

# Lab 12

## The Hertzsprung-Russell Diagram and Stellar Evolution

### 12.1 Introduction

On a clear, dark night, one might see more than two thousand stars. Unlike our distant ancestors, we recognize that each one is a huge ball of hot gas that radiates energy, like our own (very nearby) star, the Sun. Like the Sun, the stars shine by converting hydrogen into helium via nuclear fusion reactions. Unlike the Sun, they are tremendously far away. While the Sun is located a mere 93 million miles from us and seems dazzlingly bright, the next nearest star is roughly 270,000 times farther away (25 trillion miles distant, or 4.3 light years, or 1.3 parsecs) and appears millions of times fainter to us on Earth.

The Sun can be thought of as a nuclear reactor in the sky that we all depend on, planning our days secure in the belief that it will continue to send us warmth and life-sustaining energy. But will it always do so? Just as a candle eventually uses up its oil and flickers out, someday the Sun will exhaust its fuel reserves. This is not surprising when you consider that, in converting mass to energy, the Sun turns 600 million tons of hydrogen into 596 million tons of helium with every passing second (losing four million tons in the process). Knowing this, you might justifiably fear for its imminent demise – but fortunately, the Sun has lots of mass!

We refer to the part of a star's lifetime when it's most dependable and stable – when it has plenty of hydrogen fuel to burn at its core – as the Main Sequence phase. It can be unstable and erratic soon after its formation from a collapsing cloud of gas and dust and later in life when it begins to run out of fuel and experience “energy crises,” but not during the Main Sequence phase. How long will the Sun exist in this stable form?

Before this question could be answered, astronomers had to learn to distinguish stable, well-behaved stars from their more erratic, very young or very old neighbors. They did this by plotting two basic observed quantities (brightness and color) against each other, forming a plot called a Hertzsprung-Russell (H-R) Diagram, after the two astronomers who pioneered its usage nearly a hundred years ago. Astronomers realized that the positions of stable, well-behaved stars in the prime part of their lives were restricted to a small part of this diagram, along a narrow band that came to be called the Main Sequence. They also discovered that as one scanned the Main Sequence from one end to the other, the fundamental stellar property that changed along it was stellar mass.

Mass is critically important because it determines how long stars can exist as stable, well-behaved objects. We have learned this by studying H-R diagrams, particularly for large groups of stars (like the Pleiades and M67 clusters featured in this lab exercise). The most massive, luminous stars will spend only a few million years in the Main Sequence phase, while their least massive, faintest cousins may amble along like this for hundreds of billions of years. What about the Sun? We know from geological evidence that the Sun has existed in its current state for 4.5 billion years, and astronomical evidence suggests that it has another five to seven billion years to go in this state. In this lab we will evaluate the observational evidence behind that conclusion, and address the question of whether the Sun is a typical star by comparing it to other stars.

### **12.1.1 Goals**

The primary goals of this laboratory exercise are to understand the significance of the H-R diagram in interpreting stellar evolution, to learn how observations of a star's physical properties define its position on the diagram, and to visualize how it will shift positions as it ages.

### **12.1.2 Materials**

You will need a computer with an internet connection, and a calculator.

All online lab exercise components can be reached from the GEAS project lab URL, listed here.

<http://astronomy.nmsu.edu/geas/labs/html/home.shtml>

### **12.1.3 Primary Tasks**

This lab comprises three activities: 1) an H-R diagram explorer web application, 2) a Pleiades cluster activity, and 3) an M67 H-R diagram web application. Students will complete these three activities, answer a set of final (Post-Lab) questions, and write a summary of the laboratory exercise.

### 12.1.4 Grading Scheme

There are 100 points available for completing the exercise and submitting the lab report perfectly. They are allotted as shown below, with set numbers of points being awarded for individual questions and tasks within each section. Note that Section 12.7 (§12.7) contains 5 extra credit points.

Table 12.1: Breakdown of Points

| Activity | H-R Diagram | Pleiades Cluster | M67 Cluster | Questions | Summary |
|----------|-------------|------------------|-------------|-----------|---------|
| Section  | §12.3.1     | §12.4.1          | §12.4.2     | §12.5     | §12.6   |
| Page     | 5           | 12               | 16          | 22        | 26      |
| Points   | 19          | 13               | 24          | 19        | 25      |

### 12.1.5 Timeline

Week 1: Read §12.1–§12.4, complete activities in §12.3.1 and §12.4.1, and answer questions 1–4 in §12.5. We strongly suggest that you also attempt the activity in §12.4.2 and read through questions 5–8 in §12.5, so that you can receive feedback and assistance from your instructors before Week 2.

Week 2: Complete activity in §12.4.2, finish final (Post-Lab) questions in §12.5, write lab summary, and submit completed lab report.

## 12.2 The Brightness of Stars

Astronomers describe the brightness of stars in two different ways: apparent brightness, based on how bright an object looks to us here on Earth, and intrinsic brightness (or luminosity), based on how bright an object actually is, independent of how far away it lies from a viewer. We have devised a scale of relative brightness called the “magnitude scale.” All objects of the same apparent magnitude appear equally bright when viewed from Earth. The 25 brightest stars in the sky are said to be first magnitude or brighter. The unaided eye can find about two thousand stars from first down to sixth magnitude in a dark sky, and large telescopes can reveal trillions more. In this lab exercise, you’ll learn how astronomers measure the magnitudes of stars.

There are two important features of the magnitude scale: 1) brighter objects have smaller magnitudes, and 2) the scale is not linear (it is logarithmic). This means that a first-magnitude star is brighter (not fainter) than a second-magnitude star, and it is more than two times brighter than a second-magnitude star. If two stars differ by one magnitude, they differ in brightness by a factor of about 2.5; if they differ by two magnitudes, one is brighter than the other by a factor of  $2.5 \times 2.5 = 6.3$ ; if they differ by five magnitudes, one is brighter than the other by a factor of  $2.5^5 = 100$ ; if they differ by ten magnitudes, they differ by a factor of  $2.5^{10}$ , or  $100 \times 100$ , or 10,000. *An increment of one magnitude translates to a factor of 2.5 change in brightness.*

### Example 12.1

A first-magnitude star is about 2.5 times brighter than a second-magnitude star, and 100 times brighter than a sixth-magnitude star. A sixth-magnitude star is 2.5 times brighter than a seventh-magnitude star, 100 times brighter than an eleventh-magnitude star, and 10,000 times brighter than a sixteenth-magnitude star.

If you are comfortable using exponents, you may express the change in relative brightness, of two stars ( $B_1$  and  $B_2$ ) as a function of the difference in their magnitudes ( $m_1$  and  $m_2$ ) as follows.

$$\frac{B_1}{B_2} = 10^{-\frac{m_1 - m_2}{2.5}}.$$

If we compare a sixth-magnitude star and a fainter seventh-magnitude star,  $m_1 - m_2 = 6 - 7 = -1$ , and

$$\frac{B_1}{B_2} = 10^{-\frac{-1}{2.5}} = 10^{+\frac{1}{2.5}} = 10^{0.4} = 2.51 \approx 2.5.$$

and we can confirm that the first star is 2.5 times brighter than the second. How much brighter is that seventh-magnitude star than a twelfth-magnitude star?

$$\frac{B_1}{B_2} = 10^{-\frac{7-12}{2.5}} = 10^{+\frac{5}{2.5}} = 10^2 = 100.$$

Astronomers use a similar magnitude scale to gauge intrinsic brightness, but it depends on a thought experiment. They imagine an object lies a certain distance away from Earth; a standard distance of ten parsecs (32.6 light years) is typically used. They then ask “how bright would this object appear from a distance of ten parsecs?” The resulting measure of brightness is called its absolute magnitude. While the Sun appears to be tremendously bright and thus has the smallest apparent magnitude of any star ( $-26.7$ ), if it were placed ten parsecs away, it would appear no brighter than a fifth-magnitude star. Given its close proximity, the Sun is extraordinarily special to us. Its apparent brightness exceeds that of the next brightest star, Sirius, by a factor of ten billion.

### Example 12.2

The apparent magnitudes of the Sun and Sirius are  $-26.7$  and  $-1.6$  respectively. Note two things: 1) the brightest objects have the smallest magnitudes and magnitude values can be negative (smaller than zero), and 2) if two objects differ by 25 magnitudes – like the Sun and Sirius, the one with the smaller apparent magnitude appears ten billion times brighter than the one with the larger magnitude.

A star’s apparent brightness depends on both its intrinsic brightness and its distance from Earth. Viewed from 30 times further away, or from Pluto, the Sun would appear  $30^2$ , or 900 times fainter (though still very bright). What if we could view it from far outside the solar system?

### Example 12.3

Viewed from a distance of 10 parsecs (32.6 light years), the Sun would look forty trillion times fainter. With a magnitude of 4.8, it would barely be visible to the unaided eye. This

value represents the Sun's absolute magnitude. Comparing absolute magnitudes (imagining objects are viewed from the same distance) enables us to compare their intrinsic brightnesses, and to confirm that bright stars emit more energy per second than faint ones.

#### Example 12.4

Sirius is a bright, massive Main Sequence star, and emits twenty times more light than the Sun. If both stars were viewed from a standard distance of ten parsecs, Sirius would appear much brighter than the Sun (3.4 magnitudes brighter, given 1.4 magnitudes for Sirius versus 4.8 magnitudes for the Sun).

The magnitude scale is initially used to specify how bright a star appears, to quantify its apparent brightness. If the distance to the star is known, apparent magnitude and distance can be combined to compute an intrinsic brightness, or absolute magnitude. We can then easily convert absolute magnitude into energy output per second, or luminosity.

We can connect luminosity to other important physical quantities, by treating stars as idealized spherical radiators. The luminosity of a star depends primarily on its size and its surface temperature, in a fairly straightforward fashion. We can use the Stefan-Boltzmann Law to compute a star's luminosity  $L$ , where  $L = (4\pi\sigma)R^2T^4$  and  $4\pi\sigma$  is a constant,  $R$  is the star's radius, and  $T$  is its surface temperature. Given two of these three variables, we can use this relationship to estimate the third one.

## 12.3 The Main Sequence and the H-R Diagram

A casual glance at the night sky reveals that stars span a wide range of apparent magnitudes (some are bright, and some are faint). Closer inspection suggests that they also have different colors. It turns out that the color of a star is related to its surface temperature. Blue stars (stars which radiate most of their light at blue wavelengths) are hot, yellow stars (like the Sun) are cooler, and red stars are the coolest of all. Suppose we plot apparent magnitude (vertically) and color (horizontally) for a set of stars. Does a pattern emerge? The answer is no – our graph is just a random scatter of points (see Figure 12.1a). If we instead plot absolute magnitude (or luminosity) versus color (creating an H-R Diagram), a pattern emerges.

While the diagram's overall appearance depends on the actual sample of stars we use, for many stellar populations lots of points lie within a narrow strip (as in Figure 12.1b), which we link with the Main Sequence phase of stellar evolution.

### 12.3.1 The H-R Diagram and Stellar Properties Activity

In this activity we'll concentrate on two special samples of stars – the nearest stars, and those that appear the brightest from Earth – and consider H-R diagrams for each. These diagrams can be constructed in somewhat different ways. The ones we'll initially examine have luminosity (in units of the Sun's luminosity) plotted vertically versus surface tempera-

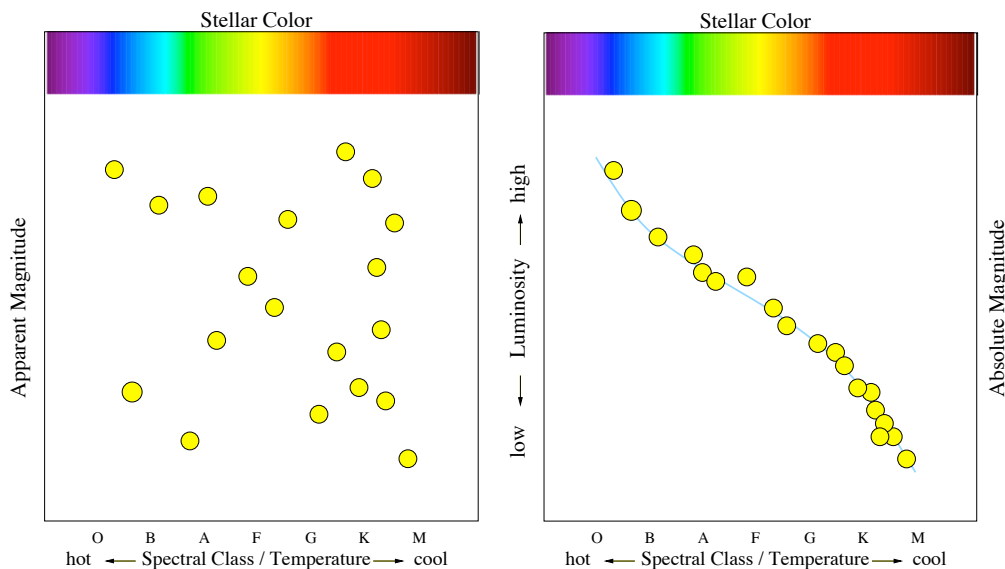


Figure 12.1: Plotting (a) apparent magnitude against color, we observe a random scattering of points. When (b) we convert to absolute magnitude, or luminosity, a clear pattern emerges. This is the fundamental form of an H-R Diagram.

ture (plotted horizontally). The red  $X$  cursor initially marks the point plotted for the Sun, with a luminosity of  $10^0$ , or 1, and a surface temperature of 5800 Kelvins (characteristic of a yellow star). Note that the Sun is a member of both the nearest star and the brightest star sample populations. Table 12.2 contains the basic stellar data for the Sun, collected in one place for easy reference.

Table 12.2: Basic stellar data for the Sun

| Luminosity<br>(solar units) | Radius<br>(solar units) | Surface<br>Temperature (K) | Spectral<br>Class | Color<br>(B-V) | Absolute<br>Magnitude |
|-----------------------------|-------------------------|----------------------------|-------------------|----------------|-----------------------|
| 1.00                        | 1.00 <sup>a</sup>       | 5800                       | G2                | +0.66          | 4.8                   |

<sup>a</sup>The radius of the Sun is nearly 1/2 million miles.

Access the first web application (H-R Diagram) for this lab exercise from the GEAS project lab exercise web page (see the URL on page 2 in §12.1.2). Complete the following, filling in blanks as requested. (Each of the 36 filled blanks, and 2 circled answers, is worth 1/2 point.)

1. Beneath the H-R Diagram that appears on the right side of the screen, under “Options,” uncheck the box to the left of “show main sequence.” The red line that will disappear represents the Main Sequence. Stars plotted on (or very near to) it are in a fairly stable evolutionary phase. Re-check the box to get the Main Sequence back. Note that the Sun appears on this line – the initial red  $X$  represents its position. The Sun also lies on a second, green, line. Check the box to the left of “show isoradius lines.” The parallel lines that disappear represent lines for groups of stars with the same radius. Re-check this box

to get these lines back. The Sun appears on the line labeled  $1.0 R_{\odot}$ . All stars of this size, regardless of their luminosity or surface temperature, will lie along this line.

In which corner of the diagram (upper right, upper left, lower right, or lower left) would stars with radii 1000 times larger than that of the Sun be plotted? \_\_\_\_\_

In which corner would stars with radii 1000 times smaller than that of the Sun appear? \_\_\_\_\_

2. The H-R Diagram is fundamentally a plot of two variables (luminosity,  $L$ , versus surface temperature,  $T$ ), but it also contains a third important variable: radius,  $R$ . (Recall that we reviewed the relationship between these three variables in §12.2.) To investigate this relationship further, click on the red  $X$  for the Sun (it is actually a cursor). The “Cursor Properties” box at the lower left now shows the corresponding values for  $T$ ,  $L$ , and  $R$ , with the latter two expressed in terms of values for the Sun (in solar units). Use the mouse to move the cursor (noting how the size of the first star in the “Size Comparison” box changes), to answer the following six questions (write your answers in the table below).

Note that temperatures above 10000 K can only be entered in this web application to the nearest 1000 K, so try a value of 12000 K rather than 11600 K for a temperature twice that of the Sun below. Don’t worry if you notice a small variation (less than 10%) in the luminosity values that are output for certain temperature and radius combinations; this is merely an artifact of the way the the program models energy production in the cores of stars.

What is the relative luminosity (in solar units) of a star with the same surface temperature as the Sun but (a) only one-tenth the radius? (b) twice the radius?

What is the relative luminosity of a star which is the same size as the Sun but has (c) twice the surface temperature (11600 K, or 12000 K)? (d) only one-half the surface temperature (2900 K)?

Finally, what is the relative luminosity of a star with (e) one hundred times the Sun’s radius, but only one-half the surface temperature (2900 K)? (f) only one-hundredth its size, but twice the surface temperature (11600 K, or 12000 K)?

You may answer these six questions by moving the cursor to the positions of stars with the requested temperatures and radii on the H-R diagram. You may also choose to use the Stefan-Boltzmann relation expressing stellar luminosity as a function of stellar radius and temperature. If the luminosity, radius, and temperature of a star are expressed in solar units (relative to those of the Sun), then

$$L(L_{\odot}) = R^2(R_{\odot}) \times T^4(T_{\odot}).$$

For example, the luminosity of a star which is ten times larger than the Sun and twice as hot is

$$L(L_{\odot}) = 10^2 \times 2^4 = 100 \times 16 = 1600$$

and the star is thus 1600 times more luminous than the Sun.

Table 12.3: Basic stellar data for selected stars

| Star   | Luminosity<br>(solar units) | Radius<br>(solar units) | Surface<br>Temperature (K) |
|--------|-----------------------------|-------------------------|----------------------------|
| Sun    | 1.00                        | 1.00                    | 5800                       |
| Star a |                             | 0.10                    | 5800                       |
| Star b |                             | 2.00                    | 5800                       |
| Star c |                             | 1.00                    | 11600 (or 12000)           |
| Star d |                             | 1.00                    | 2900                       |
| Star e |                             | 100                     | 2900                       |
| Star f |                             | 0.01                    | 11600 (or 12000)           |

When you are finished, return the cursor to the position of the Sun. (Either reload the web-app in your browser, or select the “reset” option within the web-app.)

We hope that you’re beginning to realize that the H-R Diagram can take many forms. The vertically plotted variable can be luminosity, or it can be another quantity related to intrinsic brightness, such as absolute magnitude. The horizontally plotted variable is often surface temperature, but it can also be color, or spectral class. To illustrate these different forms of the diagram, do the following. Under “Options,” to the right of “x axis scale: temperature,” click the down arrow and select “spectral type” as the new x-axis label. Note that the Sun lies within the spectral class G (run a vertical line down from the  $X$  for the Sun and check where it intersects the x-axis).

3. Beneath the H-R Diagram under “Plotted Stars,” check the circle for “the nearest stars.” The properties of the nearest hundred or so stars will be shown. Examine the plot, and answer the following questions.

(a) Considering the measurement uncertainty inherent in the data, do most of the points lie on (or near to) the Main Sequence line (within the Main Sequence strip)? \_\_\_\_\_

If you can’t decide (or to double-check), under “Options,” click the box to the left of “show luminosity classes.” The green band that appears marked “Dwarfs (V)” is the Main Sequence strip.

(b) Match the four regions marked A, B, C, and D in Figure 12.2 with the areas where white dwarfs, blue supergiants, red giants, and red dwarfs are found.

REGION A = \_\_\_\_\_, REGION B = \_\_\_\_\_

REGION C = \_\_\_\_\_, REGION D = \_\_\_\_\_

What object’s position is marked by the  $X$ ? \_\_\_\_\_

What two lines intersect at this spot?



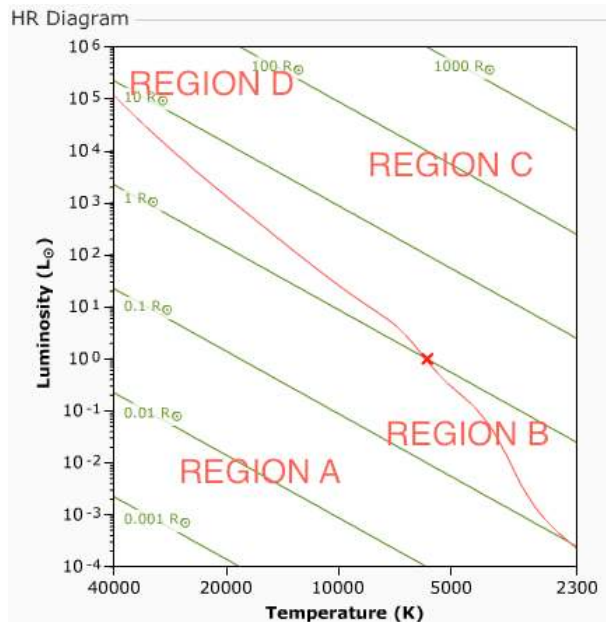


Figure 12.2: Consider which types of stars (white dwarfs, blue supergiants, red giants, and red dwarfs) are found in each of the four regions identified above.

(c) The “Dwarfs (V)” label for the Main Sequence strip is unfortunate because the most luminous stars at the upper end of this strip have radii roughly \_\_\_\_\_ times that of the Sun – they are hardly “dwarfish.” But we still haven’t compared the Sun to typical stars, so let’s rectify that. Assume that the hundred or so stars nearest to us form a representative sample that we might find in a typical volume of our Milky Way galaxy. Let’s think about how the Sun compares to these stars.

(d) Of the hundred nearest stars, only \_\_\_\_\_ are obviously intrinsically brighter than the Sun.

(e) Move the cursor to the middle of the nearest star sample, where many of them are concentrated. This region is labeled \_\_\_\_\_ on the diagram. The luminosities for these typical stars are \_\_\_\_\_ that of the Sun’s, their radii are \_\_\_\_\_ that of the Sun’s, and their surface temperatures are around \_\_\_\_\_ K.

(f) The nearest star sample shown is technically incomplete; at least five nearby white dwarfs were omitted. The most famous is the companion to the bright, nearby star Sirius A; Sirius B has a luminosity of  $0.027 L_{\odot}$  and a surface temperature of 25,000 K. Moving the cursor to where this star would be plotted, its radius is \_\_\_\_\_ that of the Sun’s (justifying the descriptive term dwarf). When finished, return the cursor to the position of the Sun.

Now consider another population of stars. Under “Plotted Stars,” check the circle for “the brightest stars.” The new points plotted on the diagram correspond to the 150 or so brightest

stars which can be seen from Earth. Examine the plot and answer the following questions.

(g) Of these 150 brightest stars, only \_\_\_\_\_ is/are intrinsically fainter than the Sun. While all the nearest stars were predominantly Main Sequence (V) stars, the brightest stars sample also includes many objects of luminosity classes \_\_\_\_\_ and \_\_\_\_\_.

(h) Move the cursor to the star representing the most luminous star in this sample. Its luminosity is \_\_\_\_\_  $L_{\odot}$ , its radius is \_\_\_\_\_  $R_{\odot}$ , its surface temperature is \_\_\_\_\_ K, and its B–V color is \_\_\_\_\_. The region where the cursor is now located is labeled \_\_\_\_\_ on the diagram.

(i) Move the cursor to the star representing the largest star in this sample. Its luminosity is \_\_\_\_\_  $L_{\odot}$ , its radius is \_\_\_\_\_  $R_{\odot}$ , and its surface temperature is \_\_\_\_\_ K; its B–V color is \_\_\_\_\_. The region where the cursor is now located is labeled \_\_\_\_\_ on the diagram. When finished, return the cursor to the position of the Sun.

(j) There are \_\_\_\_\_ stars that are members of both samples (both nearest and brightest stars). Under “Plotted Stars,” check the circle for “overlap” to verify your answer.

(k) In summary, the nearest / brightest (circle one) star sample is more representative of a typical volume of stars, whereas the nearest / brightest (circle one) star sample is a specially selected sample, heavily weighted towards relatively rare, highly luminous objects.

*Congratulations, you have completed the first of this lab’s three activities. You may want to answer Post-Lab questions 1 through 3 on page 22 at this time.*

## 12.4 The Evolution of Stars

The Sun is a yellowish spectral type G star, with a diameter of 864,000 miles, a surface temperature of 5800 K, and an intermediate luminosity. Its physical properties place it in the middle of the H-R Diagram. To its lower right, cooler, redder Main Sequence stars (with spectral types of K and M) are plotted, while hotter, bluer Main Sequence stars (spectral types O, B, A, and F) are found to the upper left. Will the Sun’s position in this diagram change as it ages? Yes! As it runs out of hydrogen fuel in its core, it will become a cooler, more luminous, and much bigger red giant star. Similar giants appear to the upper right of the Sun’s current position (which means that they are brighter and redder than the Sun). As the aging Sun runs out of fuel, it will eventually shed its bloated outer atmosphere and end its days as a white dwarf. White dwarfs are hotter, bluer and much less luminous than the Sun, so they are plotted to the lower left of the Sun’s current position.

It would be fascinating to conduct a time-traveling experiment and observe how the Sun’s position in the H-R diagram changed over time (charting its future path), but, alas, this is not possible. Though we can’t conduct such a controlled experiment with the Sun, we can still get a good idea of its future evolutionary path.

Given all the diversity among observed stellar properties, you may be surprised to learn that it is the mass and the chemical composition of a star at formation which determine most of its other properties, and (provided it is not a member of a binary system) its subsequent life history. In addition to mass and chemical composition, two other variables can make stars differ: stars can have different ages (they form at different times) and they typically lie different distances away from us. Fortunately, astronomers can simplify our studies of stars and remove three of these four variables by using dense star clusters as “laboratories.” In doing this, we assume that all of the stars in a given cluster have the same chemical composition and age, and lie the same distance from Earth. Mass is thus the critical variable.

The more massive a star is, the faster it burns through the hydrogen reserve in its core and evolves off the Main Sequence into a red giant. Figure 12.3 shows how a cluster’s H-R diagram changes as it ages. We can’t observe a single cluster for long enough to see these changes, as we’d need to observe it for millions of years. Instead, we can examine many clusters of varying ages and compare their H-R diagrams.

The diagrams shown in Figure 12.3 represent clusters which are 50 million, 500 million, two billion and six billion years old. We want you to appreciate how astronomers estimate how many more years the Sun, a lower intermediate mass star, will spend on the Main Sequence. There is growing evidence that the Sun was actually born in a cluster, one three to ten light years in size and containing 1500 to 3500 stars. It’s believed that one of the most massive of these stars died in a cataclysmic supernova explosion. This event is thought to have occurred within just a few million years of the Sun’s birth. Indeed, the telltale signs it left behind are the main evidence suggesting that the Sun was born in a star cluster.

Since all the stars in a cluster lie at essentially the same distance from Earth, we can use their apparent magnitudes to gauge their relative luminosities. We’ll construct an H-R diagram using such data for stars in the Pleiades bright star cluster, in the constellation of Taurus, the bull. These data come from two telescope images taken of the cluster, one with a V (for visual) filter, and one with a shorter wavelength B (for blue) filter. (We need images taken in two filters to determine the colors of the stars.) Our Pleiades cluster H-R diagram (shown in Figure 12.4) plots V filter magnitudes vertically and colors horizontally (instead of surface temperature, or spectral class). The color indices were obtained by measuring apparent magnitudes from both B filter and V filter images and subtracting these two magnitudes to produce a B–V color. (Note that “apparent magnitude” typically refers to an apparent brightness, often measured through a V filter, expressed on a magnitude scale.)

The Pleiades is a young cluster, and its H-R diagram will look similar to Figure 12.3(a). We can imagine that the Sun was once a young star in such a cluster. The Pleiades contains stars similar to the Sun in mass, luminosity, and color, as does the other star cluster whose H-R diagram we’ll study later (M67). How can we identify solar-like stars in these star clusters? We can simply search for Main Sequence objects of the appropriate color. While such stars have a characteristic intrinsic brightness, their apparent V magnitudes will depend on their distance from us, as Table 12.4 illustrates.

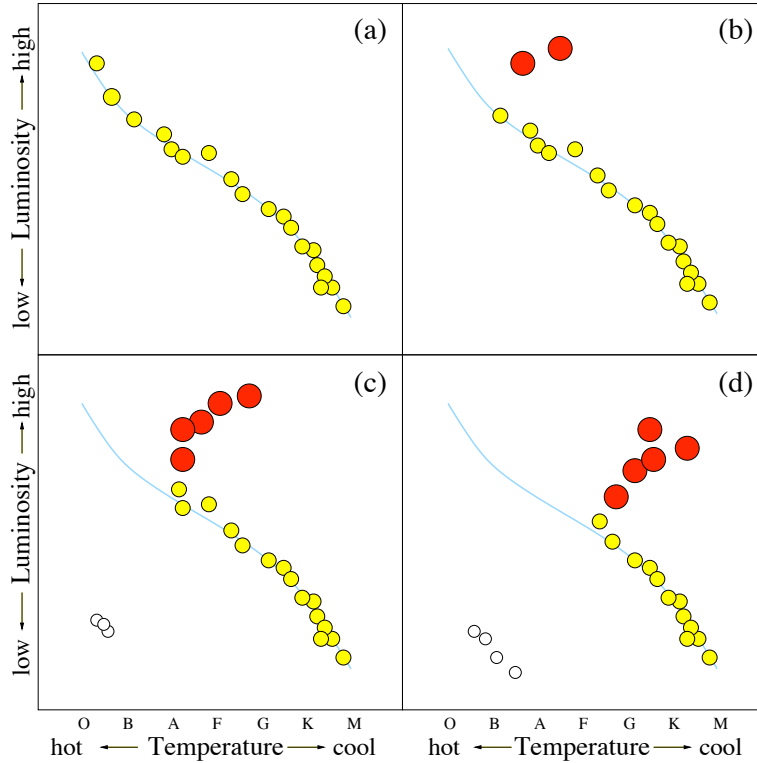


Figure 12.3: A star cluster's H-R diagram evolves with time. (a) A young cluster, with plenty of hot, blue, high-mass stars. All objects shown are on the Main Sequence (the highest mass stars, exploding as supernovae, are not shown). (b) A fairly young cluster, missing only the highest mass stars which have gone supernova or evolved off Main Sequence to become giant stars. (c) A moderate-age cluster missing the highest, high, and a few intermediate mass stars which have evolved off the Main Sequence. Note the presence of both red giants and white dwarfs. (d) An older cluster, with many intermediate mass stars evolving off the Main Sequence and turning into giant stars. Note the increasing number of white dwarfs.

### 12.4.1 The H-R Diagram for the Pleiades, a Young Star Cluster

1. The Sun lies a mere 93 million miles from the Earth and seems incredibly bright, as illustrated by its very small apparent magnitude in Table 12.4. If we could shift the Sun farther and farther away from us, however, it would appear fainter and fainter in the sky. By the time it approached the distance of the Pleiades cluster (at 135 parsecs, or 2,500 trillion miles), it would have an apparent magnitude of 10.5 and a small telescope would be needed to find it at all.

Check your understanding of the data listed in Table 12.4 by completing the following three statements. If the Sun were to be viewed from larger and larger distances, it would appear brighter / fainter / unchanged (circle one). Its apparent magnitude would increase / decrease

Table 12.4: The Apparent Magnitude of the Sun from Different Distances

| Apparent magnitude | Distance         | Significance                   |
|--------------------|------------------|--------------------------------|
| -26.7              | 93 million miles | Earth-Sun separation           |
| 4.8                | 10 parsecs       | standard distance <sup>a</sup> |
| 10.5               | 135 parsecs      | distance to Pleiades cluster   |
| 14.2               | 770 parsecs      | distance to M67 cluster        |

<sup>a</sup>Absolute magnitudes are calculated assuming this distance.

/ remain unchanged (circle one), while its absolute magnitude would increase / decrease / remain unchanged (circle one). (1 1/2 points total)

As you work through this activity, keep in mind that the faintest objects have the biggest magnitude values.

2. The Pleiades are sometimes called “The Seven Sisters” since this cluster contains seven stars which are bright enough to be found by eye on a clear, dark night. Use the data in Table 12.5 to complete the following questions and explore the properties of the cluster stars.

(a) Identify the seven brightest Pleiades stars from their apparent V magnitudes:

#\_\_\_\_\_, #\_\_\_\_\_, #\_\_\_\_\_, #\_\_\_\_\_, #\_\_\_\_\_, #\_\_\_\_\_, #\_\_\_\_\_. (1 point total)

Remember that the unaided eye can only see stars down to sixth magnitude, and stars fainter than that will have even larger magnitudes. The seven sisters should thus each have apparent magnitudes quite a bit smaller than 6.

(b) The brightest cluster star is #\_\_\_\_\_, with an apparent V magnitude of \_\_\_\_\_. (1 point total)

If this star also has an apparent B magnitude of 2.78, and a B-V color index of -0.09, explain how the color index was computed. (1 point)

Some of the Pleiades stars listed are too faint to be seen without a telescope. Refer back to Example 12.1 (on page 3), and use apparent V magnitudes to make the following two comparisons.

(c) Star #1 is roughly \_\_\_\_\_ times brighter than star #4. (1/2 point)

(d) Star #\_\_\_\_\_ is almost 100 times brighter than star #15. (1/2 point)

Figure 12.4 shows an H-R diagram for the Pleiades cluster, constructed in part from the

Table 12.5: Apparent V Magnitudes of Bright Pleiades Stars

| Star | V     |
|------|-------|
| 1    | 2.87  |
| 2    | 3.62  |
| 3    | 3.70  |
| 4    | 3.87  |
| 5    | 4.18  |
| 6    | 4.30  |
| 7    | 5.09  |
| 8    | 5.45  |
| 9    | 5.46  |
| 10   | 5.65  |
| 11   | 5.76  |
| 12   | 6.17  |
| 13   | 6.43  |
| 14   | 7.24  |
| 15   | 8.86  |
| 16   | 10.48 |

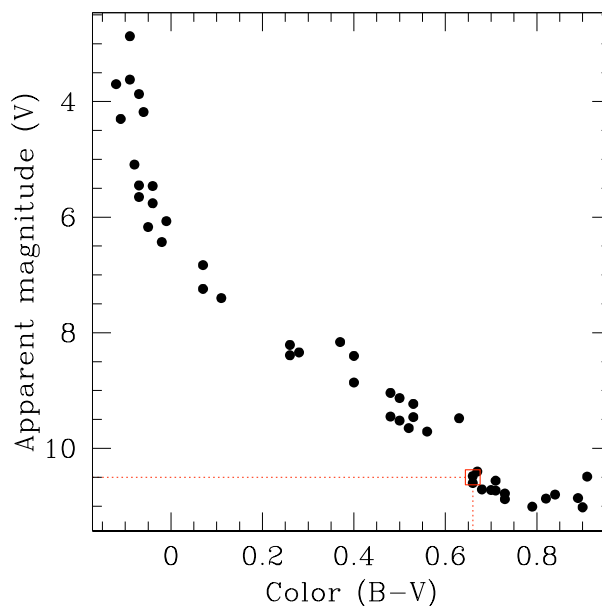


Figure 12.4: An H-R diagram for the Pleiades star cluster, with solar-type star #16 boxed in red. Note that the y-axis runs from large magnitudes to small, so that the brightest stars appear at the top of the figure.

data in Table 12.5, and from observations of 31 additional cluster stars. Could you find the star most like the Sun in this diagram, or the star most like Sirius? Consider the examples below.

#### Example 12.5

Table 12.4 tells us that the Sun would have apparent (V) magnitude of roughly 10.5 if it were a member of the Pleiades cluster, and Table 12.2 gives its B–V color index as 0.66. Inspection of Table 12.5 reveals that star #16 (with an apparent V magnitude of 10.48) closely resembles the Sun. It too has a B–V color of 0.66, and it is boxed in red on Figure 12.4.

3. If the stars in the Pleiades cluster lay only ten parsecs from Earth, they would appear brighter / fainter / unchanged (circle one), though their absolute magnitudes would be brighter / fainter / unchanged (circle one). Solar-type star #16 would have an apparent V magnitude of \_\_\_\_\_ and would just be visible to the unaided eye as a faint star. Star #16 is actually much farther away than ten parsecs (it lies around \_\_\_\_\_ parsecs away) so it appears much fainter. Its actual apparent V magnitude is \_\_\_\_\_. (2 1/2 points total)

Remember that any star which is fainter than sixth magnitude is not visible without a telescope.

### Example 12.6

From Example 12.4, we know that Sirius is 3.4 magnitudes intrinsically brighter than the Sun. At the distance of the Pleiades, we would look for it on the Main Sequence at an apparent V magnitude of  $10.5 - 3.4 = 7.1$ . Star #14, with an apparent V magnitude of 7.24, is the closest match.

4. Imagine that you could go back to a time when the Sun was relatively young (say fifty million years old), and construct an H-R diagram for the star cluster in which it formed. This diagram would look like the one shown for the Pleiades in Figure 12.4, with star #16 representing the Sun, and the cluster's brightest star, Alcyone (star #1), highest up on the Main Sequence at the upper left.

What will happen to star #1 in the Pleiades (or to similar stars in the Sun's original cluster) as time marches on? Being 1000 times more luminous than the Sun, Alcyone is also much more massive, by a factor of seven. The more massive a star is, the faster it progresses through the phases of stellar evolution. Alcyone will spend less time in its stable (Main Sequence) phase, will run out of core nuclear fuel faster, and will move off the Main Sequence much sooner, compared to the Sun. While we believe that the Sun will ultimately spend around ten billion years on the Main Sequence, a star as massive as Alcyone will spend less than one hundred million years there. Given its current properties, we believe its age (and thus the age of the Pleiades cluster) to be less than one hundred million years. This is less than the blink of a cosmic eye, compared to the age of the Universe (14 billion years).

(a) Review Figure 12.3. As a star cluster ages, its Main Sequence turn-off point steadily becomes brighter / fainter (circle one) and bluer / redder (circle one). The masses of the stars around the turn-off point decrease / increase (circle one). (1 point total)

(b) The difference between absolute and apparent magnitude is the same for all members of the Pleiades cluster, because it is purely a function of the cluster distance from Earth. Use the absolute magnitude of the Sun and the apparent magnitude of solar-type star #16 to estimate this difference, and then determine the absolute magnitude of star #1, Alcyone (the brightest star in the Pleiades). Show your work, as well as stating your final answer. (2 points)

The brightest, bluest star still remaining on the Main Sequence is sometimes used to define a cluster's turn-off point. The term "turn-off" comes from recognizing that this star will be the next one to leave (or turn off) the Main Sequence, and become a red giant. For the Pleiades, this turn-off point is currently at absolute magnitude \_\_\_\_\_ and B-V color \_\_\_\_\_. (1 point total)

(c) Review Example 12.6 (on page 14) and locate star #14 (resembling Sirius) in Figure 12.4. There are only \_\_\_\_\_ stars on the diagram that are brighter and bluer than it. (1 point)

Today, these massive, luminous blue stars give the Pleiades cluster its characteristic, youthful appearance. The cluster will look rather different in a few billion years, however, when these stars evolve off the Main Sequence. The next cluster that we will study, M67, lies in this age range. How different do you think its H-R diagram will be?

*Congratulations, you have completed the second of this lab's three activities. You may want to answer Post-Lab question 4 on page 23 at this time.*

### 12.4.2 An H-R Diagram for M67, an Older Star Cluster

You were given magnitudes for a number of stars in the Pleiades cluster in Table 12.5. We did not discuss how these magnitudes were obtained, but we shall do so now. You will measure apparent magnitudes (and record colors) for a set of stars in the star cluster M67 in the constellation of Cancer, the crab. As you work, remember that the faintest stars have the largest magnitude values.

1. Access the second web application for this lab exercise (M67 Cluster) from the GEAS project lab exercise web page (see the URL on page 2 in §12.1.2). This activity focuses on a color image of the star cluster M67. You will carefully measure the brightnesses of 12 individual stars, and use them as a basis for constructing an H-R diagram for the entire cluster. You will choose for yourself which of the hundreds of stars to measure, within certain guidelines.

When choosing stars to measure, try to avoid the brightest stars on the image (those which bleed sharp spikes of light into their nearest neighbors), stars which are very close to others and thus hard to isolate and sample without contamination, and the multitude of tiny, faint red field stars in the background.

When you click on a star on the image of the sky, four changes will occur on the screen. A green circular aperture (a ring) will be drawn around the star on the image, to the left of the image a large green dot will appear at the position matching the brightness and color of the star on the H-R diagram and the plot labeled "distribution of counts" will be updated to show the radial distribution of light around the center of the aperture, and on the right an entry will be made and highlighted in the list of Marked Stars.

Start by clicking on the button labeled "Help," and read through some basic information



on how to use the web application efficiently. The “Zoom” option, for example, will double the size of the image on-screen, which can be quite useful when fine-tuning the position of an aperture around a star. Some options will be “grayed out” (hidden) when you are in the process of fitting an aperture, so remember to type “s” or click on the “Save aperture” button when you have finishing sizing your final aperture, so that the “Print,” “Write to disk,” and “Delete all apertures” options will become visible again. As you save an aperture, the aperture drawn on the image and the associated large dot on the H-R diagram will both turn from green to blue, and the star will no longer be highlighted in the list of Marked Stars.

2. Begin by identifying a solar-type star, one with properties similar to those of the Sun (as it would appear if it was placed within M67). A recent study found sixty of these within the cluster, so this should be a fairly straightforward exercise. Re-examining the data in Tables 12.2 and 12.4, we note that the Sun has a B–V color of 0.66, and at a distance of 770 parsecs (the distance to M67) it would have an apparent V magnitude of 14.2. We shall thus define a “solar-type” M67 star as one with a V magnitude between 13.7 and 14.7 and a B–V color between 0.56 and 0.76. Stars with magnitudes less than 13.7 are too bright, while those greater than 14.7 are too faint. Those with B–V colors less than 0.56 are too blue, and those greater than 0.76 are too red. Select an intermediate to faint yellowish looking star near the center of the image to measure.

(a) Use your mouse to click on the center of the star’s image. A green circle (an aperture) will appear around the star, and related data will appear in two charts: star # (for ID purposes),  $X$  and  $Y$  coordinates (indicating the position of the star on the image, where the origin is in the upper left corner), radius  $R$  of the aperture (an angular size expressed in arcseconds), corresponding apparent V magnitude, color index B–V, and the number of counts registered by the detector for the pixels enclosed by the aperture and their radial distribution around the center of the aperture. The color index is literally the difference between the number of counts recorded at blue wavelengths and the number recorded at visual (green) wavelengths, in units of magnitudes. Because fainter fluxes (less light) are equivalent to larger magnitudes, very blue objects have small B–V colors and very red ones have large B–V colors.

(b) Refine your aperture to better match the star location and contain all of its light by using the “Update Aperture” panel to the right of the image. From there you can shift your circle left or right, or up or down, by clicking on the four rectangular directional arrow symbols, or you can increase or decrease its radius (to contain all of the light from the star, but none from its neighbors) via the two circular up or down arrow symbols. You can duplicate these actions using the arrow keys, and the plus and the minus keys, on your keyboard.

Note how the counts and the corresponding apparent magnitudes and colors change as you vary the aperture properties. The distribution of counts around the center of the aperture should be sharply peaked when your aperture is properly centered. (Some of the brightest stars will have flat, or slightly dimpled, cores because they are so bright. Don’t worry about these artifacts.) When you have centered the aperture as best you can, and adjusted its size

to include all significant “starlight” counts, but not too many “dark sky background” counts and light from neighboring objects, examine its V magnitude and B–V color in the chart of Marked Stars. Do they match the definition of a solar-type star? If not (and in general if you wish to abandon your attempt to measure any star) click the “delete aperture” button in the “Update Aperture” panel (or type the letter “d”), and choose another candidate to continue your search for a solar-type star.

#### Example 12.7

Suppose you select star #132, and measure a V magnitude of 15.42 and B–V color of 0.76. This star lies within the color range of a solar-type star (as  $0.56 \leq 0.76 \leq 0.76$ ), but it is too faint ( $14.7 < 15.42$ ). You then look for a brighter star with a similar color and settle on star #152. It has a V magnitude of 14.21 and a B–V color of 0.54. This star lies within the required magnitude range ( $13.7 \leq 14.21 \leq 14.7$ ), but is too blue ( $0.54 < 0.56$ ), so you look for a redder star of similar brightness and settle on star #123. Your measurement yields a V magnitude of 14.02 and a B–V color of 0.62. This star is a solar-type star ( $13.7 \leq 14.02 < 14.7$ , and  $0.56 \leq 0.62 \leq 0.76$ ).

(c) When you find an acceptable star, click the “Save” button in the Update Aperture panel. The green aperture will turn blue, and the data for the star will be permanently fixed in the data chart.

There is a second chart, a graph showing the radial distribution of counts around the center of the selected aperture. This plot illustrates the distribution of light within the aperture (the green circle) as defined by two short green bars, while the plot extends a bit farther out to show how much light lies just beyond the aperture. This will help you select the best size for the aperture, a decision that determines how much light to count when measuring the star’s brightness.

As you vary the position and size of the aperture around each star and simultaneously watch the displayed H–R diagram, you’ll note that the point where the star is plotted in this diagram typically varies in the vertical direction, since the measured brightness varies depending on the size and position of the aperture.

3. After you’ve found and marked an acceptable solar-type star, you’ll repeat this basic process to find 11 more stars that fit into four categories. We want you to find at least two stars fainter and bluer than the Sun, at least two fainter and redder than the Sun, at least two brighter and bluer than the Sun, and at least two brighter and redder than the Sun. Try to guess whether each star that you select is brighter or fainter, and redder or bluer, than the Sun before reading its magnitude and color from the chart. We want to confirm that you can correctly compare the brightnesses and colors of stars, so be sure to place each of the 11 additional stars that you mark into the appropriate category.

#### Example 12.8

Let us re-examine the first star which we rejected in our search for a solar-type star. We can classify star #132 as both fainter and redder than the Sun, since for apparent V magnitudes,

$14.2 < 15.42$ , and for B–V colors,  $0.66 < 0.76$ . This star thus qualifies for the redder, fainter category.

As you select your set of 12 stars, sort them into the five defined categories below. You will receive one point for the solar-type star and two points for each of the other four categories, if all stars are correctly categorized.

(a) The solar-type star is #\_\_\_\_\_. (This star should have a V magnitude between 13.7 and 14.7, and a B–V color between 0.56 and 0.76.)

(b) The 2 to 4 stars fainter and bluer than solar are #\_\_\_\_\_. (These stars are fainter than a V magnitude of 14.2, so  $14.2 < V$ , and they have colors bluer than 0.66, so  $B-V < 0.66$ .)

(c) The 2 to 4 stars fainter and redder than solar are #\_\_\_\_\_.

(d) The 2 to 4 stars brighter and bluer than solar are #\_\_\_\_\_.

(e) The 2 to 4 stars brighter and redder than solar are #\_\_\_\_\_.

Print out your completed data chart to add to your lab report.

4. After all 12 stars have been measured and marked, points for an additional 400 stars within the M67 cluster (down to an apparent magnitude of 16) will suddenly appear on the H-R diagram plot. These stars were marked in the same way you marked your set, and their magnitudes were measured similarly. Keep the diagram on the screen for a few minutes; it will take awhile to properly interpret it, assess the quality of its data, and extract important information from it. If you have trouble reading it from within the application, go ahead and save a copy as a file on your local disk (or print out a paper copy). This version should be easier to view, as it will be somewhat larger.

5. Your first task in interpreting the H-R diagram for M67 is to find the Main Sequence, which is not quite as obvious as it was for the much closer Pleiades cluster (recall Figure 12.3). There are several important reasons for this. Some stars that we think lie in M67 may actually be closer foreground stars or more distant background stars; some stars which appear to be isolated may actually be unresolved binary stars; there may be small variations in chemical composition (the ratio of various metals) within this stellar population; and measurement uncertainties (every measured quantity has some uncertainty to it) and procedural errors (errors in technique) may exist. To simplify this task, note the four stellar evolutionary tracks (drawn in four colors), which merge into a single track in the diagram's lower center right. Let them define the center of the Main Sequence for low-mass stars.

6. When measuring the magnitudes of stars in M67, any errors in the sizes or positions of the stellar apertures will lead to poor measurements. Consider this point when answering the following four questions. (1 point each).

(a) What happens if an aperture is too small? Where will the associated star appear on the H-R diagram, relative to its correct position?

(b) What happens if an aperture is too large? Does it matter whether the extra space is dark sky, or contains a neighboring object?

(c) What happens if the aperture is offset from the center of the star?

(d) What happens if you place an aperture directly between two stars?

If you are unsure about any of your answers, go ahead and experiment by shifting one of your apertures on and off of its target, and examine the result in the radial plot of stellar fluxes. (Be sure to reset your aperture to its correct position and size when you are done experimenting!)

7. Having made our measurements and considered common sources of error, we can now use our derived H-R diagram to estimate the age of the M67 cluster. Examine the four evolutionary tracks (drawn in four colors) showing the expected brightnesses and colors of stars as they turn off the Main Sequence and evolve (moving upwards and to the right) into red giant stars. These tracks are based on sophisticated models of stellar evolution, which simulate the nuclear processes by which stars burn their fuel. Each track has a stellar age associated with it.

The low-mass stars at the bottom part of the Main Sequence (where the four tracks effectively merge into a single line) are of no help here. Instead, look above and to the right of this region – where stars “turn off” the Main Sequence as they become red giants – and decide which one of four tracks (if any) best fits the *edge* of the region which contains the giant stars. Base your age estimate for M67 on the corresponding age for that track, or interpolate between two adjoining tracks if you think that the best fit to the data lies between them.

Discuss your results (your age estimate) for M67 below, explaining how you came to your conclusion. Note the particular features on the H-R diagram which were most important to your decision-making process. (6 points)

8. Compare your results for M67 with those for the Pleiades, with respect to the following five factors. (1 point each)

(a) Cluster turn-off point:

(b) Presence of red giants:

(c) Presence of red dwarfs:

(d) Presence of massive blue Main Sequence stars:

(e) Age of cluster:

9. Besides answering the remaining Post-Lab questions (see below), you need to save two figures for your lab report: (a) the M67 data chart for your 12 stars, and (b) the M67 cluster H-R diagram. You may also include any radial charts of flux around a particular aperture, if you wish to do so to help in answering the four questions in question 7 above.

*Congratulations, you have completed the third of this lab's three activities. You may want to complete your answers to Post-Lab questions 5 through 7 on page 24 at this time.*

## 12.5 Final (Post-Lab) Questions

*Questions 1 through 3 relate to the materials discussed in §12.3.1. Review this section if you are unsure of your answers.*

1. How does the Sun compare to the other members of the nearest star sample? If one assumes this sample is representative of typical stars found throughout the Universe, to what extent is the Sun a typical star? (3 points)

2. Consider the brightest stars in the sky, and why they appear so bright. Three students debate this issue. Student A: “These stars must be very close to us. That would make them appear brighter to us in the sky.” Student B: “These stars are intrinsically very luminous, so they emit a tremendous amount of energy.” Student C: “I think it’s because these stars are very close and very luminous.” Use what you’ve learned in this lab to support the views of one of the three students and answer the question “Why do the stars which appear the brightest in the night sky seem so bright?” (3 points)

3. Are these apparently bright stars very common (do stars like them make up a large percentage of all stars)? Explain your reasoning. (3 points)

*Question 4 relates to the materials discussed in §12.4.1. Review this section if you are unsure of your answer.*

4. Consider how the H-R diagram of the Pleiades would look far in the future.

(a) Suppose all of the Main Sequence stars above solar-type star #16 had run out of fuel and left the Main Sequence. What other regions in the diagram (besides the Main Sequence) would now be populated? (1 point)

(b) How old would this cluster be? Explain. (1 point)

*Questions 5 through 7 relate to the materials discussed in §12.4.2. Review this section if you are unsure of your answers.*

5. The best explanation for why the H-R diagram for M67 does not include any white dwarf stars is (a) this cluster is not old enough for any of its stars to have evolved to this stage, or (b) the data this H-R diagram is based on only includes stars brighter than an apparent V magnitude of 16, and we expect any white dwarfs in M67 to be fainter than this. Explain your choice of answer. (2 points)



6. When measuring apparent magnitudes for stars in M67, if two equal-mass stars were tightly clustered in a binary system and could not be separated (they appeared as one star), where would their combined properties place them on the H-R diagram (versus where they would be placed if they were separable)? (2 points)

7. The constellation of Cancer contains the star cluster M44, which, like the Pleiades, is visible to the unaided eye on a clear night.

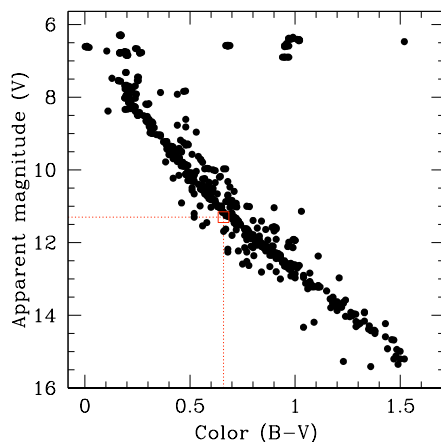


Figure 12.5: An H-R diagram for the M44 star cluster, with a solar-type star boxed in red. Note that the y-axis runs from large magnitudes to small, so that the brightest stars appear at the top of the figure.

(a) Using its H-R diagram in Figure 12.5, compare this cluster's age with that of the Pleiades and M67 clusters. Explain how you arrived at your conclusion. (2 points)

(b) Is M44 closer to or farther away from us than the Pleiades, and closer to or farther away from us than M67? Explain your answer. (2 points)

## 12.6 Summary

After reviewing this lab's goals (see §12.1.1), summarize the most important concepts discussed in this lab and discuss what you have learned (include both techniques for data analysis and scientific conclusions). (25 points)

Be sure to consider and answer the following questions.

- How are H-R diagrams constructed? Why are they useful, and how are they used? Start with the necessary telescope observations and required data, explain how they are obtained, and then proceed to the use and significance of the derived diagrams.
- Astronomers say that the Sun has another five billion or so years remaining of stable, well-behaved existence on the Main Sequence. If someone were to express skepticism, saying, "How can we possibly know that?" what would you say in response?

Make use of the H-R diagram constructed for M67 as an illustrative example, and reference the three figures that you created at the end of §12.4.2.

Use complete, grammatically correct sentences, and be sure to proofread your summary. It should be roughly 300 to 500 words long.

## 12.7 Extra Credit

The brightest star in the sky, Sirius, has a faint companion (Sirius B) whose existence was predicted from orbital irregularities by Friedrich Bessel in 1844. It is ten magnitudes fainter than Sirius, and was at first assumed to be a cool, red dwarf. In 1914, observations showed that it was both hot and roughly the size of Earth. How was this discovery made? Describe the observations which were made, and the mathematical argument behind the size estimate. In 2005, the mass and size of Sirius B were measured to unprecedented precision. How was this done? (5 points)

Be sure to cite your references, whether they are texts or URLs.