The Hertzsprung-Russell Diagram

11

Astronomy Laboratory Exercise

Learning Objectives

In this laboratory exercise, students will:

- Explore the concept of stellar spectral types.
- Learn the relationship between stellar spectral types and absolute magnitudes.
- Learn about the Hertzsprung-Russell diagram.
- Explore how to use determine the distances to stars using the Hertzsprung-Russell diagram.

Definitions: spectral type, spectral classification sequence, main sequence

Review concepts of: apparent magnitude, absolute magnitude, distance modulus, spectral lines

Introduction

In a previous exercise *"Stellar Distances and the Solar Neighborhood"*, you learned about how astronomers can measure the distances to the stars using the method of parallax. The apparent shifting of the stars that results from the Earth's journey around the Sun each year can be used to triangulate the distances to the stars. You also learned that this technique has its limitations. If the apparent shift of the stars (caused by the Earth's movement) is so small that it is imperceptible, then parallax becomes useless. An alternative technique was then presented to you. The method using the ***distance modulus*** employs measuring the apparent magnitude of a star and comparing it to the absolute magnitude of that star (see Equation 1 below). The difference between these two values is an indicator of the star's distance. The distance modulus is a very important tool in determining the distances to objects in astronomy since it works for any object that emits light and it works for objects at any distance.

However, there is one very significant problem that astronomers faced when using this technique. Recall (from *"Stellar Distances and the Solar Neighborhood"*) that the definition of the *absolute magnitude* is related to how much energy a star (or any object) is giving off. It is related to a star's luminosity. What troubled astronomers early in the 20th Century, was *how do we know how much energy a star is giving off?* This is not something that can be determined by simply looking at a star. Therefore, without knowing the absolute magnitude of a star, astronomers could not measure their distances using the all-important distance modulus. However there is a way around this problem. Let's explore how this works.

$$m - M = 5(\log D) - 5$$

Equation 1

Stellar Spectral Types

In a previous exercise you learned that stars emit light that contains a set of spectral lines within it (see the *"Spectral Lines"* exercise). When the light from a star is passed through a prism, a set of dark absorption lines will appear. These dark absorption lines are the "fingerprints" of all the chemical elements that the star has within it. This was a very important discovery. Unfortunately in the 19th Century, astronomers did not know how these spectral lines were formed.

In the early part of the 20th Century, physicists were beginning to understand the nature of atoms. Slowly, an understanding of what atoms were made of and how they behaved led physicists to create a whole new branch of science called *quantum mechanics*. This new field of physics deals with the inner workings of the atom and how atoms create and interact with light. Quantum mechanics led physicists to an understanding of how spectral lines are created by atoms and under what circumstances the lines are formed.

By this time, astronomers were busily photographing the spectra of thousands of stars in an effort to understand the nature of the stars. It was soon realized that the stars showed a great variety of different spectral lines in their spectra. Many of the stars showed the "fingerprints" of the same chemical elements, but many stars showed the fingerprints of *different* chemicals. This led astronomers to devise a category system for stars based upon the appearance of their spectra. Originally the system was set up to be categories that were labeled with letters of the alphabet. The spectrum of a category A star looked different from a spectral category B star, which was different from a spectral category C star...etc. All of the stars in each category showed similar features (similar to when species of animals that show similar features are all given the same species name... cats, dogs, etc.) therefore they were all labeled as the same ***spectral type***. This seemed to work well until physicists discovered one very important reason why the spectrum of stars look different from each other. It was discovered that the *surface temperature of a star plays a major role in why certain spectral lines appear in one star's spectrum, but not another.* This radical discovery forced astronomers to rethink the way that the lettering of the spectral classification categories had been laid out. The original A,B,C, etc. categories were no longer systematic nor did they make sense. In addition, some categories were no longer needed at all! As a solution, astronomers rearranged the categories and eliminated some categories to represent the fact that the spectral types of stars are related to surface temperatures of the stars. The final set of categories ended up being categories O, B, A, F, G, K, and M. This is known today as the ***spectral classification sequence***. Although the lettering sequence of the categories is no longer conveniently in alphabetical order, it represents an important concept. The lettering sequence represents categories of stars that range from hottest surface temperatures to coolest surface temperatures (see Figure 1). The spectral type-O stars have the hottest surface temperatures of all stars. Spectral type-B stars are not as hot as O-type stars; spectral type-A stars are cooler still etc. Spectral type-M stars have the coolest surface temperatures of them all.

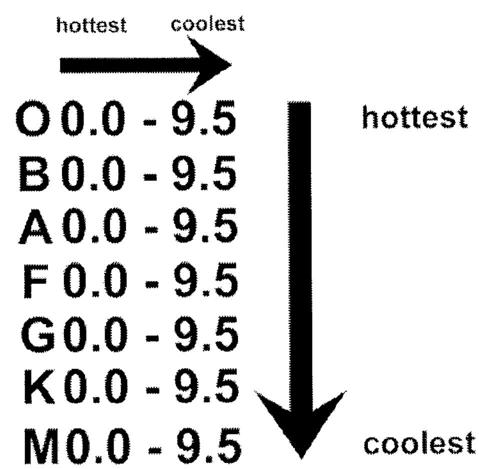


Figure 1: Spectral Classification Sequence

It was soon realized that there was a need to modify the spectral classification sequence to allow for more diversity in describing the spectral types of stars. Astronomers modified the OBAFGKM sequence by adding a sub-category of numbers. Each spectral-type letter is accompanied by a number between 0.0 and 9.5 (in increments of 0.5). The logic behind the sub-category numbering is the same as the lettering sequence in each lettered category; 0.0 is the hottest and 9.5 is the coolest (see Figure 1). For example, a spectral type B7.0 star is hotter than a type B9.5 star, whereas a spectral type A1.5 star is hotter than an spectral type F0 star, etc.

The Hertzsprung-Russell Diagram

In the early part of the 20th Century, two different astronomers discovered an important relationship for stars. A Danish astronomer named Ejnar Hertzsprung and an American astronomer named Henry Norris Russell independently discovered that the spectral type of a star is an indicator of the star's absolute magnitude. They discovered this relationship by using stars that were close enough to the Earth for parallax to work to determine their distances, and by observing the apparent magnitudes of these stars. By doing so they could rearrange the distance modulus (see Equation 1) and calculate the absolute magnitudes for these stars. Next, they graphed the absolute magnitude of the stars versus the spectral types of the stars. In doing so, a relationship became very evident between the two quantities.


Figure 2: Hertzsprung and Russell

It turns out that stars have physical characteristics that are very predictable based upon certain physical relationships. The graphical relationship between the spectral type of a star and the absolute magnitude of the star became known as the ***Hertzsprung-Russell diagram***. Let's see how this works.

Procedure

Table A lists 44 stars that are located near the Sun in our Milky Way galaxy. Some of the stars are the nearest stars to the Sun, whereas some of the stars are among the brightest stars in the sky.

Table A: 44 Nearest / Brightest Main Sequence Stars

	Star Name	Absolute Magnitude	Spectral Type
1	Proxima Centauri	15.53	M5.5 V
2	Alpha Centauri A	4.37	G2 V
3	Alpha Centauri B	5.72	KO V
4	Barnard's Star	13.23	M5 V
5	Wolf 359	16.57	M6.5 V
6	Lalande 21185	10.46	M2 V
7	Sirius A	1.45	A1 V
8	Luyten 726-8A	15.42	M5.5 V
9	UV Ceti	15.38	M6 V
10	Ross 154	13.14	M3.5 V
11	Ross 248	14.77	M5.5 V
12	Epsilon Eridani	6.15	K2 V
13	Ross 128	13.48	M4 V
14	Luyten 789-6	14.63	M7V
15	Epsilon Indi	7.00	K4 V
16	61 Cygni A	7.50	K5 V
17	61 Cygni B	8.33	K7 V
18	G 227-046	11.18	M3.5 V
19	Groombridge 34	10.32	M2 V
20	Lacaille 9352	9.56	M2 V
21	TAU Ceti	5.71	G8 V
22	Altair	2.21	A7 V
23	G 051-015	17.00	M6.5 V
24	YZ Ceti	14.20	M5.5 V
25	G 089-019	11.94	M4 V
26	Lacaille 8760	8.74	M0 V
27	Kapteyn's Star	10.94	M1 V
28	Spica	-3.6	B1 V
29	Kruger 60 B	11.59	M4 V
30	Ross 614	13.08	M4.5 V
31	Achernar	-1.0	B5 V
32	G 012-043 B	14.83	M5.5 V
33	L 1159-16	14.02	M4.5 V
34	G 208-044	15.12	M6 V
35	G 267-025	10.25	M2 V
36	Vega	0.58	A0 V
37	G 240-063	10.88	M3.5 V
38	Regulus	-0.53	B7 V
39	CI 20-1290	10.33	M2 V
40	Fomalhaut	1.73	A3 V
41	G 158-027	15.38	M5 V
42	Groombridge 1618	8.19	K7 V
43	G 054-023	10.95	M3.5 V
44	Procyon	2.67	F5 V

1. Using a sheet of graph paper, plot each of the 44 stars with spectral type along the x-axis and absolute magnitude along the y-axis (see Figure 3). Make your graph as large as your graph paper will allow. [Note: (1) recall that the more negative an absolute magnitude is the brighter it is; the more positive the number is the fainter it is (2) there are no O-type stars on this list, so do not include it on your graph]. _You do not need to label the data points._

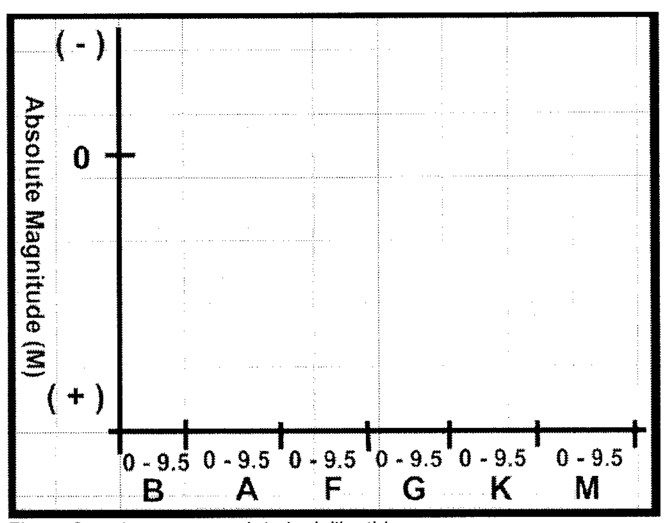


Figure 3: set up your graph to look like this.

2. Draw a thin, smooth continuous curving line through the distribution of the data points on your graph. DO NOT CONNECT THE DOTS!

3. The curve you have created is referred to as the ***Main Sequence***. These stars are referred to as main sequence stars (which are indicated by the Roman numeral "V" next to the spectral type designation in Table A).

4. Notice that there is a connection between the spectral type of a star and its absolute magnitude. If you know the spectral type of the star, you can use the Hertzsprung-Russell diagram to deduce its absolute magnitude. *It is important to understand that the data points establish the curving line, and the line is now a tool that can be used to link the two properties (absolute magnitude and spectral type) together.* Practice using the main sequence curve on your Hertzsprung-Russell diagram by determining what the absolute magnitude would be for each of the stars listed in Data Table 1 on the Data Sheet. *Record the absolute magnitudes in the same table in the space provided.*

Question 1: Examine the main sequence of your Hertzsprung-Russell diagram. Describe in your own words what the line tells you about the connection between the *spectral type* of a star and its *absolute magnitude*. *Write your answer in the space provided on the Data Sheet.*

Question 2: Recall that the spectral type of a star is an indicator of its surface temperature. Examine the main sequence line of your Hertzsprung-Russell diagram. In your own words, describe what the line tells you about the connection between the *surface temperature* of a star and it's *absolute magnitude*. *Write your answer in the space provided on the Data Sheet.*

Question 3: The Sun is a spectral type G2 V star. Using your Hertzsprung-Russell diagram determine what the absolute magnitude of the Sun is. *Write your answer in the space provided on the Data Sheet.*

Question 4: The stars that are listed in Table A are stars that are located in the same region of our galaxy that the Sun is located. What is the most common spectral type of stars located in our neighborhood? (Examine your Hertzsprung-Russell diagram for help in answering this question). *Write your answer in the space provided on the Data Sheet.*

Using the Hertzsprung-Russell diagram to determine distances

Recall from the introduction that the ***distance modulus*** can be used to determine the distance to a star if the apparent magnitude and the absolute magnitude of a star are known. However, astronomers faced the problem of not knowing the absolute magnitude of a star since it is not a property that can be directly observed from a star. The Hertzsprung-Russell diagram can now be used to solve this problem. In step 4 you saw how the absolute magnitude of a star can be determined if only the spectral type of the star is known. This is possible because the Hertzsprung-Russell diagram links these two properties together. Let's see how this is done:

5. Data Table 2 on the Data Sheet lists three stars of unknown distances. Use the given spectral types of each star and your Hertzsprung-Russell diagram to determine the absolute magnitudes of each of the three stars. *Record your answers in the space provided in Data Table 2 on the Data Sheet.*

6. The apparent magnitudes of each of the stars can be determined by measuring how bright they look through a telescope (recall the definition of *apparent magnitude*). Using the apparent magnitudes for each of the three stars (listed in Data Table 2 on the Data Sheet) and the distance modulus shown in Equation 2 (to the right), determine the distances to each of the three stars. The distances you calculate will be in parsecs. *Record your answer in Data Table 2 on the Data Sheet.*

$$D = 10^{\left(\frac{m-M+5}{5}\right)}$$

Equation 2

7. Finally, convert each of the distances calculated (in step 6) to *light years* using the conversion factor listed in Appendix A. *Record your answers in Data Table 2 on the Data Sheet.*

With the Hertzsprung-Russell diagram and the distance modulus, the distance to *any* star can be determined.

The Hertzsprung-Russell Diagram

Name:

Astronomy Laboratory Data Sheet

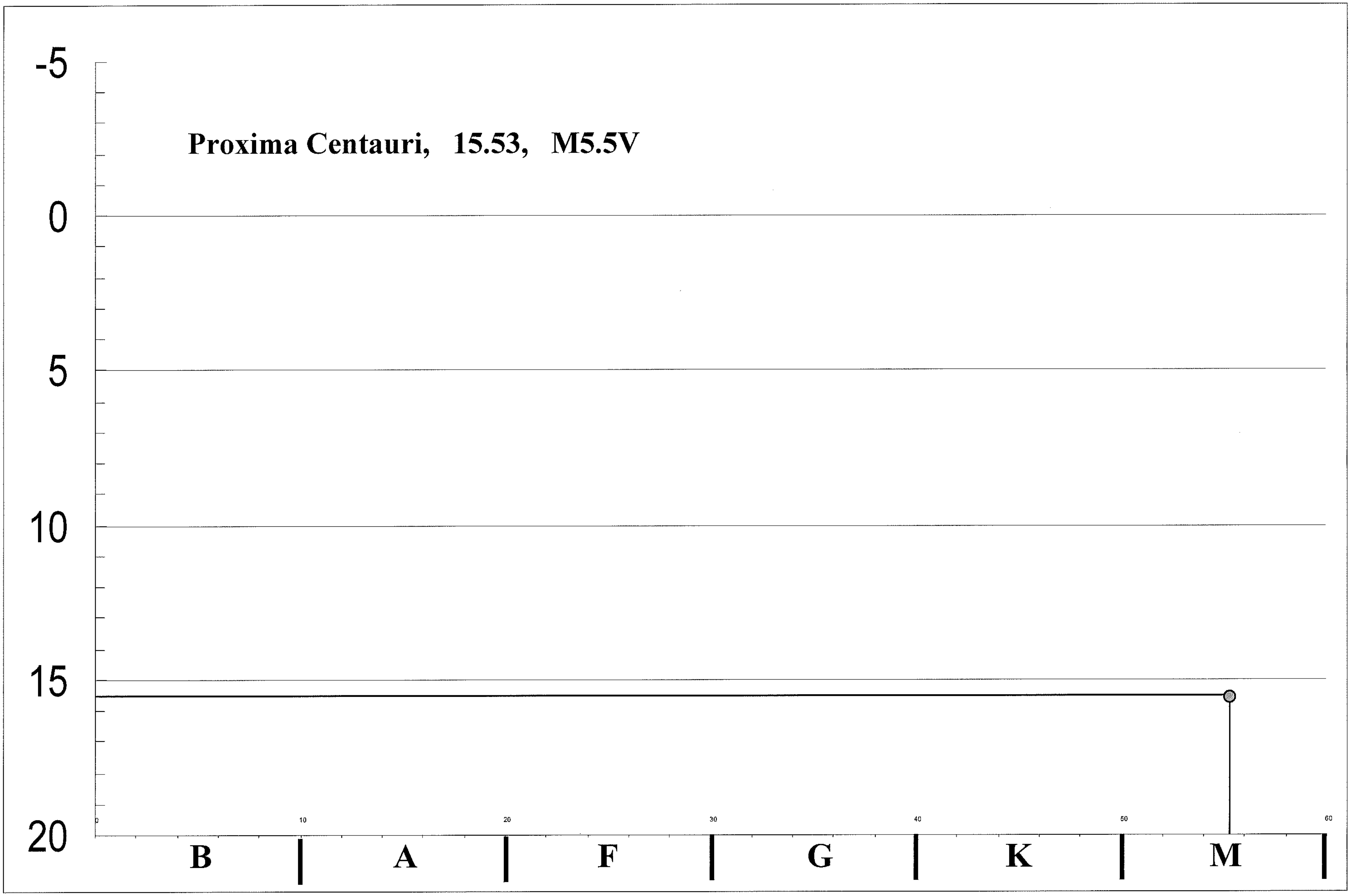
Data Table 1

Spectral Type	Absolute Magnitude (M)
A0	
F7.5	
G6	
K3.5	
M2	

Question 1	
Question 2	
Question 3	
Question 4	

Data Table 2

Star Name	Spectral Type	Apparent magnitude (m)	Absolute magnitude (M)	Distance (pc)	Distance (light years)
Denebola	A3 V	2.14			
Algol	B8 V	2.12			
Wolf 25	K2 V	5.74			



Proxima Centauri, 15.53, M5.5V
-5
0
5
10
15
20
0
10
20
30
40
50
60
B
A
F
G
K
M