Chapter 10

Hertzsprung-Russell Diagrams and Distance to Stars

10.1 Purpose

In this lab, we will explore how astronomer classify stars. This classification is one way that can be used to determine the distance to stars that are more distant than those that can be measured using parallax.

10.2 Introduction

One of the most obvious observations about the night sky is that some stars are bright and some are dim. This qualitative observation has been quantified by astronomers and can be used with other information to determine a stars distance.

Apparent Brightness is a measurement of how bright a star appears to us. We can determine a star's brightness quantitatively by pointing a photometer at it and counting the number of photons that we receive in a given amount of time. Apparent brightness depends on two factors: the distance to the star and the star's **luminosity**. Brightness is a measurement of how much stars radiate in visible wavelengths.

Luminosity is a measure of the *intrinsic* power that a star radiates. It depends on the star's surface area (as bigger stars can radiate more) and the star's temperature (hotter stars radiate more). The Stefan-Boltzmann Law gives us this relation:

$$L = 4\pi R^2 \sigma T^4 \tag{10.1}$$

where L is the luminosity, R is the stellar radius, T is the temperature and σ is a constant.

If we know a star's luminosity, we can determine its brightness, since $L \propto (brightness)(distance)^2$ by the inverse-square law for light.

There is a very wide range of values for the brightness of a star. For this reason, astronomers convert this brightness into an **Apparent Magnitude**. The apparent magnitude, abbreviated as m, is simply the (base-10) logarithm of the Brightness. Because of historical reasons, magnitudes have an awkward scale. Really bright objects have a negative magnitude. Dim objects have a positive magnitude. It is important to note that we always compare the brightnesses of two objects. For historical purposes, the star Vega was arbitrarily chosen to have an apparent magnitude of zero. The table 10.1 lists the apparent magnitudes of some common objects.

App. Mag.	Celestial object
-26.73	Sun
-12.6	full Moon
-4.4	Maximum brightness of Venus
-4.0	Faintest objects observable during the day with naked eye
-2.8	Maximum brightness of Mars
-1.5	Brightest star in the night sky: Sirius
0	Vega
2	Polaris
6	Faintest stars observable with naked eye
12.6	Brightest quasar
30	Faintest objects observable with Hubble Space Telescope

 Table 10.1: Apparent Magnitudes of Common Objects

But we want a way to compare stellar brightnesses that's independent of distance. For this reason, astronomers introduced the idea of **Absolute Magnitude**, abbreviated M. Essentially, we're taking all of the visible stars and moving them so that they're a standard distance of **10 parsecs** (32.6 ly) away. Then, we record how bright they appear. The only factor that differs between the m and M measurements is the distance to the star. The equation that relates these three parameters is

$$d = 10 \times 10^{(m-M)/5},\tag{10.2}$$

where d is the distance to the star in **parsecs**.

10.2.1 The H-R Diagram

In the early 1900s, a method to classify stars was discovered by Ejnar Hertzsprung and Henry Norris Russell. Up until that time, it was naively believed that the brightness of a star was directly related to its temperature, or color. It was expected that intrinsically brighter stars would be hotter and therefore bluer, in much the same way a metal rod changes its color from red, to white, to blue as it is heated up. Discovering whether this was true presented some obvious challenges. Since the distances to the stars were unknown, one could not determine the intrinsic brightness of a star, but only its apparent brightness. As we've already said, a bright star that's very far away would appear much fainter than a dim star that's much closer. To overcome this problem, scientists began to look at stars that were found in *clusters*.

In general, it's safe to assume that all the stars in a cluster, except for a few random anomalies, are at roughly the same distance away. Even if this distance is unknown, scientists realized that it was still possible to directly compare the relative brightnesses of the stars and their respective colors.

The *color* in these early observations was determined by observing each star through two different filters. The magnitude of a star would be measured using a blue filter (B), which let light pass toward the blue end of the spectrum, and then with a visual filter (V), which was centered more in the green-yellow visual band. The difference in magnitudes between these two bands, B - V (B minus V), was called the B-V color index. Hot stars have a negative index and cooler stars a positive index since in the magnitude system, fainter measurements have greater magnitudes. The B-V color index depends **only** on a star's Temperature.

Modern astronomers use two other systems for this color classification. The most obvious is simply a temperature scale from a few thousand degrees to several ten thousands of degrees. The other system is the **spectral class** which are labeled by the letters **O B A F G K M** with **O** being the hottest and **M** the coolest. In addition, each class is divided into ten division so you might see a star classified as B7 or G1.

Surprising Results in Hertzsprung-Russell Plots

Hertzsprung and Russell plotted V vs. B - V for a large number of stars in the same cluster. What they found was that most of the stars in the plot lie along a very tight but curved line (later called the *main sequence*), which extended diagonally from the low luminosity-low temperature to the high luminosity-high temperature stars. A star's position on this line was basically a function of its mass. These plots were given the name "H-R diagrams" and are discussed further in your text.

Other groupings of stars were also evident on the plot. Two of these were later found to be red giant stars and white dwarf stars; both groups contain stars near the end of their life cycles.

Measuring the Distance to a Cluster

As the study of stars progressed, the absolute or intrinsic brightness of many nearby stars was determined by measuring the distance to these stars using the parallax method. With this information, astronomers could create what an H-R diagram would look like for a cluster of stars at any distance away. By comparing the difference between the H-R diagram of stars



Figure 10.1: Groupings of Stars on the HR Diagram

in this 'ideal' cluster and that of a real cluster, it was possible to estimate the distance to the cluster by measuring the shift in magnitudes, m - M, and using Equation 10.2.

10.3 Procedure

In this lab, we will first use the 'HR Diagram Explorer' in the NAAP software to understand the relationship between spectral classes and luminosity. Then we will use the HR diagram to measure the distance to several star clusters. In a web browser, open the class web page, select 'software' on the top menu. Open the 'hrExplorer' link.

10.3.1 Spectral Class and Luminosity

In this section of the procedure, we will examine the HR diagram and the relationship of luminosity, temperature and spectral type for several stars.

1. At the top of page is a panel which displays the spectral type of a star and its surface temperature. You can slide the marker back and forth to various spectral type and the

surface temperature will be display below. The color of the star is shown in on the left side of the panel. The panel is shown in Figure 10.2.



Figure 10.2: Software to convert spectral class to surface temperature

2. The panel below the spectral type/temperature is the 'HR Diagram explorer' panel which is shown in Figure 10.3. Check the 'show luminosity classes', 'show isoradius lines' boxes. The 'show main sequence' should already by checked. The x-axis should be set to 'temperature' and the y-axis to 'Luminosity' A red 'x' indicates the the position of our Sun on the red line of main sequence.



Figure 10.3: HR diagram explorer

3. You can click and drag the red x around the HR diagram. Move the red x around and answer the following questions.

The hottest stars are found	
The coolest stars are found	
The faintest stars are found	
The most luminous stars are found	-
The largest stars are found	
The smallest stars are found	

4. A list of stars is shown in the table below. Complete the table by first determining the stars surface temperature from the spectral type (class) and color. Put the temperature and luminosity (in solar luminosity units) into the HR explorer at the lower left. (The temperature can only be entered to two significant digits so round your temperature numbers to 2 significant digits). The red x on the position of the HR diagram determines the type of star (white dwarf, red dwarf on the main sequence (red line), main sequence, red giant, blue giant or blue dwarf). The calculation of the star's radius is shown in the lower left area.

Name	Spec Type	Color	Temp	Luminosity(L_{\odot})	HR Type	Radius (R_{\odot})
Sirius	A1			26		
Vega	A0			59		
Pollux	K0			46		
Aldebaran	K5			400		
Rigel	B8			50,000		
Achernar	B3			3,000		
Hadar	B1			74,000		
Arcturus	K2			220		
Sirius B	≈B8			0.003		

10.3.2 Cluster Fitting

In this section of the procedure, we will fit several star clusters to an HR diagram. From the apparent magnitude and absolute magnitude, we can determine the distance. The 'HR Diagram Star Cluster Fitting Explorer' program is shown in Figure 10.4

- 1. The 'HR Diagram Star Cluster Fitting Explorer' is the last panel on the page you opened earlier. Check the box 'show horizontal bar' box. You can select various cluster from the pull down menu labeled 'select cluster'.
- 2. Select the 'Pleiades Cluster'. The red line on the HR diagram shows the main sequence star line. If you click and drag the white area of the HR plot vertically, you can align the stars of the cluster with the red main sequence line. Slide the horizontal line up and down until it is located in the main part of the star cluster.



Figure 10.4: HR cluster fitting software

- 3. Read off the absolute magnitude (M) and the apparent magnitude (m) and the left and right scales and enter them into the appropriate boxes on the distance calculation in the lower right of the panel. When you finishing entering M and m, the distance calculation will show the distance to the cluster in parsecs.
- 4. Complete the table below for the clusters shown.

Cluster	Abs Magnitude(M)	App Magnitude(m)	Distance (pc)
Pleiades			
Messier 67			
Hyades			
Praesepe			
NGC 188			

10.3.3 Questions

1. Use the distance equation (equation 10.2), the apparent magnitude (-26.73 from Table 10.1) and the distance to the Sun (d = 1 AU with 1 pc = 206,265 AU), find the absolute magnitude of the Sun.

2. If the Sun were at a distance of 10 pc, what would be its apparent magnitude? Would it be visible with the naked eye at night?

3. Even the best telescopes can not 'resolve' a star. Stars appear as points of light. In the 'HR explorer' section of the procedure, the program calculated the star's radius in R_{\odot} . Use equation 10.1 to show the equation $R = \frac{\sqrt{L}}{(T/T_{\odot})^2}$ is correct. Hint: Solve equation 10.1 for R. Use the Sun's values $(R_{\odot}, L_{\odot} = 1 \text{ and } T_{\odot})$ in equation 10.1 and solve for R_{\odot} . Then take a ratio of R and R_{\odot} $(\frac{R}{R_{\odot}})$.

4. Recent Hubble space telescope data give the distance to the Pleiades cluster to be 440 ly. Convert your answer for the distance to the Pleiades cluster to ly and calculate the percent error.

Distance to Pleiades in ly _____ % error _____

10.4 Conclusion

Write a conclusion about what you have learned. Include all relevant numbers you have measured with errors. Sources of error should also be included.