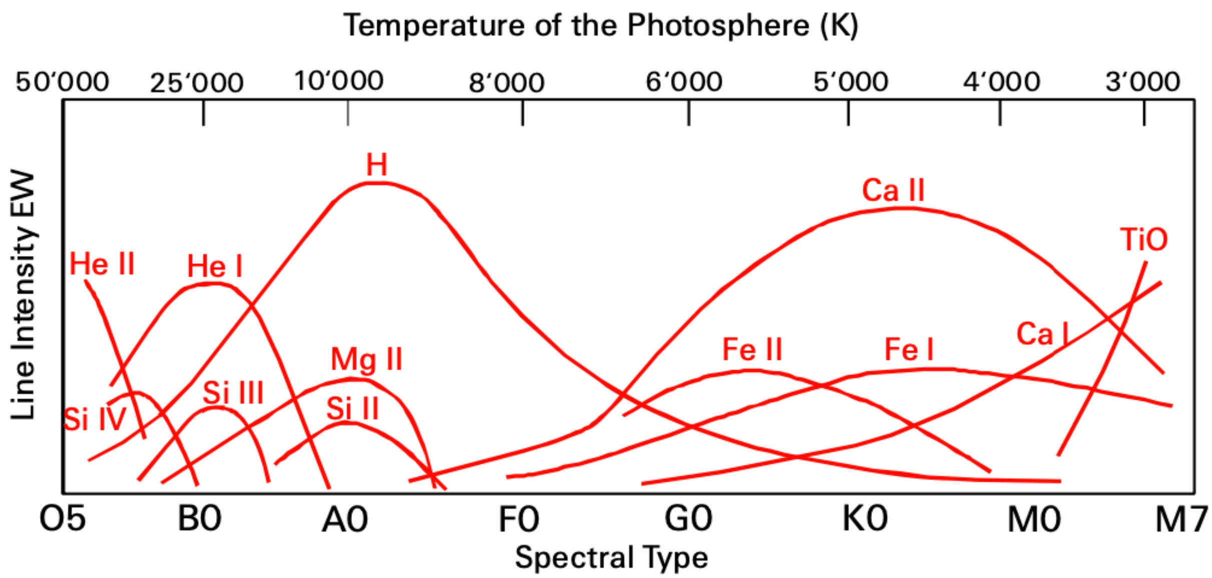

Figure 3. A schematic of line strength vs temperature for several absorption lines commonly found in stellar spectra. Figure from Walker (2017).

2. Produce flux-calibrated spectra of these stars that show the varying shape of the continuum with temperature (similar to the top panel of Fig. 1).

2. Equipment

- “high-resolution” DADOS spectrograph with 900 l/mm grating - ST402ME CCD camera (NOT the big STL1001 camera)
- Orion StarShooter AutoGuider
- same laptop as for imaging lab

3. Targets and wavelength range

Select $\sim$ 7 bright stars (mag 5 or brighter) with a range of temperatures. For example, you can pick one star from each stellar class (OBAFGKM).

There are two options in terms of which wavelength range to target:

$\sim 3900 - 4600$ Å: This range targets many important features, including the “4000 Å” break visible in the spectra of elliptical galaxies. However, it does not include any strong TiO band. Because of the limited throughput in the near-UV, the reddest star (M type) should be quite bright.

$\sim 4800 - 5500$ Å: This range includes TiO bands, but has only one Balmer line, and misses the strong Calcium H+K lines.

You only need to observe one of these options. The most prominent observable lines that we expect are listed in Table 1.

Table 1. Absorption lines that should be observable in each wavelength range.

$\sim 3900 - 4600$ Å		$\sim 4800 - 5500$ Å	
CaII H+K	3933Å, 3968Å	Hβ	4861Å
Hϵ	3970Å	He I	4922Å
HeI	4025Å	TiO	∼5000Å
Hδ	4101Å	Mg triplet	5167-83Å
CaI	4227Å	Fe I	5328Å
CH	4300Å	He II	5411Å
Hγ	4340Å		
HeI	4348, 4471Å		
CIII	4647Å		

4. Preparation

- Prepare a google doc with your observing request. The google doc should include the 3 nights that you are requesting. It should also include a table of your target stars; for each star, list its name, stellar type, temperature, magnitude, and coordinates. Prepare three StarAlt plots that show all of your targets; i.e. one StarAlt plot for each observing night. Write up a brief observational plan, i.e. the sequence in which you will observe the targets and acquire calibration. Assume that you need ~ 40 minutes for each star. Specify which calibration exposures you need to acquire, and when you will do so.
- Look up the Neon and Mercury arc lamp spectra, and come up with a strategy of how to correctly set the wavelength range. Keep in mind that 1 pixel $\sim$ 1Å. Include a description of this strategy in the google doc.

5. Data Acquisition

Follow the *Data Acquisition guide* from the Spectroscopy wiki page. Your aim is to acquire the following:

- 1 exposure of the spectrum of each star. Aim to get 5000-20000 counts (above) brackground in the brightest pixels, if possible. Note that you likely need different exposure times for different stars.
- 10 dark frames for each exposure time, taken with the same temperature as the observations.
- For each wavelength range / observing date, you need to acquire:
  - 1 arclamp spectrum.
  - ≥ 3 flat-fields. Use Auto-Dark if the exposure time is short; otherwise also take dark frames for the flat-fields.

6. Data Reduction and Analysis

Follow the *Data Reduction guide* from the Spectroscopy wiki page. The steps are:

1. *Dark subtraction:* Construct a master dark for each exposure time. Correct each star spectrum image for the appropriate dark current. If you did not use Auto-Dark, also correct each flat-field.
2. *Flat-field:* Take the median of the dark-corrected flat-fields. Follow the *Data Reduction guide* to flat-field the stellar spectra images.
3. *Extraction of 1-d spectrum and background subtraction:* For each stellar spectrum, determine on which rows the spectrum falls, and collapse the 2-d spectrum to a 1-d spectrum. Also determine, and subtract, the sky background.
4. *Wavelength calibration:* Use the arclamp spectrum to determine the dispersion relation (the pixel to wavelength mapping), and perform the wavelength calibration to all spectra. In each spectrum, identify some prominent absorption lines, and verify their wavelength. If necessary, adjust the wavelength solution by shifting its zeropoint.
5. *Normalization:* Normalize each spectrum to its continuum by fitting a low-order polynomial to its spectral shape. Mask any strong absorption features.
6. *Line widths:* Measure the strengths of the specified absorption lines. Make a plot of line strength vs. stellar temperature for the specified lines.
7. *Flux calibration:* Use the A star as spectrophotometric standard star to determine the flux calibration. Assume that its intrinsic spectrum follows a black-body curve.
8. *Spectral shape:* Calibrate the fluxes of the stars (up to an arbitrary factor). Make a plot that shows the overall shape of the spectra.

7. Discussion

In the report, make sure to discuss *why* the absorption lines vary as function of temperature in the way that you measured. Similarly, discuss the observed shape of the continuum. Make sure to note unusual features, e.g. emission lines, particularly wide absorption lines, etc. What could cause these features?

8. Lab report

The lab report is to be submitted in the style of a journal paper. Students are encouraged to also submit a notebook that documents their data analysis. Both documents need to be in pdf.

The timeline for the lab report, and intermediate check-ins is the following:

+1 week: Complete steps 1-4 from Sect. 6.
+2 weeks: Complete steps 5-6 from Sect. 6.
+3 weeks: Complete steps 7-8 from Sect. 6.
+4 weeks: Submit your lab report.

REFERENCES

Kutner, M. L. 2003, Astronomy: A Physical Perspective, 2nd edn. (Cambridge University Press)

Walker, R. 2017, Spectral Atlas for Amateur Astronomers: A Guide to the Spectra of Astronomical Objects and Terrestrial Light Sources (Cambridge University Press)