

Stellar Spectral Classes & the Hertzsprung-Russell Diagrams

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Goal of the Lab

The goal of this lab is to explore the spectral classes of stars to understand that stellar properties are related. In this lab, you explore how the spectral class and color-index relates to temperature; and how the absolute magnitude relates to the luminosity. To understand how these properties of stars relate to one another, as a class, you will build a Hertzsprung-Russel Diagram (HR Diagram). The HR diagram is one of the most important graphs in all of astronomy. An HR diagram reveals commonalities between stars and their properties, and it reveals the evolutionary life cycles of stars. By the end of this lab, students are expected to know:

1. The spectral classes of stars, and how they relate to the star's surface temperature
2. What an Hertzsprung-Russell Diagram is
3. The general life stages of stars.
4. What a color-index, how it is measured, and how it relates to a star's temperature and spectral class
5. How distance, apparent magnitude, absolute magnitude, and luminosity all connect to one another.

Tools used in this lab:

- UNL Astronomy Simulation: Blackbody Curves (NAAP)
<https://astro.unl.edu/classaction/animations/light/bbexplorer.html>
- Google Response Form: Link on course website.

1. The Hertzsprung-Russell Diagram (HR Diagram)

If you were to closely examine a large number of stars, you would notice that they come in a variety of colors and brightness. Some stars are red and dim, while others are blue and bright. Some are red and bright, while others are blue in dim. Some are white in color, while others might appear more red, orange, or blue. What properties of the stars that cause these variations and are these properties connected in some physical way to one another? How do these stellar properties relate to how a star lives, changes, and dies? The changes a star experiences over its lifetime is referred to as **stellar evolution**. Astronomers usually begin explaining the properties and evolution of stars using what is known as a **Hertzsprung-Russell Diagram**, or often just **HR Diagram**. An example of an HR diagram is shown in Figure 1.

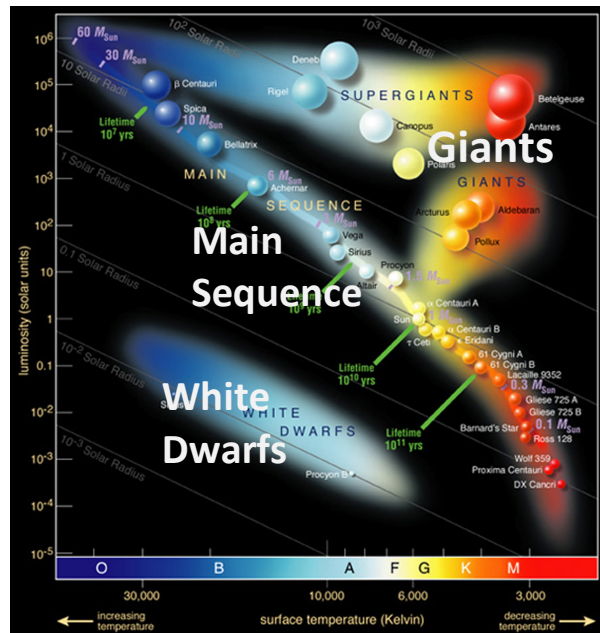


Fig. 1: A Hertzsprung-Russell Diagram. In this scatterplot of luminosity versus temperature, stars cluster into three primary regions: The giant region, the main sequence, and the white dwarf region

1.1 Life Stages of Stars and the HR Diagram

There are three main regions on an HR Diagram: The *main sequence*, the *red giant region*, and the *white dwarf region*.

The Main Sequence

The majority (90%) of stars fall in a diagonal line from upper left (high luminosity and high temperature) to the lower right (low luminosity and low temperature). This line is called the *main sequence*. The stars on the *main sequence* are in the longest lasting stage of their lifecycle. Main sequence stars have nuclear fusion of hydrogen into helium in their cores. How long they will remain on the main sequence depends on how much hydrogen they have and how fast they fuse it into helium. Since stars are just over 70% hydrogen by mass, this is an enormous fuel supply. Counter-intuitively, however, the more massive the star, the shorter the lifetime. This is because with more mass, the star has much higher internal core temperatures and pressures, which makes them ferociously fuse hydrogen into helium at an incredible rate. This results in a short lifetime (millions to hundreds million years), but an enormous energy output and high surface temperatures. These stars (O- and B-type stars have incredibly large luminosities and appear blue in color. Low mass stars have much lower internal core temperatures and pressures, so while they have less total hydrogen to fuse into helium, they fuse hydrogen into helium incredibly slowly giving the M-type stars lifetimes on the main sequence of trillions of years

The Red Giant Region

Only about 1% of all stars will have temperatures and luminosities that place them in the *red giant region*. This region falls in the upper-right corner of the HR diagram. That means they are cool, red, and high luminosity. As we will see in this lab, they also have large sizes, and hence are called red giants. Given that they are very high luminosities, they are easier to spot from Earth than dimmer stars. So, when you make your HR diagram, you will likely have this region more populated than the true percentage of just 1% of all stars.

Stars in the *red giant region* are stars that are dying. They have exhausted their fuel of hydrogen in their cores, and they are now extending their lifetimes by fusing heavier and heavier elements in their cores. For example, many red giants are fusing helium into carbon in their cores to power themselves. A rare few are fusing carbon into heavier elements eventually ending in fusing iron, which cannot be fused into heavier elements. These stars stay bright by fusing whatever they can in their cores. What they can fuse is limited by how much total mass the star has. With more mass, they reach hotter core temperatures and can fuse heavier elements. Regardless of the mass, however, all stars eventually reach a point where they can no longer fuse the elements in their core. At this point they are fated to die. Low mass stars (less than 8 solar masses) will do so as planetary nebulae. High mass stars (greater than 8 solar masses) will do so in supernovae explosions, which are one of the most energetic phenomena in the universe.

The White Dwarf Region

Roughly 9% of all stars fall in the lower left corner of the HR diagram. These stars have high surface temperatures, but low luminosities. They are hot enough to look white in color. As we will see in this lab, they have incredibly small sizes, and hence overall low luminosity despite their high temperatures. This means they are small and white in color, or rather they are what astronomers call *white dwarfs*. White dwarfs are the dead cinders of low mass stars that have lived out their entire lifetime on the main sequence, went through their death throws in the red giant region, and after going through a planetary nebula phase, have ended up as the hot, dead core of what used to be a star. They are made of the elements that their progenitor stars could not fuse into heavier elements, which for most stars is carbon and oxygen.

Summarizing the life of a star

So, the HR diagram tells us the tale of how stars live and die. Stars are born onto the *main sequence*, where they live the vast majority of their lives. Here they are happily fusing their large supply of hydrogen into helium in their cores. Being the longest phase in the lifetime of star, the vast majority (about 90%) of stars are on the *main sequence*. Eventually, these stars run out of hydrogen in their cores, and extend their life by starting to fuse helium and other heavier elements. This change in energy production causes the stars to increase to incredibly large sizes with cooler surface temperatures. They have become *red giants*. Stars cannot last long as red giants, eventually running out of elements they can fuse into to generate energy. At this point, the star is fated to die. The high mass stars (greater than 8 solar masses) explode in supernovae explosion and can no longer be plotted on an HR diagram. The low mass stars (less than 8 solar masses) shed their outer, non-core layers exposing the hot core that is incapable of fusion. These cores are incredibly hot, but also incredibly small. This end state for low mass stars are the *white dwarfs*.

2 Working with HR Diagrams

The *HR Diagram* comes in a few different forms, but if you relate it to the most fundamental stellar properties, it is a scatterplot of stars' luminosity (y-axis) versus stars' surface temperature (x-axis). *Luminosity* is the total energy output of a star every second, which typically measured in Watts [W]. The surface temperature is the temperature of a star's photosphere, which is measured in Kelvin [K]. While luminosity and temperature of fundamental properties of stars, they are not the ones that can be directly measured.

1.1 Indirect Measures of Surface Temperature

The surface temperature of stars can be measured indirectly in primarily two different ways: 1) determining the stars B – V (B minus V) color-index, or equivalently any other color-index; or 2) measuring the spectrum of a star to determine the stars *spectral class*. Each of these deserves further discussion.

Color-Index

A *color-index* is the apparent magnitude of a star measured in one wavelength range subtracted from the apparent magnitude of the same star measured in a different wavelength range. To do this, astronomers use what are known as *photometric filters*. Photometric refers to a *photometry*, which is the measure of something's brightness over a large range of wavelengths. To make a color photometric measurement, a colored filter is placed in the path of the light as it goes through the telescope. This color filter will block out all light that isn't in the designated wavelength range. Astronomers typically use five *photometric filters*: U, B, V, R, and I, corresponding to an ultraviolet (U), blue (B), visible (V), red (R), and infrared (I). The wavelength ranges these filters allow to pass through them are given in Table 1.

Filter	Wavelength Range
Ultraviolet, U	320 – 400 nm
Blue, B	400 – 500 nm
Visible, V	500 – 700 nm
Red, R	550 – 800 nm
Infrared, I	700 – 900 nm

By placing one of the UBVRI filters in the path of the light, astronomers measure the apparent magnitude of the star in each one of the filters. You can think of this as the star's blue apparent magnitude (B) or the star's visible apparent magnitude (V). Since stars emit light that closely matches a blackbody spectrum, and the functional form of a blackbody is well-understood and determined by only the temperature, a comparison of how bright a star is in one color compared to another gives a unique way to determine the temperature of a star. Astronomers make this comparison by subtracting the apparent magnitude in one photometric filter from another giving a value called a *color-index*. The most often used color index to determine a star's temperature is the blue magnitude (B) minus the visible magnitude (V), or the $B - V$

Table 2: The Harvard Spectral Classification System

Class	Temperature	Spectral Characteristics
O	>30,000 K	Strong ionized helium lines; multiply ionized heavy elements; hydrogen lines are faint
B	10,000 – 30,000 K	Moderate neutral helium lines; singly ionized heavy elements; hydrogen lines are moderate
A	7,500 – 10,000 K	Weak neutral helium lines; singly ionized heavy elements; hydrogen lines are strong
F	6,000 – 7,500 K	Singly ionized heavy elements; neutral metal lines; hydrogen lines are moderate
G	5,200 – 6,000 K	Singly ionized heavy elements; neutral metal lines; hydrogen lines are weak
K	3,700 – 5,200 K	Singly ionized heavy elements; strong neutral metal lines; faint hydrogen lines
M	2,400 – 3,700 K	Neutral atoms have strong lines; molecular lines present (e.g., TiO lines); very faint hydrogen lines

color-index. The same could be done with any other color-index, e.g., $U - B$ or $V - R$. You will explore photometric filters, color-indices, and their connection to temperature as one of today's lab activities.

Stellar Spectral Class – The Harvard Spectral Classification System

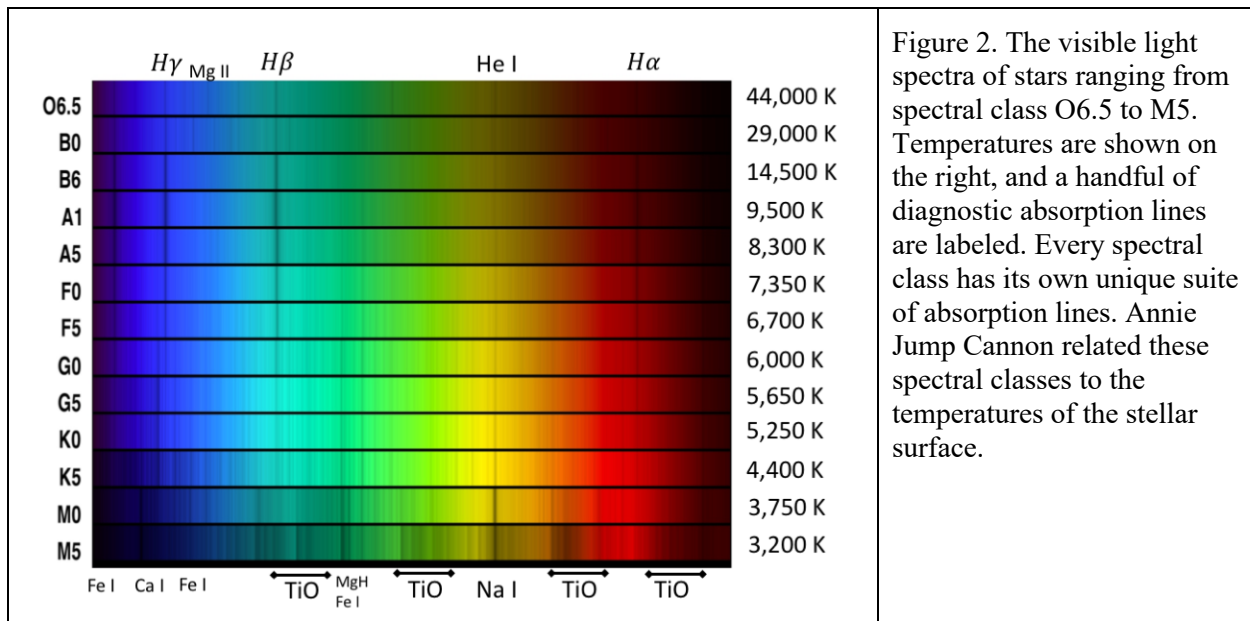


Figure 2. The visible light spectra of stars ranging from spectral class O6.5 to M5. Temperatures are shown on the right, and a handful of diagnostic absorption lines are labeled. Every spectral class has its own unique suite of absorption lines. Annie Jump Cannon related these spectral classes to the temperatures of the stellar surface.

Another proxy for temperature comes from relating a star's spectral characteristics to its temperature. The spectral characteristics are the presence and absence of absorption lines and the strength (width and depth) of those absorption lines. The most often used stellar classification system is the *Harvard spectral classification system (Harvard System)* developed by Annie Jump Cannon in the early 20th century. Her system altered an older, classification system which classified star's spectra by the strength of their

hydrogen absorption lines, such that Class A stars (typically called A-type) had the strongest hydrogen absorptions, Class B were slightly weaker, Class C weaker still, and ending with Class P with no hydrogen absorption lines. Annie Jump Cannon's connected the strength of the hydrogen absorption lines to the temperatures of the stars, and she used this method to create a classification system ordered from highest surface temperature to lowest surface temperature. She also eliminated most of the classes, keeping only seven. In order from hottest to coldest, the **Harvard System** has the following spectral classes: O, B, A, F, G, K, and M. Additionally, a number 0 through 9 has been attached to the spectral class (OBAFGKM), where 0 is the hottest and 9 is the coldest surface temperature across the spectral class. The **OBAFGKM Harvard System** is summarized in Table 2. The spectra of stars of each one of these classes is shown in Figures 2 and 3.

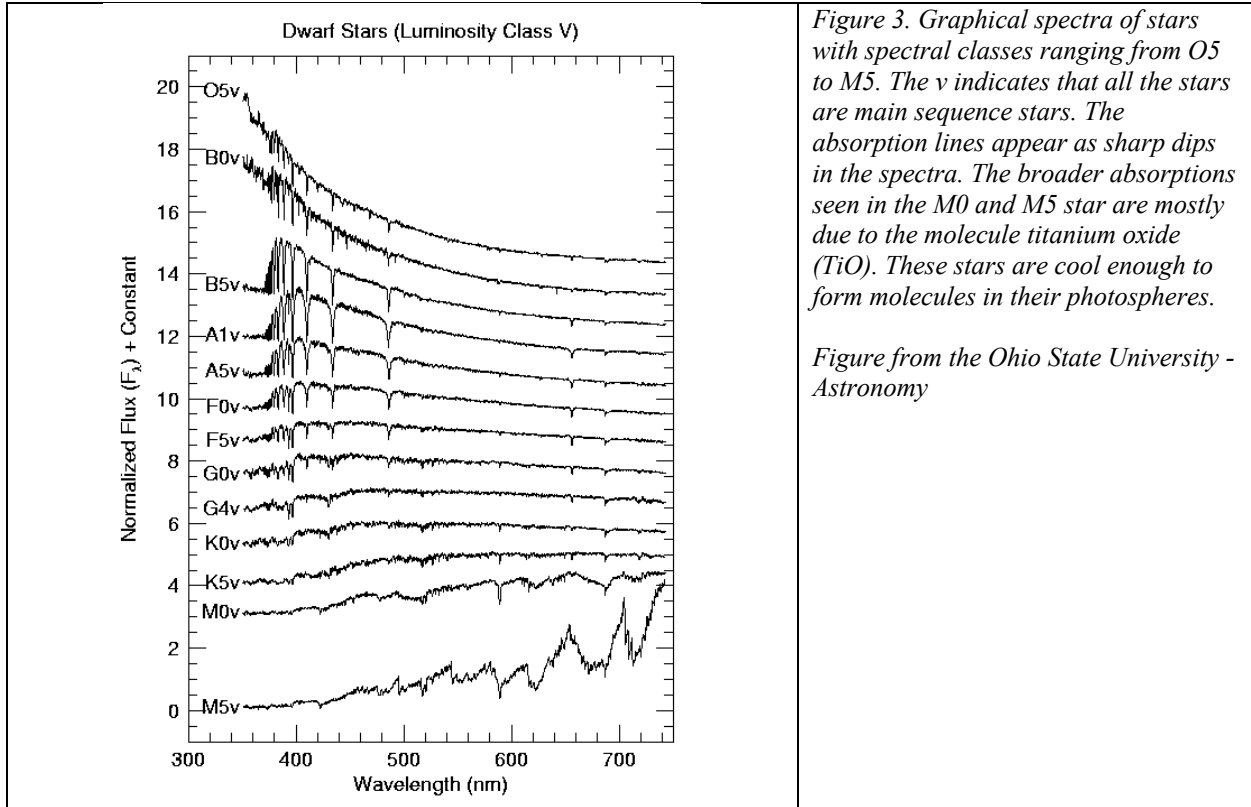


Figure 3. Graphical spectra of stars with spectral classes ranging from O5 to M5. The v indicates that all the stars are main sequence stars. The absorption lines appear as sharp dips in the spectra. The broader absorptions seen in the M0 and M5 star are mostly due to the molecule titanium oxide (TiO). These stars are cool enough to form molecules in their photospheres.

Figure from the Ohio State University - Astronomy

1.2 Indirect Measures of Luminosity

The *luminosity* of star is indirectly determined by measuring the star's apparent magnitude, m , and using stellar parallax to determine the distance to the star. With the apparent magnitude and distance determined, you can use the **distance modulus** to determine the **absolute magnitude, M** of the star. The distance modulus is the value $m - M$, and it connects how bright a star appears to how bright it is truly is using the distance. In equation form, the distance modulus is

$$m - M = 5 \log \left(\frac{D}{10} \right) \quad (1)$$

, where D is the distance measured in parsecs [pc]. The dividing the distance by 10 comes from the fact that the absolute magnitude of a star is defined as its apparent magnitude if it were viewed at a distance of 10 pc. Once the absolute magnitude is determined, it can be converted to luminosity in units of Solar Luminosities using the equation,

$$L_* = 10^{0.4(4.74 - M)} \quad (2)$$

, where M is the absolute magnitude of the star, and the 4.74 is the absolute magnitude of the Sun. Since Equation 2 gives you the luminosity in number of Solar Luminosities, to convert this to luminosity in Watts (energy per second), you simply need to multiply L_* by the *solar luminosity*: $1 L_{Sun} = 3.828 * 10^{26} \text{ W}$.

1.3 The Many Forms of the HR Diagram

The previous sections outlined that a star's surface temperature is equivalent to listing its spectral class or measuring its color-index, and a star's luminosity is equivalent to measuring its absolute magnitude. This means there are ways to create an HR Diagram that differ from the scatterplot of luminosity versus temperature. Popular alternative *HR Diagrams* are scatterplots of *absolute magnitude vs color-index*¹ and *absolute magnitude vs spectral class*². Notice that magnitudes, color-indices, and spectral classes are what can be measured at the telescope. These alternate forms of the HR Diagram are frequently used because they plot what is measured without having to go all the way through the conversions to temperature in Kelvin and luminosity in Watts.

¹ First done for the Hyades and Pleiades cluster by Ejnar Hertzsprung in 1911.

² First done with field stars with stellar parallax determined distances by Henry Norris Russell in 1914.

Name:

Lab Date

Lab Time

Lab Instructor

Lab Task 1 – Creating an HR Diagram

In today's lab, the class will create an *absolute magnitude vs spectral class HR Diagram*. For an HR Diagram to really be useful, we need a large number of stars with determined absolute magnitudes (equivalent to luminosities) and temperatures (equivalent to color-index or spectral class). To do this we are going to divide the class into pairs of students who will each be responsible for gathering data on 12 stars.

Instructions and Questions

- Work in pairs
- Open Stellarium on one of the lab computers
- Your Lab Instructor will assign you a constellation to hunt for stars within
- To gather data, click on a star. Information about the star will display in the upper left corner of the screen. Record the star's name, spectral class, and absolute magnitude.
 - Only record the letter and number (Example: B8). Ignore any other labels that appear after the number.
- In order to use spectral class as a plottable proxy to temperature, we need to assign a "numerical" value to each spectral class. Use Table 3 to convert the spectral class (letter plus number) to a "numerical" class.
- Repeat this task until you have collected data on 12 stars
- When done, access the Google Form on the Astronomy Lab Website to electronically enter this data. Data from all students will be put on a common HR Diagram for the class.

Table 3. Conversion from Spectral Class to "Numerical" Class

Spectral Class Letter	Base Value	Example
O	0	O4 goes to $0 + 4 = 4$
B	10	B8 goes to $10 + 8 = 18$
A	20	A2 goes to $20 + 2 = 22$
F	30	F5 goes to $30 + 5 = 35$
G	40	G2 goes to $40 + 2 = 42$
K	50	K1 goes to $50 + 1 = 51$
M	60	M7 goes to $60 + 7 = 67$

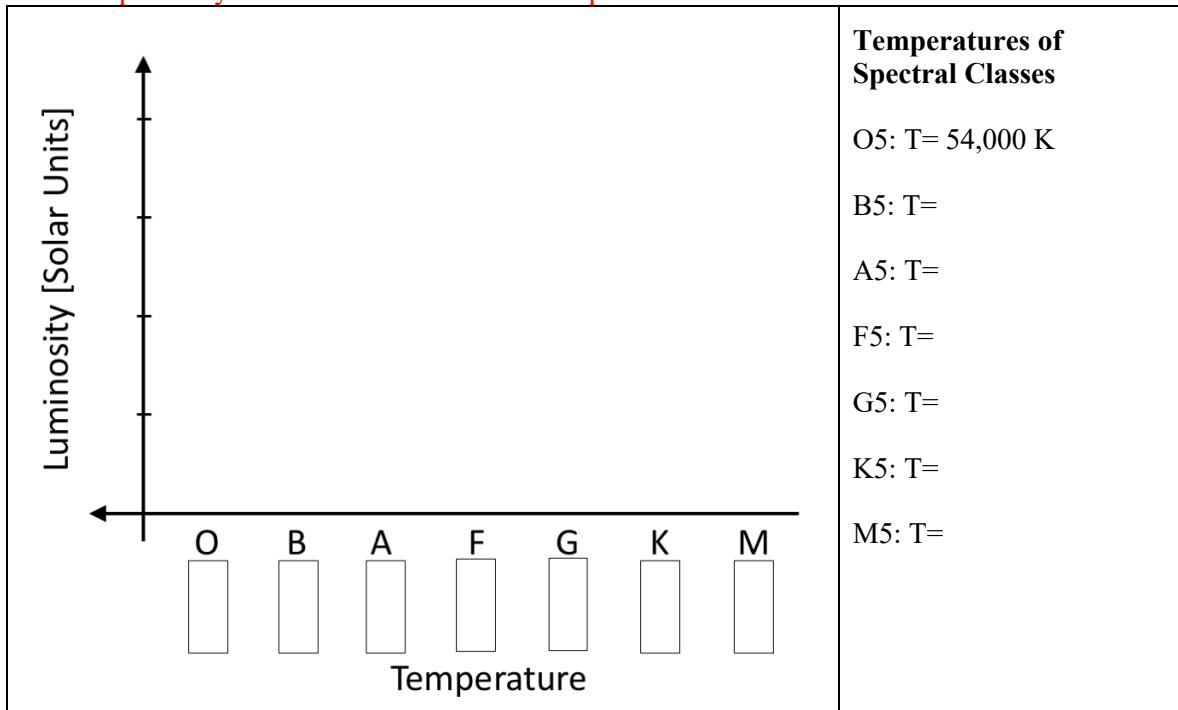
1. Complete the table below. Be sure to fill out what constellation you are gathering your data from.

Assigned Constellation:				
	Star Name	Spectral Class	“Numerical” Class	Abs. Magnitude, M
1				
2				
3				
4				
5				
6				
8				
9				
10				
11				
12				

2. Enter the data you collected using the Google Response Form: “HR Diagram Lab – Response Form.” You can find the form on the Astronomy Lab Website. Your lab instructor will add data from dim stars as they are not commonly selected by students.
3. Did your instructor add faint stars to fill out the HR Diagram. If not, ask them to do so.

(continued next page)

4. In the graph below, sketch the class's HR Diagram. The x-axis is given as spectral class. The y-axis is in Solar Luminosities. Put luminosity values next to the hash marks on the y-axis. **For now leave the temperatures blank**
Do not put every dot... use artistic license to capture the relevant information.



5. On the figure you made in figure three, can you identify the main sequence, a region for the giants, and a region for white dwarfs?
- Draw a line and label the main sequence.
 - Draw an ellipse around the giants and label the region the “Red Giant Region”
 - Draw an ellipse around the white dwarfs and label the region the “White Dwarf Region”

Lab Task 2: Connecting Temperature, Color-Index, and Spectral Class

We still do not have the temperatures for the HR Diagram we created in Question 3. To create the temperature scale, we will explore the connection between spectral class, color-index, and temperature. This task will use the [University of Nebraska – Lincoln “Blackbody Curves and Filters Explorer”](#) that you used in the the “Thermal Radiation Laws Lab.”

- Open the simulation
- Make sure Flash is enabled³
- On the righthand side of the simulation, you will notice “curves” and “filters” tabs. Select the “filters” tab. This will graphically show you the U, B, V, and R filters on the blackbody spectrum. It will also give you the magnitude in each photometric filter.
- Select the color-index to be B – V.

³ For Chrome, click on the lock button on the lefthand side of the tool bar. Select site settings, and then change Flash to Allowed. Reload the simulation page.

6. For all but the hottest stars, O-type, the simulation reproduces the B – V color indices based on blackbody temperatures. Table 4 gives you the B – V values for stars in the middle of the spectral classes, i.e., B5, A5, F5, G5, K5, M5. Use the temperature slider to find the B – V color index for each spectral class in Table 4. Record the temperature.

Table 4. Temperature, Spectral Class, Color-Index Connections

Spectral Class	B – V	Temperature
B5	- 0.17	
A5	0.15	
F5	0.37	
G5	0.61	
K5	0.90	
M5	1.65	

7. Add the temperatures to the x-axis of the HR diagram you sketched in Question 3. For ease, you may want to fill out the temperatures on the figure in the space provided.

Lab Task 3: The Long Way Around – Adding a Single New Data Point

8. The Long Way Around - Adding a single new data point as an astronomer would:
For this question, you will add one new data point to your HR diagram that plots temperature versus luminosity. You will do this using the kinds of measurements you could get at a telescope with the right equipment and know how.
- Your telescope does not have a spectrometer, so you cannot determine the spectral class of the star you are interested in. You do have photometric B and V filters though. You take a magnitude measurement in each. You measure:
B = 1.25
V = 1.16

What is the B – V color index? B – V = _____.

- Use the UNL “Blackbody Curves and Filters Explorer” to turn that B – V color index value into a temperature.

The star has a temperature, T = _____ Kelvin

- Careful measurements over a long time period, reveal that this star has a stellar parallax of 0.1298 arcsec. Use the formula

$$D = \frac{1}{p}$$

where D is the distance in parsecs and p is the parallax in arcseconds to calculate the distance to the star.

Distance to star: _____ parsec

- d. Using no filter, you measure an apparent magnitude, m , of 1.16 magnitudes. Use distance modulus equation (Equation 1) to calculate the absolute magnitude of this star.

Absolute magnitude of star: $M =$ _____ magnitudes

- e. Finally, use the equation to calculate stellar luminosity from absolute magnitude given in Equation 2.

The star has a luminosity: $L_* =$ _____ L_{Sun}

- f. Plot this star on the HR diagram you sketched in Question 3. Label it as “Lab Star” and draw it in as a small star. Is this star on the main sequence, in the red giant region, or the white dwarf region?