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A1101, Lab 5: The Hertzsprung-Russell Diagram Laboratory Worksheet

One of the most basic physical properties of a star is its *luminosity*, the rate at which it radiates energy into space. The most basic observable property of a star is its *apparent brightness*, which describes the rate at which we on Earth receive energy from the star. (In this Lab we will refer to this simply as *brightness*; the more technical term is *flux*.)

The brightness of a star depends on its luminosity but also on its distance: if two stars have the same luminosity, the more distant one appears fainter. This is the same effect as seeing two 100-watt light bulbs (which have same luminosity) at different distances --- the one across the street appears fainter than the one on the table next to you because light from the distant bulb has spread over a much larger area before it reaches you. Thus, to measure the luminosity of a star we must measure its brightness and determine its distance. As you know from Lab 4, distances can be determined from parallax, at least for stars that are close enough that their parallax shifts can be measured.

Another basic observable property of a star is its color. Astronomers typically describe this by a *color index*, which tells the ratio of the star's brightness as seen through two different colored filters. For purposes of this Lab, you just need to know that the color index is a number that usually lies between -0.5 and 2.5 and that stars with larger color indices are redder. In other words, color index is a quantitative measure of "redness." Stars with negative color indices are the bluest stars.

The color of a star depends mainly on the *temperature* of its surface. Hotter stars have bluer colors and cooler stars have redder colors. The Sun has a surface temperature of 5,800 degrees Kelvin, and it emits primarily yellow light.

In this Lab you will first compute the luminosities of a few stars from their brightnesses and distances. You will then make and examine plots of luminosity vs. color index, the so-called Hertzsprung-Russell diagram, which is one of the main tools that astronomers use to understand the properties of stars. The first versions of the such diagrams were made by the Danish astronomer Ejnar Hertzsprung and the American astronomer Henry Norris Russell around 1910.

Part 1: Distance and brightness to luminosity

As discussed in lecture, the relation between brightness, luminosity, and distance is

$$\text{Brightness} = \text{Luminosity} \div (4\pi d^2)$$

where d is the distance. Moving an object twice as far away makes it four times fainter. If we measure a star's brightness and (using parallax) its distance, we can find its luminosity by reordering this equation:

$$\text{Luminosity} = \text{Brightness} \times (4\pi d^2)$$

The star Alpha Centauri (α Cen) is one of the closest stars to the Sun, at a distance of $d = 4.37$ light years = 4.13×10^{16} meters.

The apparent brightness of α Cen is

Brightness = 2.71×10^{-8} watts/m² (watts per square meter).

From the above equation, what is the luminosity of α Cen, in watts?

Luminosity of α Cen =

What is the ratio of this luminosity to the luminosity of the Sun, 3.83×10^{26} watts?
(Luminosity of α Cen / Luminosity of Sun) =

If you did everything right, your answer to the last question should be about 1.5.

Now do the same calculation for:

Betelgeuse, the red star that is the left shoulder of the constellation Orion:

Brightness = 9.90×10^{-8} watts/m²

Distance = 6.08×10^{18} m

(Luminosity of Betelgeuse / Luminosity of Sun) = ?

Rigel, the blue star that is the right knee of the constellation Orion:

Brightness = 5.68×10^{-8} watts/m²

Distance = 8.02×10^{18} m

(Luminosity of Rigel / Luminosity of Sun) = ?

Sirius b, a faint blue star that is a binary companion to Sirius (which is itself the brightest star in the sky):

Brightness = 1.20×10^{-10} watts/m²

Distance = 8.14×10^{16} m

(Luminosity of Sirius b / Luminosity of Sun) = ?

Check your results with those of your lab partner, and resolve any errors.

As these calculations will show you, some stars are much more luminous than the Sun, some are much less luminous, and some are comparable in luminosity.

Part 2: Making an HR diagram

The table below lists the color index and luminosity of 50 stars, whose distances were determined via parallax measurements from a space mission called Hipparcos. Luminosities are all relative to the Sun's luminosity, i.e., an entry of 0.01 means that the star is (1/100) of the solar luminosity (100 times less luminous than the Sun).

Plot the positions of these 50 stars on the first page of the graph handout. The four stars in the first two rows of the table have been plotted for you as examples; check that you understand their positions on the plot. After you have finished the first ten stars, check your plot with your lab partner to see that you agree. Plotting these points will take some time, but look for patterns as they emerge.

<u>Color Index</u>	<u>Luminosity</u>	<u>Color Index</u>	<u>Luminosity</u>
0.89	0.2	0.55	0.0002
1.02	8	1.04	0.1
0.45	5	-0.08	77
1.04	34	1.36	0.05
1.02	0.15	0.80	18
0.74	0.3	0.61	4.6
1.10	0.1	1.14	0.1
0.50	8	0.89	27
1.42	0.03	1.62	0.0009
0.32	7.6	1.12	0.07
0.20	14	1.08	21
0.39	8.7	0.96	0.1
0.24	8.8	0.52	3.7
1.41	0.03	1.47	0.004
0.72	2.4	0.97	0.2
0.31	13	0.77	0.3
1.08	29	0.65	1
1.02	0.2	0.69	3
0.08	58	0.86	0.6
-0.07	58	1.07	0.2
0.50	2	0.93	29
1.03	31	0.53	9.4
0.72	0.7	0.13	27
0.36	0.0003	0.96	0.2
0.18	0.0006	0.26	0.0006

Part 2, continued

The color index of α Cen is 0.69. Plot it on your graph and label it.
The color index of Sirius b is -0.03. Plot it on your graph and label it.
Where would Rigel and Betelgeuse appear on this diagram?

Remember to write your name on your graph and turn it in with this worksheet.

Write down two things you notice about your handmade graph. Each of your observations should be written as a complete sentence:

- 1.
- 2.

Once you and your lab partner have made it this far, your Lab TA will give you a version of the plot that has 1500 stars on it instead of 50, so that you can see more details. Spend a few minutes discussing this plot with your lab partner.
Write down four qualitative observations about things you and your partner notice in the HR diagram. Each of these observations should be expressed as a complete sentence. Some repetition with the observations already made above is OK, provided that these observations still hold true for the more complete diagram.

- 1.
- 2.
- 3.
- 4.

Part 3: Making sense of the HR diagram

As discussed in the planetarium presentation, the luminosity of a star depends on its temperature and its surface area. If two stars have the same temperature (and thus the same color), then the bigger star is more luminous. If two stars have the same radius (and thus the same surface area), then the hotter star is more luminous.

With this information in mind, label the four corners of the HR diagram (the one on which you plotted points by hand) to indicate where you find stars that are

- (a) hot and big [where big means large radius]
- (b) hot and small
- (c) cool and big
- (d) cool and small.

Based on the HR diagram, what do you think is the approximate color index of the Sun? Explain your answer.

For two stars that have the same temperature, the luminosity of the stars is proportional to the surface area. Consider a star that is the same color as the Sun, and thus the same temperature, but has a luminosity 10,000 times smaller ($L/L_{\text{Sun}} = 0.0001$). As you can see from the HR diagram, such stars exist. Would the *radius* of such a star be closest to

- A. One solar radius
- B. 0.1 solar radii
- C. 0.01 solar radii
- D. 0.001 solar radii
- E. 0.0001 solar radii?

Explain your answer. (Hint: the surface area of a sphere is $4\pi r^2$.)

The radius of the Sun is 110 times larger than the radius of the Earth (700,000 km vs. 6,400 km). Would the radius of the star described above be much larger than the Earth's radius, much smaller than the Earth's radius, or similar in size?

After discussion with your lab partner, write down (in complete sentences) two hypotheses about things you have noticed in the HR diagram and/or two conclusions that you can draw about stars from the appearance of the HR diagram.

1.

2.