What will you learn in this Lab?

This lab will introduce you to Color-Magnitude, or Hertzsprung-Russell, Diagrams: one of the most useful diagnostic tools developed in 20th century astronomy. These plots can tell us much about the physical nature of stars, including their size, temperature, age and ultimate destiny. Using the Starry Night Pro software in our lab, you will construct your own CM diagrams and learn more about some of the stars you’ll be looking at in the night sky this semester. You will also try to estimate the ages of a few stars.

What do I need to bring to the Class with me to do this Lab?

For this lab you will need:

• A copy of this lab script
• A pencil
• A scientific calculator

Introduction:

In the first half of the 20th century, two astronomers, E. Hertzsprung and H.N. Russell, independently came up with a remarkable way of looking at the observed properties of stars. The observable properties of stars are quite simple: how bright they are and what color they are. These quantities can be converted into more useful properties by using some additional laws of astronomy.

First, Wien’s law relates the color of a star to the surface temperature of that star, specifically that:

$$\lambda_{\text{max}} \cdot T = \text{constant}$$

which means that the wavelength of the brightest color (wavelength) in the star's spectrum (i.e. $\lambda_{\text{max}}$) is directly related to the star's surface temperature. As the star gets hotter the wavelength or color of the brightest part of the spectrum gets smaller, or more blue. Conversely, the cooler the star, the more red the star is. This produces, at times, the counterintuitive result that hotter things are more blue, and colder things are more red. Most importantly, if you can measure the brightest color in a star's spectrum, which is generally speaking the color the star appears to the naked eye, then you can make an estimate of the star's surface temperature.
The second piece in this puzzle is the application of Stefan’s law. This law predicts the total amount of energy a star (or any hot object for that matter) should emit as radiation per second per unit area, using:

\[ E = \sigma T^4 \]

where \( \sigma \) is Stefan’s constant. That is, if you know the surface temperature of a star then you can predict how much energy is being emitted by each square meter of that star’s surface.

The third piece of this puzzle comes from an alternate expression of Stefan’s law using Luminosity instead of energy per unit area. A star’s luminosity is the total energy radiated per second from the entire surface of the star. So, it is possible to express a star’s luminosity as:

\[ L = 4\pi R^2 \sigma T^4 \]

where we’ve taken the first version of the law above, and simply multiplied it by the surface area of a sphere to give the expression for luminosity. But, you’re saying, how do we know the radius of a star? It’s way too far off to measure directly.

The final piece we use to calibrate the system, and so the whole H-R diagram, is the application of the inverse-square law for nearby stars. If a star is close enough to us we see it move relative to distant stars as we orbit the Sun through Parallax. By measuring how much it appears to move we can estimate the distance to the star. If we know the distance to the star, and we can measure how bright the star appears to be, then we can infer how the bright the star is if you’re standing next to it, using the inverse-square law. This latter law is simply the effect that the farther off you stand from a bright light, the fainter it looks, as the light gets spread over a larger and larger sphere centered on the light. The surface area of a sphere is given by \( 4\pi R^2 \), where \( R \) is the radius of the sphere, or in the case of a light it’s the distance between you and the light bulb. So as you get further away from the light, the area of the sphere the light is spread over goes up faster, as the square of that distance. So, the law is called the inverse-square law: inverse because the light level received drops, and square because of the size of the sphere the light is spread over.

So, for the closest star you can independently determine the star’s distance, brightness, temperature and size. Rather amazing given how far from these things we really are. Once this has been done for a group of the nearest stars, we can calibrate the various types of stars that there are. These categories are called spectral types and allow us to group together stars with the same types of observed spectra, colors and brightnesses. This is what ends up on an H-R diagram. Here’s what one looks like:
As you can see in this picture, if you take a random part of the sky (this is the region around the constellation Orion), the stars form very distinct regions. An H-R diagram is essentially a graph of stars with each star's location determined by their brightness or luminosity in the vertical (or y) direction, and by temperature in the horizontal (or x) direction. On the above diagram (taken from Starry Night Pro) the vertical scale is in units of absolute magnitude, while the horizontal is in units of 1000’s of Kelvin.

The thin line that runs diagonally across the diagram, through all the data points (each point is one star – there are 14,605 stars plotted here!), is called the Main Sequence, and marks the region within which stars spend most of their normal hydrogen-burning lives. It is when they depart this region that very interesting things start to happen to the size and internal structure of a star. Stars to the left are very hot; stars to the right are quite cool. Stars at the top are intrinsically very bright; stars at the bottom are quite faint. That is how a H-R diagram works. The region names indicated show where stars of various types end up on this diagram.

One final thing you can use an H-R diagram to do is to tell the age of a cluster of stars. The idea is that as a star gets older and starts to evolve its position on the diagram changes and it moves away from the main sequence. The very hot
stars evolve fastest; the less hot ones evolve more slowly. So if you look at a cluster of stars (the assumption being that they all formed together at the same time) then wherever you see stars starting to move away from the main sequence, the so-called “turn off”, then you know the age of the cluster.

This approach has been calibrated and is shown below, in the next figure. On that figure you’ll see that there are horizontal marks indicating various ages from $10^7$ to $10^{10}$ years! The way you determine the age of a cluster, or star, is you find where the Main Sequence stars start to move away from the well defined grouping by that name. Young stars move away higher up the H-R diagram than do older stars. By finding the “turn-off” point for a star or cluster you have a snapshot of a critical point in the star’s evolution and can determine the age of the star(s).
The **Starry Night** program

*Starry Night* is a very powerful virtual planetarium program that can show the sky on any date in any year from any location. It has easy to use controls, a few of which are described below:

- The Pointer tool allows you to point at an object in the sky and the program will give you information about that object, like what it is and precisely where it is.

- The Pan tool allows you to “grab” the sky and move it around so you can display a different area.

- The Magnify tool allows you to zoom in & out. To zoom in, click with the mouse on the area of interest. To zoom out, hold the Ctrl key and click with the mouse.

The Time Window shows you the current time and date for the sky being displayed. The box in the upper left shows the current time step. The box in the upper right shows the date and time for the sky. You can change any of the values in the time step or time and date windows by clicking and typing or by using the mouse. The “Now” button will reset the time and date to the current local time. The “Julian…” button will display the current Julian date (not necessary for this lab). The six buttons on the lower right act like movie controls: Back one time step, Backward at one time step per second, Stop, Forward at one time step per second, Forward at real time, Forward one timestep.

With regards to some of the specific things you’ll be asked to do in this exercise, note the following. To locate a specific object by name use the **Selection -> Find function (or Ctrl-F)** to type in the name and hit return. The software will take you to the location automatically. To build the H-R Diagram for a specific region, you can just call up the diagram window using: **Window -> H-R Diagram (or Ctrl-Shirt-R)**. The default action for this window is to build the H-R diagram for every star in the visible sky window, so if you want to narrow the set of stars you want to plot, you will need to zoom in to do so. You can do this using the **Magnify tool** or use the small magnifier buttons lower down on the side bar to zoom in “+” or out “-“.

**Procedure**

After all that, let’s start using what we’ve learned and know to do some interesting work. Using the software, locate each of the following constellations in the night sky. You may need to turn off the daylight to see them depending on the date and time settings being used. For each constellation, pick the **brightest and most familiar** stars and use the color-magnitude diagram for the region to determine their properties. Record the data in the table provided for later use. For each star you simply point the cursor at the star and a red point will appear in
the H-R diagram window indicating its position on the diagram. You will need to switch the x-axis between temperature and spectral type to get all the data you need.

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<th>Star</th>
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<th>Abs. Mag.</th>
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In each case the distance to the star will be displayed when you point the cursor at it. The Type asked for is whether the star is Main Sequence (MS) or is a
For a star of known absolute magnitude, M, its luminosity can be calculated using the following formula:

\[
\log_{10} \left( \frac{L}{L_{\text{sun}}} \right) = 0.4(M_{\text{sun}} - M)
\]

where, \(L_{\text{sun}} = 3.83 \times 10^{26} \text{ W}\), and \(M_{\text{sun}} = 4.75\). Rearranging this formula gives:

\[
L = L_{\text{sun}} 10^{0.4(M_{\text{sun}} - M)}
\]

(units of L are Watts (W))

For simplicity you can express each star’s luminosity in units of solar luminosities, and the equation becomes:

\[
L_{\text{solar}} = 10^{0.4(M_{\text{sun}} - M)}
\]

(this is unitless)

Using the data you’ve acquired, answer the following questions as best you can.

• From looking at your datasets, which star is the hottest?

• Which star is the coolest?

• Which star is the brightest?

• Which star is the faintest?

Since the size of each star also tracks diagonally across the CM diagram, the smallest objects fall in the lower left to the largest objects in the upper right of the diagram. Knowing this, answer the following questions:

• Which object is the largest?

• Which object is the smallest?
For these last two objects use the following equation (from page 2) to calculate the radius of the star.

\[ L = 4\pi R^2 \delta T^4 \]

where Stefan's constant, \( \delta = 5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4 \). What are these radii expressed in solar radii (the radius of our Sun = 6.96x10^8 m)? In other words how many times bigger or smaller than our Sun are these two stars?

Use the scrollbars to move your field of view onto a part of the Milky Way and again examine the CM diagram.

- Are there more main sequence stars than giants or vice versa?

- Now move to a part of the sky well away from the plane of the Milky Way. Answer the same question.

- What does this tell you about the relative ages of stars in the plane of the Milky Way compared to those out of the plane, as we see them?

- What does this mean physically about the two regions with regards to star formation and the evolution of the Galaxy?
Finally, scan around the sky to see if you can find any stars that are just to the upper right from the main sequence. These are stars that are in the process of evolving away from the main sequence and so adhere to the calibration for this observed phenomenon, presented in the diagram on page 4.

- Choose one of these and estimate the star’s location on the H-R diagram, i.e. its abs. magnitude and temperature or (B-V) color, and make an estimate of the star’s likely age. (You can switch between (B-V) and temperature on the x-axis of the H-R diagram window by using the button below the graph on the window.)

Additional Questions:

1. You have seen how useful the CM diagram can be. There exists a relation between mass and luminosity:

\[ \left( \frac{L}{L_{\odot}} \right) = \left( \frac{m}{m_{\odot}} \right)^n \]

where \( n \) ranges from 2 to 3.5 depending on the type of star involved. Important: this relation ONLY holds for stars ON the main sequence. Given this, go back and make an estimate for which of your stars is the most massive – i.e. which part of the H-R diagram corresponds to the area of most massive main sequence stars?

2. If all the stars in your table were twice as far away, but the apparent brightness remains the same, would the luminosities you calculated be larger or smaller? Why?
3. Similarly, if each star were instead half the temperature you measured, would the luminosity increase or decrease? Why and by how much?

4. The CM diagram underpins a lot of observations and developed theory about stellar evolution. It has been a vital tool in astronomy since the early part of the 20th century. An added complication comes from the fact that light from stars can be reduced or “reddened” by intervening dust in the interstellar medium. How would large amounts of dust affect our estimates of stellar properties (ages and distances) for stars far from us?

Conclusion: