ASTR 121 – Spring 2016

Lab 3 – Blackbody and Stellar Spectra

Important dates:

- Prelab due: Monday, [Date TBA]
- Rough draft due: Monday, [Date TBA]
- Final draft due: Friday, [Date TBA]

Science Goals:

At the end of this lab, you should be able to…

- Understand the relationship between surface temperatures and spectra of stars
- Understand Planck's function and blackbody spectra
- Learn to classify stars based on their spectra
- Compare residuals and least squares

MATLAB Goals:

In this lab, you will apply MATLAB knowledge to…

- Plot functions, overlaying multiple plots, and formatting them
- Read in data and define variables

Background

An essential tool in astronomy is spectroscopy, or the measurement of spectra and spectral lines. Through examination of spectra, astronomers can determine a variety of characteristics of distant objects, such as chemical composition, radial velocity, or temperature. With stars in particular, surface temperature and spectra are so closely related that our knowledge of a star's surface temperature is directly deduced from its spectral type.

Stellar spectral types are dependent on two things: the overall shape of the spectrum, and the spectral absorption lines superimposed on it, both of which are in part determined by surface temperature. Different absorption lines are caused by particular atoms and molecules, which are excited by the star's heat to cause different amounts of absorption. In some cases, a star's surface temperature even dictates whether or not specific ions and molecules can exist in the star's atmosphere. For example, titanium oxide (TiO) will only form at lower temperatures, but extremely high temperatures are necessary for the production of doubly ionized helium (He II.) In this lab, however, we will focus on the other component of spectroscopy: the overall shape of a spectrum.

Stars are opaque, non-reflective objects, so their spectra can be approximated by a blackbody spectrum, which is solely dependent on an object's surface temperature and defined by Planck's law:

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1}$$

where I is the intensity (W sr^{-1} m^{-3}), which is the energy emitted per second (W) at a certain wavelength (m^{-1}) from a given amount of surface area (m^{-2}) as received by an outside object that covers a given solid angle (sr^{-1}). (Note: solid angle is the two-dimensional angle that an object subtends at a point, giving the size an object appears to be.) The three physical constants are: the speed of light in a vacuum c, Planck's constant h, and the Boltzmann constant k_B.

Because stars have atmospheres, Planck's law is only an approximation of their spectra. Particles in stars' atmospheres create absorption lines that differentiate real stellar spectra from a pure blackbody curve. This deviation is visible in the stellar spectra you will be using in Part 2.

Like in Lab 2, we will use the concepts of residuals for data analysis, in addition to least squares. A residual r is simply the difference between an observed value y and the theoretical value $f(x)$:

$$r = y - f(x)$$

The residual is a measure of how much data differs from theory: ideally, it is zero, but in reality, we can only strive for a minimum. The residual is used in calculation of the least-squares statistic S:

$$S = \sum_{i=1}^{n} {r_i}^2$$

where the subscript i from 1 to n denotes the i-th data value. Because a smaller value of S indicates a better match with the theory, scientists try to minimize it by varying the model function $f(x)$. In this lab, we will use the same concept in a slightly different way: instead of varying a model, we will compare one set of data to two different models, and observe which has the lower sum of squares.

About the Data

This lab has two parts: in the first, you will generate your own "data" with Planck's law. In the second part, you will need to unpack two folders from ELMS: 'Unknown Spectra' and 'Standard Spectra'. The former contains the spectra of 5 unknown stars, the latter, 13 spectra of stars with defined spectral types. Each spectrum file contains an array with two columns: the first contains wavelengths ranging from 3900 Å to 4500 Å (1 Å = 0.1 nm) and the second contains normalized intensity.

To use the data, you will need to download the folders and read the data into MATLAB (hint: in addition to 'dlmread', which we've used, a useful function may be 'textread', look it up).

Part 1: Plotting Planck's Law

In this part of the lab, you will plot the spectra of an M0 star, the Sun, and an A0 star.

1. Write a function to calculate the intensity given by Planck's law for a given surface temperature. The function should have two inputs: an array of wavelengths and a single temperature. The output will be an array of intensities. Keep everything in SI units.
2. In a script, create an array of wavelengths to use in this function. The wavelengths should range from 10^{-10} m to $1.5\text{x}10^{-6}$ m. Include as many points as needed for a smooth plot.
3. Using this array and your function, plot the spectrum of an A0 star. Before moving on, make sure the function and script work*. Does the plot look like what you'd expect?*
4. Plot the spectra of the Sun and an M0 star on the same figure. Format the plot so that each star is represented with a different color and line style. Include axis labels, a title, and a legend.
5. Now that you've looked at purely theoretical spectra, let's see how it compares to a real spectrum. Read in and plot the standard spectrum for a B0 star in a new figure.
6. Generate a spectrum for a star of the same temperature from your Planck function using the range of wavelengths given from the standard spectra data. After normalizing this array (to normalize is to divide each point by the maximum point), plot it over the real spectrum. Add the appropriate formatting. *What differences and similarities do you see in the two spectra?*

Part 2: Spectral Identification

Now we will use a set of standard models to classify five stars with unknown spectral types.

1. In a new script, read in the data for Unknown 1 and plot the spectrum.
2. To roughly identify the star, determine which two standards it most closely resembles. To do this, read in any two consecutive standard spectra, and plot the standards along with the unknown in a single figure. Format the figure as in the previous section (try adapting the script from the previous section instead of doing it all over again).

3. Using your script, change the standards until you find the two consecutive standards that match the unknown spectrum best. *What characteristics do you look for in a match?*
4. In the same script, calculate the residual of the unknown with each standard. Plot both of the residuals as a function of wavelength in a single figure with all the relevant formatting.
5. Now calculate the sum of squares of the residuals of the two standards, keeping two decimal places. Unlike the calculation of the residuals, which resulted in an array, the sum of squares should be a single number. Compare the two sum of squares to determine which standard is a better model of the data. *How is the sum of squares used for this comparison?*
6. You should now have a single script that does this whole process; use it to identify the remaining four unknowns. In your lab report, include all of the figures and data showing the process of classification for the first unknown star, but only your final classification for the other four unknowns.

Report

Your report should contain the following:

1. *Cover page*: Follow the model and guidelines in the rubric.
2. *Abstract:* In a paragraph, summarize the scientific purpose of the lab, what was done, the results, and your conclusions.
3. *Introduction:* In a few paragraphs, discuss the background information regarding the purpose of the lab and its goals.
4. *Methodology:* Explain the procedure you used to construct your figures in Part 1. Then, describe how you identified the unknown stars in Part 2. Make sure to discuss characteristics you used to match the unknowns to the standards.
5. *Analysis:* Report your determined spectral types for all the unknowns, and a figure of Unknown 1 with its corresponding standard superimposed. Discuss your use of residuals and least squares for identifying the spectral types. Include a figure of the residual of Unknown 1 with its matching standard, as well as its sum of squares.
6. *Discussion:* Discuss the quality of your results. For part one, discuss whether or not your plots match what you would expect, as well as any interesting features you observe. Do real stellar spectra look like the Planck function curves? How do they differ from the real spectra? For Part 2, consider: are the unknown stars exactly the same type as their closest standards? What is limiting your ability to determine exact spectral types? How could you improve this? Why are your residuals non-zero?
7. *Appendix:* Include the function you wrote for Planck's law and the two scripts: one for plotting the blackbody spectra and one for the spectral identification. They should be completely self-contained, meaning I should be able to hit 'run' and get the same results as you.

Remember to upload any functions and scripts as .m files on ELMS, as well as a PDF of your lab report.