1 Introduction

Read through this information before proceeding on with the lab.

1.1 Spectral Classification of Stars

1.1.1 Types of Spectra

Astronomers are very interested in spectra—graphs of intensity versus wavelength for an object. They basically tell you how much light is produced at each color. Spectra are described by Kirchhoff’s Laws:

1. A hot opaque body, such as a hot, dense gas (or a solid) produces a continuous spectrum—a complete rainbow of colors.
2. A hot, transparent gas produces an emission line spectrum—a series of bright spectral lines against a dark background.
3. A cool, transparent gas in front of a source of a continuous spectrum produces an absorption line spectrum—a series of dark spectral lines among the colors of the continuous spectrum.

It should be noted that the bright lines in the emission spectrum occur at exactly the same wavelengths as the dark lines in the absorption spectrum. Thus, one can think of the absorption spectrum to the right as the continuous spectrum minus the emission spectrum.

1.1.2 Absorption Spectra From Stars

The light that moves outward through the Sun is what astronomers call a continuous spectrum since the interior regions of the sun have high density. However, when the light reaches the low density region of the solar atmosphere called the chromosphere, some colors of light are absorbed. This occurs because the chromosphere is cool enough for electrons to be bound to nuclei there. Thus, the colors of light whose energy corresponds to the energy difference between permitted electron energy levels are absorbed (and later re-emitted in random directions). Thus, when astronomers take spectra of the sun and other stars they see an absorption spectrum due to the absorption of the chromosphere.

(a) The three different types of spectra.

(b) The chromosphere is responsible for absorbing photons from the Sun’s hot interior. This is what creates the Sun’s absorption spectrum.

Figure 1: Spectra and the generation of the Sun’s spectrum.
1.1.3 OBAFGKM

Astronomers have devised a classification scheme which describes the absorption lines of a spectrum. They have seven categories (OBAFGKM) each of which is subdivided into 10 subclasses. Thus, the spectral sequence includes B8, B9, A0, A1, etc. A traditional mnemonic for the sequence is Oh, Be, A Fine Girl/Guy, Kiss Me!

Although based on the absorption lines, spectral type tells you about the surface temperature of the star. One can see that there are few spectral lines in the early spectral types O and B. This reflects the simplicity of atomic structure associated with high temperature. While the later spectral types K and M have a large number of lines indicating the larger number of atomic structures possible at lower temperatures.

1.1.4 Planck Curves

The outward appearance of stars depends more strongly on the underlying continuous spectrum coming from the inner parts of a star than the absorption at its surface. Continuous spectra for stellar interiors at different temperatures are described by Planck Curves shown in Figure 2(b). Note that as the temperature increases the total amount of light energy produced (the area under the curve) increases and the peak wavelength (the color at which the most light is produced) moves to smaller more energetic wavelengths.

![Planck Curves](image)

(a) Spectral Type.

(b) Three blackbody curves at different temperatures.

Figure 2: Spectral types and Planck curves.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Temperature</th>
<th>Max Wavelength</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>O0</td>
<td>40,000 K</td>
<td>72.5 nm</td>
<td>Blue</td>
</tr>
<tr>
<td>B0</td>
<td>20,000 K</td>
<td>145 nm</td>
<td>Light Blue</td>
</tr>
<tr>
<td>A0</td>
<td>10,000 K</td>
<td>290 nm</td>
<td>White</td>
</tr>
<tr>
<td>F0</td>
<td>7,500 K</td>
<td>387 nm</td>
<td>Yellow-White</td>
</tr>
<tr>
<td>G0</td>
<td>5,500 K</td>
<td>527 nm</td>
<td>Yellow</td>
</tr>
<tr>
<td>K0</td>
<td>4,000 K</td>
<td>725 nm</td>
<td>Orange</td>
</tr>
<tr>
<td>M0</td>
<td>3,000 K</td>
<td>966 nm</td>
<td>Red</td>
</tr>
</tbody>
</table>

Table 1: This table lists corresponding values of color, spectral type, and peak wavelength. Note that these are all different ways of talking about the surface temperature of a star.

1.1.5 Annie Jump Cannon

Most of the early work on stellar spectra was done early in the 20th century at Harvard University. The principal figure in this story was Annie Jump Cannon. She joined Harvard as an assistant to Observatory Directory Edward
C. Pickering in the 1890’s to participate in the classification of spectra. She quickly became very proficient at
classification examining several hundred stars per hour. She completed a catalogue of spectral types for hundreds of
thousands of stars.

1.2 Luminosity

Luminosity is the total energy that a star produces in one second. It depends on both the radius of the star and on
its surface temperature. One can calculate luminosity by finding the product of

1. how much energy each section of the surface of a star is producing \((\sigma T^4)\), the Stefan-Boltzmann Law, and
2. the entire surface area of the star \((4\pi R^2)\).

Thus, the luminosity of a star can be calculated using

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

(1)

where \(L\) is the luminosity, \(\sigma = 5.67 \times 10^{-8}\) W/(m\(^2\)·K\(^4\)), \(T\) is the stellar surface temperature, and \(R\) is the stellar
radius. The luminosity of a star would increase if one increased either the size \(R\) or the surface temperature \(T\) with
temperature being the dominating factor. If we work in solar units indicated with a \(\odot\) symbol, we can ignore the
constants and simply write

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

(2)

For example, if a star has the same surface temperature as the sun and a radius that is twice as big, its luminosity
must be \(L = (2R)^2 (T)^4 = 4L_\odot\).

1.3 The Hertzsprung-Russell Diagram

1.3.1 Origin of the Hertzsprung-Russell Diagram

Many scientific discoveries are made first theoretically and then proven to be correct, or nearly so, in the laboratory.
That was not the case however, for the Hertzsprung-Russell diagram. A significant tool to aid in the understanding
of stellar evolution, the H-R diagram was discovered independently by two astronomers in 1912 using observational
comparisons. They found that when stars are plotted using the properties of temperature and luminosity, the
majority form a smooth curve. The actual properties originally plotted were properties which can be determined
observationally. The resulting diagram was named after the two discovering astronomers, Ejnar Hertzsprung of
Denmark and Henry Norris Russell of America.

Imagine plotting a random sampling of stars from our galaxy. The majority of these stars when plotted on an H-R
diagram go down from left to right in a diagonal line. The temperature scale along the bottom axis goes from coolest
on the right to hottest on the left. This is contrary to the normal convention, where values increase going left to
right on an axis. The Luminosity scale on the left axis is dimmest on the bottom and gets brighter towards the top.
This places the cooler, dimmer stars towards the lower right and the hotter, more luminous stars at the upper left.
Our own star, the Sun, is nearly in the middle of both the temperature and luminosity scales relative to other stars.
This puts it around the middle of the diagonal line.

1.3.2 The Basic H-R Diagram

The stars which lie along this nearly straight diagonal line are known as main sequence stars. The main sequence
line accounts for about 80% to 90% of the total stellar population. The basic H-R diagram is a temperature vs.
luminosity graph. The temperature may be replaced or supplemented with spectral class (or color index as noted
earlier). The main spectral classes in order from hottest to coolest are O, B, A, F, G, K, and M. These classes have
particular colors. Spectral type is most often written across the top of the H-R diagram going from hot, bluer “O”
stars on the left to cool, more red “M” stars on the right.
A Closer Look

Stellar luminosity, or a stars “brightness,” depends on two things: its surface area and its temperature. Using Equation (1), the Stefan-Boltzmann Law, we can see that stars above the main sequence on the H-R diagram (higher luminosity), with the same temperature as cooler main sequence stars, have greater surface areas (larger radii). Also, stars that have the same luminosity as dimmer main sequence stars, but are to the left of them (hotter) on the H-R diagram, have smaller surface areas (smaller radii).

Bright, cool stars are therefore necessarily very large. These enormous stars are called Red Giants and lie above the main sequence line. Antares is a good example of a red giant. Its temperature is a cool 3548 K (the Sun is about 5770 K), while its luminosity is about 50,000 times brighter than the Sun. This must mean that it has a very large radius, in fact about 600 times larger than the solar radius! Similarly, stars that are very hot and yet still dim must have small surface areas. These small, hot stars are called White Dwarfs and lie below the main sequence. They can have radii as small as the Earth, having temperatures around 10,000 K.

Looking back at Equation (1) we may notice that by holding $R$ constant and plotting the luminosity as the temperature varies, we generate a set of diagonal lines. These constant radius lines go from the upper left to the lower right (negative slope) of the diagram. Figure 3(b) shows these constant radius lines on the H-R diagram. Stars fall into three general categories. These categories are main sequence stars, red giants, and white dwarfs. It is important to note that the location of a star on the H-R diagram does NOT relate to its position in space. In fact, many of the brighter stars on the diagram are not among the closest to Earth.

Mass Luminosity Relation

There is a correlation between a main sequence star’s mass and its luminosity. Stars that are higher up (brighter) on the main sequence are more massive. This correlation is known as the Mass Luminosity relation. It says that the stars luminosity is proportional to the cube of its mass.

$$L \propto M^{3.5}$$  \hspace{1cm} (3)

where $L$ is luminosity and $M$ is stellar mass. Main sequence stars more massive than this relative to their luminosity would be in danger of collapsing under their own gravitational force. Stars less massive would be blown apart by radiation pressure from the intense luminosity.


1.3.5 Spectral and Luminosity Classes

Stars may be split up even more than just into Giants, Dwarfs, and Main Sequence stars. The spectral class of a star is closely related to its temperature. This class is actually determined by the lines in the star’s spectrum, which are heavily dependent on temperature. Spectral classification can place a star on the horizontal axis H-R diagram, but what the vertical axis? We need to classify stars according to their luminosity. Doing this would allow us to convey a lot of information about a star by its spectral and luminosity classification, including placing it fairly well on the H-R diagram. One way to classify by luminosity is to look at the star’s spectrum. This time instead of looking at which lines are present, as we do to get the temperature or spectral class, we look at the width of the lines. It turns out that more luminous stars have narrower spectral lines than less luminous ones of the same spectral class. For example, in Figure 4 the lines of the class Ia star are much narrower than the class IV star.

The luminosity classes are labeled I, II, III, IV, and V, where I is the brightest and is split up into Ia and Ib stars. Our Sun is classified as spectral class G2 and luminosity class V, placing it on the main sequence nearly in the middle.

Figure 4: Two A2 stars. The top is luminosity class Ia and the bottom luminosity class IV.

1.3.6 Instability

Some stars have times in their evolutionary track where they are not in equilibrium. These stars pulsate, expanding and contracting like a lung. It is a battle between the thermal pressure in the star and its gravitational force. When stars are in this state of imbalance or instability, they are crossing an area called the Instability Strip on the H-R diagram. This is an area around 1000K wide that sits above the main sequence, as shown in Figure 5.

Stars called Cepheid Variables are an important type of star in this state. They are used as distance indicators (standard candles) because the period of their pulsation varies in proportion with their luminosity. Cepheids are near the top of the Instability Strip. Other notable stars in this region of the diagram are W Virginis Stars, around the middle of the strip, and RR Lyrae Stars towards the bottom.

Figure 5: The Instability Strip on the H-R Diagram.
2 Pre-Lab Questions

1. One can experiment with the relationships between spectral type, temperature, and color with the simple animation below. Use the Star Color Slider tool at

   [http://astro.unl.edu/naap/hr/animations/starColorSlider.swf](http://astro.unl.edu/naap/hr/animations/starColorSlider.swf)

   to fill in Table 2. Drag the slider through different spectral types to see the change in temperature, color, and brightness.

<table>
<thead>
<tr>
<th>Star</th>
<th>Surface Temperature</th>
<th>Spectral Type</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Betelguese</td>
<td>3,530 K</td>
<td>M2</td>
<td>Red</td>
</tr>
<tr>
<td>Arcturus</td>
<td>4,300 K</td>
<td>K5</td>
<td>Orange</td>
</tr>
<tr>
<td>Sol</td>
<td>5,830 K</td>
<td>G2</td>
<td>Yellow</td>
</tr>
<tr>
<td>Procyon</td>
<td>6,530 K</td>
<td>F5</td>
<td>Yellow-White</td>
</tr>
<tr>
<td>Sirius A</td>
<td>9,145 K</td>
<td>A1</td>
<td>White</td>
</tr>
<tr>
<td>Rigel A</td>
<td>11,000 K</td>
<td>B8/B9</td>
<td>Pale Blue</td>
</tr>
<tr>
<td>Delta Orionis</td>
<td>33,200 K</td>
<td>O9</td>
<td>Real Blue</td>
</tr>
</tbody>
</table>

   Table 2: Fill in the empty fields above.

2. One can experiment with the relationships between luminosity, temperature (spectral type), and radius with a stellar luminosity calculator. Use the calculator at

   [http://astro.unl.edu/classaction/animations/stellarprops/stellarlum.swf](http://astro.unl.edu/classaction/animations/stellarprops/stellarlum.swf)

   to fill in Table 3. The values given are in Solar Units \((R_\odot, T_\odot, L_\odot)\).

<table>
<thead>
<tr>
<th>Radius ((R_\odot))</th>
<th>Temperature ((T_\odot))</th>
<th>Luminosity ((L_\odot))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>2 (2.02)</td>
<td>16 (16.8)</td>
</tr>
<tr>
<td>3 (3.02)</td>
<td>1</td>
<td>9 (9.12)</td>
</tr>
<tr>
<td>1</td>
<td>1/2 (0.49)</td>
<td>0.073 (0.057)</td>
</tr>
</tbody>
</table>

   Table 3: The numbers in parenthesis correspond to values the Stellar Luminosity Calculator will let you pick.

3. The mass luminosity relation given in Equation (3) describes the approximate mathematical relationship between luminosity and mass for main sequence stars.

   \[ L \propto M^{3.5} \]

   Calculating the luminosity of a star with a given mass is straight-forward. To calculate the mass of a star with a given luminosity, however, requires the equation to be reversed.

   \[ M \propto \sqrt[3]{L} = L^{1/3.5} \quad (4) \]

   Use these two equations to complete Table 4.

<table>
<thead>
<tr>
<th>Mass ((M_\odot))</th>
<th>Luminosity ((L_\odot))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4</td>
<td>0.0078</td>
</tr>
<tr>
<td>2</td>
<td>11.3</td>
</tr>
<tr>
<td>10</td>
<td>3.162</td>
</tr>
<tr>
<td>3.73</td>
<td>100</td>
</tr>
<tr>
<td>13.9</td>
<td>10,000</td>
</tr>
<tr>
<td>50</td>
<td>(8.84 \times 10^5)</td>
</tr>
</tbody>
</table>

   Table 4: Fill in the empty fields above.
3 H-R Diagram Explorer

Open the NAAP H-R Diagram Explorer, shown in Figure 6 from this link:

http://astro.unl.edu/naap/hr/animations/hr.html

Begin by familiarizing yourself with the capabilities of the Hertzsprung-Russell Diagram Explorer through experimentation.

- An actual H-R Diagram is provided in the upper right panel with an active location indicated by a red ×. This active location can be dragged around the diagram. The options panel allows you to control the variables plotted on the x-axis: (temperature, B-V, or spectral type) and those plotted on the y-axis (luminosity or absolute magnitude). One can also show the main sequence, luminosity classes, isoradius lines, or the instability strip. The Plotted Stars panel allows you to add various groups of stars to the diagram.

- The Cursor Properties panel has sliders for the temperature and luminosity of the active location on the HR Diagram. These can control the values of the active location or move in response to the active location begin dragged. The temperature and luminosity (in solar units) are used to solve for the radius of a star at the active location.

- The Size Comparison panel in the upper left illustrates the star corresponding to the active location on the HR Diagram. Note that the size of the sun remains constant.

4 Analysis

1. Drag the active location (the red ×) around on the H-R Diagram. Note the resulting changes in the temperature and luminosity sliders. Now manipulate the temperature and luminosity sliders and note the corresponding change in the active location. Check the appropriate region of the H-R diagram corresponding to each description in Table 5 (Hint: you should have only one check for each row.)
Phys-1050  
Hertzsprung-Russell Diagram Solutions  
Spring 2013

<table>
<thead>
<tr>
<th>Description</th>
<th>Top</th>
<th>Right</th>
<th>Bottom</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot stars are found at the:</td>
<td></td>
<td></td>
<td></td>
<td>×</td>
</tr>
<tr>
<td>Faint stars are found at the:</td>
<td></td>
<td></td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>Luminous stars are found at the:</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cool stars are found at the:</td>
<td></td>
<td></td>
<td>×</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Fill in the empty fields above.

2. Drag the active location around on the H-R Diagram once again. This time focus on the Size Comparison panel. Check the appropriate region of the H-R diagram corresponding to each description in Table 5. (Hint: you should have only one check for each row.)

<table>
<thead>
<tr>
<th>Description</th>
<th>Upper</th>
<th>Upper</th>
<th>Lower</th>
<th>Lower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Blue stars are found at the:</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small Red stars are found at the:</td>
<td></td>
<td>×</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small Blue stars would be found at the:</td>
<td></td>
<td></td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>Really Large Red stars are found at the:</td>
<td></td>
<td></td>
<td></td>
<td>×</td>
</tr>
</tbody>
</table>

Table 6: Fill in the empty fields above.

3. Check show luminosity classes and show isoradius lines (if they are not already checked). The green region (Dwarfs (V)) is known as the main sequence and contains all stars that are fusing hydrogen into helium as their primary energy source. Over 90% of all stars fall in this region on the H-R diagram. Move the active cursor up and down the main sequence and explore the different values of stellar radius. Describe the sizes of stars along the main sequence. What are stars like near the top of the main sequence, the middle, and the bottom?

**Solution:** The size of stars increases from lower right to upper left along the main sequence. Near the top of the main sequence, the stars are large and blue. At the bottom they are small and red. In the middle they are mid-sized and yellow-white.

4. Section 1.3.4 talked about the mass-luminosity relationship for stars on the main sequence by introducing Equation (3). What can you conclude about the masses of stars along the main sequence?

**Solution:** Equation (3) says that luminosity increases exponentially with increasing mass to the 3.5 power. Since the luminosity of stars on the main sequence increases as we move from the lower right to the upper left, the mass of the stars must also increase as we move from the lower right to the upper left.

5. Uncheck show luminosity classes and check show instability strip. Note that this region of the H-R Diagram indicates where pulsating stars are found, such as RR Lyrae stars and Cepheid variable stars. These stars vary in brightness because they are pulsating—alternately growing bigger and smaller—which changes their radii and surface temperatures and, thus, affects their luminosities. Describe the characteristics of stars that are found in the instability strip. You should cover their range of temperatures, colors, luminosities, and sizes. (Hint: Comparing them to the sun is useful.) Are variable stars necessarily on the main sequence?

**Solution:** Variable stars are not on the main sequence. In the stellar life cycle, they are almost completely out of hydrogen in their cores. At this point, their cores are mostly helium that has not begun to undergo nuclear fusion yet. Instead, hydrogen burning occurs in a shell surrounding the core. Their temperatures range from about \(1 - 2T\odot\), meaning that they’re mostly light blue, white, and yellow stars. Their luminosities and radii vary greatly, however. The luminosities range from \(10 - 1000L\odot\). The radii range from \(1 - 100R\odot\).

6. Check the plotted stars option the nearest stars. Describe the characteristics of the nearest stars. You should cover their range of temperatures, colors, luminosities, and sizes.

**Solution:** The nearest stars are mostly white and yellow down to red stars because their temperatures range from \(0.4 - 2T\odot\). Their sizes range from \(0.1 - 1R\odot\), and their luminosities range from \(10^{-3} - 10L\odot\). In all, these stars are mostly much smaller, cooler, dimmer, and redder than our star.
7. Change the plotted stars option from the nearest stars to the brightest stars. Why are these stars the brightest in the sky? Three students debate this issue:

**Student A** “I think it’s because these stars must be very close to us. That would make them appear brighter to us in the sky.”

**Student B** “I think it’s because these stars are very luminous. They are putting out a tremendous amount of energy.”

**Student C** “I think it’s because these stars are very close and very luminous.”

Use the tools of the H-R Diagram to support the views of one of the three students. Why are the stars we perceive as bright in the night sky really bright? *(Hint: You may find the options labeled both the nearest and brightest stars and the overlap useful.)*

**Solution:** Using the overlap option, it’s quite clear that the nearest stars and the brightest stars are not the same, so Student C is definitely wrong. Student A says essentially the same thing, so he’s wrong, too. From here, we can prove Student B is correct by noting that the brightest stars are the brightest stars in the sky solely because their luminosities are $10 - 10^5 L_\odot$. They really are just freaking luminous as hell.