# Lab #4:
# Blackbody and Stellar Spectra

February 20, 2012

Due February 24, 2012

Objectives:

To demonstrate the relation between color index and temperature.

To understand the position of main sequence stars on the HR Diagram.

To demonstrate how temperature affects the spectra of stars.

To understand why stars can be classified by their temperature.

Equipment:

MATLAB

# 1 Introduction

The spectrum of light emitted by a star is approximately a continuous blackbody spectrum with spectral absorption lines superimposed upon it. These two components of the spectrum are each affected by temperature. Thus, the light we receive from stars tells us a great deal about their temperatures. Each component is probed using a different observational technique; Broad-band photometry tells us how the energy output at shorter wavelengths compares to the output at longer wavelengths, thereby testing the shape of the blackbody continuum, while spectroscopy shows us the spectral lines, telling us about the energy states of the atoms and molecules present in the star's atmosphere and allowing us to assign the stars a spectral type. We cannot directly measure the temperatures of stars, and so these two methods provide observational measures of stellar temperatures which are used as substitutes for temperature on the Hertzsprung-Russell (HR) diagram. In this lab, you will plot some blackbody spectra, and then explore how these substitutions are made by simulating broad-band photometry of blackbody spectra to create an HR diagram and by examining spectra of stars to classify them by spectral type based on the spectral lines present.

The backbone of the spectrum we see from stars, known as the continuum, is essentially a blackbody spectrum. The shape of this spectrum is entirely dependent on temperature and is defined by the Planck function:

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

where $I$ is the intensity (SI units: W sr$^{-1}$ m$^{-2}$ m$^{-1}$), 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 amount of solid angle (sr$^{-1}$). (The sr, or steradian, is the unit of solid angle, which is an angular area. It's not terribly important for the purposes of this lab.) Also in the equation are Planck's constant $h = 6.626 \times 10^{-34}$ J*s, Boltzmann's constant $k_B = 1.381 \times 10^{-23}$ J/K, and the speed of light $c = 2.998 \times 10^8$ m/s. The slope of the blackbody spectrum through the visible part of the electromagnetic spectrum varies substantially depending on temperature.

Broad-band photometry, using filters which each span a range of about 1000 Å, basically samples two regions of the visible spectrum and determines this slope. Stars that are very hot emit most of their light in the UV, and so they have a lot more blue light than green or red light. Conversely, stars that are very cool emit most of their light in the IR, and so they have much more red light than green or blue light. The examples of HR diagrams you saw in lecture used the B (blue, centered at 4360 Å) and V (visual, or green, centered at 5450 Å) filter combination, but if you take ASTR310 in the fall, you will create HR diagrams of star clusters using V and R (red, centered at 6380 Å). The principle is the same, so we can use V and R, which cover photon energies that the camera at the observatory detects very well, rather than B, which covers photon energies that the camera does not respond to quite as well.

Stars, however, are not perfect blackbodies, because they have atmospheres. The star's atmosphere starts where the star first becomes transparent to light. The blackbody spectrum is produced at this transition from opaque to transparent, while the atmosphere above the transition gives rise to the absorption lines in the spectrum. The lines seen in the spectrum of a star depend on temperature, because the temperature determines what fraction of the atoms present are in the right excited state to produce a given line. For example, stars around 10,000 K (A0 stars) have the strongest Balmer lines ($\alpha = 6563$ Å, $\beta = 4861$ Å, $\gamma = 4341$ Å, $\delta = 4101$ Å, $\epsilon = 3970$ Å) of hydrogen, because there is an ideal mix of H atoms with their electrons in the n = 2 state and photons of a proper energy to excite transitions from n = 2 to higher states. At lower temperatures (A-M type stars), a larger fraction of the H atoms are instead in the n = 1 state, and so there is less absorption of the photons at the wavelengths of the Balmer series. At higher temperatures (O and B stars), a growing fraction of the H atoms are either in states higher than n = 2 or ionized completely, also resulting in less absorption at the Balmer line wavelengths.

Other elements (and molecules) will show the strongest absorption at various temperatures, because each element has its own unique set of electron energy level spacings (see the figure below, and the appendix to this lab). Since one often has to look at the relative strengths of the lines from different elements to classify a star, the easiest way to do this is to compare the spectrum of the unknown to spectra of standard stars, whose spectral types have already been determined. The known spectrum which best matches the lines present as well as the relative strengths of those lines tells you the spectral type of the unknown. Sometimes the unknown will appear to be between the classes of the standard stars, if there are subtypes that are not represented in the standard library. For example, if an unknown spectrum has ionized He with weak neutral He lines, but stronger Balmer lines than an O5 star, that would place it somewhere between an O5 and a B0. Also note that the slope of the continuum of the spectrum is a hint as to the temperature of the star, because it is the blackbody spectrum.

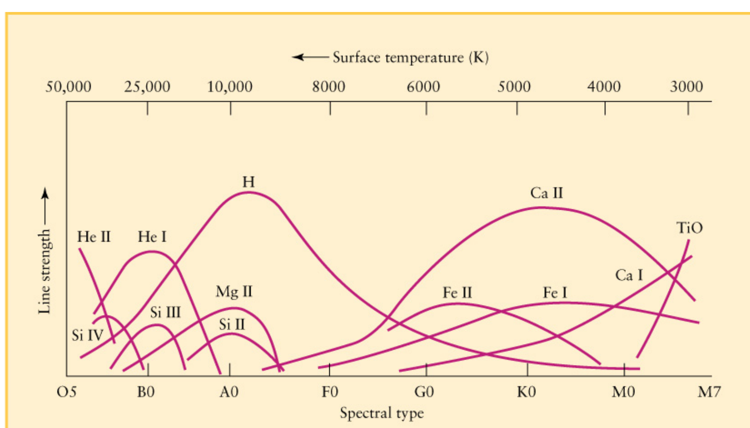


Figure 1: Line strengths for various atoms and ions vs the surface temperature and spectral type of the star. (Fig. 17-12, *Universe, 9th Edition*)

# 2 Procedure

First, create a new folder in the A121 folder on the desktop using your (and your partner's) initials and the number of this lab, which is 4. Open MATLAB and change your directory to that folder. Open a web browser and bring up the lab's website: `http://www.astro.umd.edu/~cychen/MATLAB/ASTR121/labBB/` to use as a reference. Note that the website is provided as a guide, not as word-for-word instructions. Follow the examples in the website but insert the appropriate information for today's lab. You need not do the examples verbatim before applying the examples to today's lab.

## 2.1 Photometry

### 2.1.1 Plotting the Planck Function

GOALS: Create a plot to turn in that shows the Planck function for an A0 star (roughly 10,000 K) and the Sun (G2, about 5700 K), with both stars on the same plot. Include a legend, axes labels, and an appropriate title, and make sure to use different line styles for each star. You should turn in a copy of an m-file that reproduces this plot. You should also turn in a copy of your function file that calculates the Planck function.

1) Using the instructions on writing a function .m file and the functionExample.m file on the lab's website, write a function to calculate the Planck function given in the introduction. Name the file something obvious, like "planck.m". The function should take, as inputs, wavelength (in meters) and temperature (in K). Make sure that you use the .*, ./, and .^ operators liberally in your function to ensure that MATLAB does not try to do matrix math. You will be giving your Planck function an array of wavelengths in this section of the lab and an array of temperatures in the next section.

2) Create an array with an appropriate name that has 1500 linearly-spaced wavelengths from 1 to 15,000 Å. Create a second array, appropriately named, which converts the array in Å to meters (1 m = $1 \times 10^{10}$ Å, or, 1 Å = $1 \times 10^{-10}$ m). (You WILL need two separate arrays here, one in Å and one in meters, for plotting purposes later.)

3) Create an array, using your array (in meters) from step 2 in this section and your planck.m function, that contains the values of the Planck function for a temperature of 10,000 K (roughly an A0 star). Create another array, this time using a temperature of 5800 K (roughly the Sun). Give each array an obvious name, so that you can call them for your plot.

4) Plot the Planck function for 10,000 K and 5800 K, using the arrays you created above. For the x-axis, though, use the wavelengths in Å rather than in meters. Use a different line style for the two temperatures. Give the plot an appropriate title (**title()**) and axes labels (**ylabel()** and **xlabel()**). Include a legend (**legend()**). Refer to the "Multiple Plots" section of the website or use the **help** command for more information on these commands.

### 2.1.2 Creating the HR Diagram

GOALS: Make an HR diagram of the main sequence, using a scale-free relative measure of luminosity (explained below) on the y-axis and the B - V estimate on the x-axis. Your plot should have at least 100 stars, covering the range from 3,000 K to 30,000 K. Again, remember to include axes labels and an appropriate title. Also create a plot to turn in with temperature on the y-axis and estimated B - V on the x-axis, again with appropriate titles and axes labels. You should also turn in a copy of an m-file that contains the code needed to reproduce these plots.

1) Create an appropriately-named array of at least 100 linearly-spaced temperatures between 3000 K and 30,000 K.

2) Create an appropriately-named array of intensities (i.e. from the Planck function) at the central wavelength of the B filter, which is 4360 Å, for the temperatures you created in step 1 in this section. Create another appropriately-named array, this time using the central wavelength of the V filter, which is 5450 Å. Remember that your Planck function takes wavelength in meters, not Å.

3) A filter only allows light in a specific range of wavelengths through to the detector, and then the detector adds all that light together. Thus one gets a measure of the total intensity (W $sr^{-1}$ $m^{-2}$) over the range of the filter; This is equivalent to finding the area under the Planck curve for the range of wavelengths covered by the filter. We can crudely estimate the total intensity received through the filter by taking the value of $I(\lambda, T)$ at the central wavelength of the filter (which you have from step 2 above) and multiplying by the width of the filter in wavelength. The width of the B filter is 940 Å (remember to convert Å to meters), and the width of the V filter is 850 Å (remember to convert to meters). Calculate the color index using these estimated total intensities, using the equation:

$$B - V = 2.5 * \log(I_{tot,V}/I_{tot,B})$$

where $I_{tot,V}$ is the estimated total intensity in V, and $I_{tot,B}$ is the estimated total intensity in B. NOTE THAT THE FUNCTION IN MATLAB FOR $\mathrm{LOG}_{10}$ IS **log10()**. Don't forget that pesky ./ operator.

4) Create a scale-free relative measure of luminosity by creating an array which is the log (i.e. $\log_{10}$) of your estimated total intensity for V.

5) To create your HR diagram, plot your scale-free relative measure of luminosity (y-axis) vs your estimated B - V (x-axis). Use points instead of lines. Give the plot appropriate axes labels and a title. Now plot temperature (y-axis) vs B - V (x-axis), and you will see that the temperature does indeed increase toward the left. Give the plot appropriate axes labels and a title.

## 2.2 Spectroscopy

GOALS: Classify the 5 unknown stars by comparing their spectra to the standard star spectra. The first question in the Questions section asks you to indicate what spectral type you selected for each unknown, making clear which type goes with which unknown. For ONE of the unknown stars, make a copy of the plot showing the unknown spectrum, overplotting the spectrum of the standard star that best matches it, and make a copy of the plot of the corresponding residuals. The m-file you turn in for this section only needs to reproduce the specific plots that you are turning in (since you will likely use the same m-file to do all the plotting for all the unknowns, editing it as you go - otherwise, it would be a very large file).

1) Download the standards.zip and unknowns.zip files from the lab's website into your folder. Unzip the files outside of MATLAB (or download them individually, if you cannot unzip them). Each file contains the spectrum of a star from 3900 Å to 4500 Å. The first column is wavelength and the second column is a scaled intensity. Each spectrum has been divided by the maximum value in the spectrum (and not by the continuum, as it was in the binary lab, so the shape of the continuum is still preserved in these spectra).

2) Refer to the "Plotting Residuals" section of the lab's website if you need guidance. In a script m-file, write the commands to open 1 unknown spectrum and 2 standard star spectra. Write the commands to plot the unknown spectrum and overplot the standard spectra in figure(1). You should use two consecutive spectral types as your two standards: the standards, from hot to cold, are O5, B0, B6, A1, A5, F0, F5, G0, G6, K0, K5, M0, and M5. Remember your title, axes labels, and legend. Make the three lines you are plotting distinct. The y-axis is "scaled intensity". Note that the spectra files are two columns: if your array for a file is called "unk", then "unk(:,1) is the first column (wavelength in Å, in this case) and the second column (scaled intensity) is "unk(:,2)", but all without the quotes.

3) Next you should determine the residuals between the unknown spectrum and the standard spectra. The residuals are just the result of subtracting the standard from the unknown, and it gives you an idea of how far off each point in the standard is from the unknown. Ideally, the residuals would be zero across the wavelengths. Science is rarely ideal, however; Some of the unknowns might be in between two of the spectral types for which you have standard stars, which means you must try to make the residuals as small as you can, and then pick a spectral type in between the two standards (or just give the two standards it is between). To see this, you should make a plot of the residuals in figure(2), and use two consecutive spectral types as your standards, as mentioned in the previous step. To compare the residuals each time you try a different standard, you need to keep the vertical scale of the residuals plot the same. Don't forget your title and axes labels (you can just call the y-axis "Unknown-Standard").

4) For each of the 5 unknowns, determine the spectral type by comparing to the standard stars. Use the m-file you have created in steps 1 and 2 of this section, and just change the name of the unknown and the standard star files, rather than repeating all the commands a million times in

your m-file. You only need to print out the code for ONE of your unknowns and the standard stars that go with it. Print out the plots of the spectra and the residuals that go with the code for that ONE unknown. It is your choice which of the 5 unknowns to turn in.

Tips for a quick classification:
a) Look at the slope of the continuum of the unknown. Does it slope sharply downward from left to right (i.e. is it blue)? If so, start with the standards that are A5 or hotter. Does it slope sharply upward from left to right (i.e. is it red)? If so, start with the M stars, perhaps a K5 or K0. Is it relatively flat, with only a very slight slope one way or the other? It's probably somewhere between a K0 through A5.

b) How ragged is the spectrum? M stars are extremely jagged, middle stars like G stars moderately so, and hot stars like O and B are fairly smooth-looking, because they are getting so hot that there relatively few atoms or ions left to make lines in the part of the spectrum we are looking.

c) If you're having trouble deciding between a couple of the spectral types, there are some hints in the last paragraph of the introduction to this lab, as well as in the Appendix. Note that you can quickly use the data cursor tool to determine the wavelength of a line. It is the third icon over from the zoom out magnifying glass and looks like this:

## 3 Questions

1) What spectral type did you get for each unknown? Make sure you give the number of the unknown with its spectral type so I know which type goes with which. Give a brief reason for each of your 5 classifications.

2) If you take ASTR310 in the fall, you will create an HR diagram of two different star clusters using V and V - R, instead of V and B - V. Using what you've learned in the Photometry section of this lab, explain, in your own words, why this is equivalent.

3) To plot the main sequence in the Photometry section of this lab, we have made a subtle assumption in transforming from intensity (which is essentially flux, once you have integrated over wavelength) to luminosity. By comparing the relationship between flux (specifically, the $F = \sigma * T^4$ definition) and luminosity, figure out and explain what this assumption was. Justify your answer using the equations for flux and luminosity. Note that this assumption fails miserably for giants, supergiants, and white dwarfs. What would you need to do to put the white dwarfs and giants/supergiants onto your plot?

4) Say you took the spectrum of a star and found that it had spectral lines from TiO and He

II. Why would this be quite surprising? Assuming there was no problem with the data, what could cause this?

# 4 Appendix

## 4.1 Spectral lines

The very coolest stars, M stars, are so cool that molecules can survive in their atmospheres. Molecules have a much richer structure of energy levels, and so their absorption features can take out large chunks of the spectrum. Titanium oxide, TiO, for example, takes out a good bit of the green and blue parts of the spectrum in M stars, but gets increasingly weaker with increasing temperature. M stars are also characterized by very strong neutral calcium (Ca I) absorption at 4226 Å, which weakens with increasing temperature from M9 to M0. By K5 it is relatively weak, but is still present through the K and G stars, fading out completely by about F0. As Ca I dies down in the K stars, ionized calcium (Ca II) picks up, gaining strength with increasing temperature from K9 to K0, where it is strongest (indicated by not only the depth, but also the breadth of the 3933 Å line), before gradually fading off through the G, F, and A stars. The strength of the Balmer lines are a good indicator of temperature from G through A stars, until about A5. A second Ca II line, 3969 Å, blends with the Balmer line H$\epsilon$, though, so one needs to be careful with H$\epsilon$. Around A5, the slope of the continuum shifts from being roughly flat from K through F to being decidedly blue. The Balmer lines are strongest in an A0 star, and then begin to weaken again through the B and O stars. Thus a B star and an A star might have similar depths of the Balmer lines , but only a B star would also show neutral helium lines at 4144, 4387, and 4471 Å, while only the A star would show an ionized magnesium line at 4481 Å. The hottest stars, O stars, become too hot for neutral He, so these lines begin to fade again, while lines for ionized He appear at 4200 Å. O stars are so hot, in fact, that they have relatively few lines between 4000 and 4500 Å compared to cooler stars, because not many atoms and ions are left that can create lines.

## 4.2 Magnitudes

The magnitude of an object in a given filter is determined by comparing the measured brightness (flux) of that object through the filter with measured brightness (flux) of some standard reference object. This system was originally designed so that the visual magnitude ($m_V$) of the star Vega (a.k.a. $\alpha$ Lyrae) was defined to be zero. Thus, when someone says a star has an apparent magnitude in V (i.e. m$_V$) of 7, what this really means is that

$$m_{star,V} - m_{Vega,V} = 2.5 * \log(F_{Vega,V}/F_{star,V})$$

where $m_{star,V}$ is the $m_V$ of the star in question, $m_{Vega,V} = 0$, $F_{Vega,V}$ is the flux measured from Vega in the V filter, and $F_{star,V}$ is the flux measured of the star in question in the V filter. Note that, because of the way logs work, this equation becomes

$$m_{star,V} = -2.5 * \log(F_{star,V}) + m_{Vega,V} + 2.5 * \log(F_{Vega,V})$$

$$m_{star,V} = -2.5 * \log(F_{star,V}) + \text{some constant}$$

meaning that to calibrate the measured magnitude, one just adds a constant to $-2.5*\log(F_{star,V})$.

In a similar fashion, the B magnitude ($m_B$) of a star is just

$$m_{star,B} = -2.5 * \log(F_{star,B}) + m_{Vega,B} + 2.5 * \log(F_{Vega,B})$$

$$m_{star,B} = -2.5 * \log(F_{star,B}) + \text{some other constant}$$

where now $F_{Vega,B}$ is the flux measured from Vega in the B filter and $m_{Vega,B}$ is set such that Vega has a B-V color of 0. To determine the B - V color of a star, then, one takes

$$m_{star,B} - m_{star,V} = -2.5 * \log(F_{star,B}) + 2.5 * \log(F_{star,V}) + \text{some other constant} - \text{some constant}$$

$$m_{star,B} - m_{star,V} = 2.5 * \log(F_{star,V}/F_{star,B}) + \text{constants we don't care about}$$

This is why you have calculated $B - V = 2.5 * \log(I_{tot,V}/I_{tot,B})$ in Part 2, step 3.

It turns out that, with improvements in astronomical detectors and equipment, Vega actually has $m_V = 0.03$ and is variable to boot. Adjustments have been made to the system to account for this. That's okay, though, because very rarely these days does one observe Vega to calibrate the magnitude from the fluxes calculated from the detector. There are a set of standard stars that have well-determined magnitudes, and those stars are spread out across the sky. Thus it is easy to find a standard star near your object of interest with which you can calibrate your measurements. Since you only need to add a constant to get the calibrated $m_V$ for an object, you can just find the difference between the non-calibrated magnitude you have for a standard star in V and the calibrated value, and add that to all your non-calibrated magnitudes for other objects. You can then correct B, knowing what the B - V of the standard should be, by adding another constant.