Color-Magnitude Diagram Lab Manual

Due Oct. 21, 2011

1 Pre-Lab

1.1 Photometry and the Magnitude Scale

The brightness of stars is represented by its value on the magnitude scale. The ancient Greek astronomer Hipparchus originally developed this scale, such that the brightest stars had magnitude 1 while the faintest stars that were visible had magnitude 6. In modern terms, the magnitude scale has been refined such that a difference of 5 magnitudes between two stars corresponds to one star being 100 times brighter than the other. If two stars differ in magnitude, then they also differ in terms of the radiant flux (energy per unit area per unit time) received. Because the magnitude scale is logarithmic, the formula that relates flux to magnitude is as follows:

$$\frac{F_2}{F_1} = 100^{\frac{m_1 - m_2}{5}} \tag{1}$$

When we measure the magnitude of a star, we are measuring its apparent magnitude, m. This is its brightness as perceived when measured from Earth. Astronomers also use the absolute magnitude, M, of a star, which is defined as the apparent magnitude a star would have if we were observing it from ten parsecs away. Consequently, using the inverse square law ($F = 4L\pi r^2$) the luminosities of two stars can be related to their absolute magnitudes by:

$$\frac{L_2}{L_1} = 100^{\frac{M_1 - M_2}{5}} \tag{2}$$

The difference between a stars apparent and absolute magnitude is called its distance modulus. If the distance modulus is known, the distance to the star can be determined, using the following formula:

$$m - M = 5log_{10}(\frac{d}{10\text{pc}}) \tag{3}$$

Stars are not uniformly bright across all wavelengths, so a stars magnitude will be different in different wavelengths. The magnitude of stars is measured in a number of different filters. For example, the B (or blue) filter gives the stars brightness in the 391-489 nm range, while the V (or visual) filter gives the stars brightness in the 505-595 nm range. The magnitude of a star across all wavelengths together is called its bolometric magnitude. Additionally, the color of a star can be defined by its color index, which is its brightness in B minus its brightness in V, or (B V). In this lab, the B and V values for all assigned stars will be collected.
See also: C&O, pg 60-62.

1.2 Star Clusters

Stellar clusters are groups of typically tens to hundreds of thousands of stars. These clusters are very dense and tightly gravitationally bound, roughly a thousand times denser than in The traditional view of such clusters is that they all form from the same molecular cloud, so they should all be of similar composition and age. There are two kinds of stellar clusters. The first kind is the younger open clusters, which are found in the disk of the Milky Way. Open clusters are much less dense and are relatively sparsely populated.. The other kind is the globular clusters, which are much more tightly bound and contain large numbers of very old stars. Globular clusters are found in the halo of the Milky Way. Stellar clusters, both open and globular, are useful for study because they tend to represent a population of stars that has formed in isolation and are all essentially the same age.
See also: C&O pg. 474-477.

1.3 Color-Magnitude Diagram

A tool that is useful for understanding stellar populations is the Hertzsprung-Russell Diagram, more commonly known as a Color-Magnitude Diagram (CMD). A CMD is a plot of the brightness (usually in the V band) versus color index (B V) for all the stars in a particular population. Since magnitude can be related to luminosity, this means that the CMD can describe the luminosity of any star plotted. Additionally, since hotter stars emit preferentially towards the bluer part of the spectrum, the CMD also shows the relative temperature of stars on the plot. Thus, the CMD is effectively a plot of luminosity versus temperature. Typically most of the stars in any population form a diagonal band across the center of the diagram; these stars form the main sequence of the population. At the bottom left of the diagram are the very faint and hot stars, these are the white dwarfs. The top left of the diagram has relatively cool but bright stars, the red giants and supergiants. In this lab, the distance to the target cluster is not beforehand, so the plot will be of apparent, rather than absolute, brightness of the star. By fitting a theoretical main sequence curve to the observed main sequence, the distance modulus of the cluster can be determined. This method of distance determination is called spectroscopic or main sequence fitting.
See also: C&O pg. 475 and 220-224, especially Figure 8.13.

1.4 Isochrones and Ages

At a certain point along the main sequence, the stars along it will bend away from its track. This is the main sequence turn-off point. Any star that has curved away from the main sequence has passed the hydrogen-burning portion of its lifetime and goes through a complicated series of evolutionary phases that transforms the star into a red giant. Since the main sequence turn-off point moves down as more stars exhaust their hydrogen, the position of the main sequence turn-off is an indicator of the age of the cluster.In this lab, a theoretical curve of how the stellar population should be distributed will be fitted to the main sequence band and its turn-off point. This theoretical curve is called an isochrone. Isochrones depend heavily on the initial metallicity of the cluster. In astronomy, metallicity refers to the relative abundances of all non-hydrogen and non-helium elements. An isochrone predicts the distribution of stars for a given age and metallicity, so by fitting an isochrone to the observations, the age and metallicity of the cluster can be determined.
See also: C&O, pg 476 and pg 852-853: The Trend toward High Metallicity.

2 Lab Instructions

2.1 Getting Started

1. I encourage students to work with partners on the CLEA software. Each student should write up their own answers to the questions at the end, and mention who their partner is (if any).

2. Each student pair will study one of the following clusters: M39, M41, M34, IC 2391, IC 4665. Add the number of letters in the students' first and last names, divide by 5 and take the remainder; if 0, do M39; if 1, do M41; if 2, M34; if 3, IC 2391; if 4, IC 4665.

3. Open the VIREO virtual observatory software by double-clicking the icon (Windows 7, All Programs, CLEA, Vireo). The software will launch in a new window.

4. Click on the **File** button at the top of the screen and select **Login** from the drop-down menu.

5. Using the space provided, enter both your names and click the **Ok** button.

6. Click on the **File** button again and this time mouse over the **Run Exercise** option in the menu. Select **HR Diagrams of Star Clusters** from the list and the lab components will be loaded.

7. Before you can start observing, you will have to load a list of all the stars in the cluster you have been assigned. Do this by clicking **File** and choosing the **Cluster** Data option.

8. In the window that pops up, click on the **File** button and choose **View/Select Cluster from List**. Find the cluster assigned to you by your instructor and double click on it.

9. Press the **Ok** button to bring up a list of stars in the cluster for observing in a new window. In this window, click the **Selection** button and choose **Create New Hot List of Entire List**. This will store the positions of all the stars you will be observing on a hot list so that you can easily move from one to the other without manually entering their coordinates into the telescope controls.

10. Now you need to take control of your telescope. In the main window click the **Telescopes** button, select Optical, and then choose **Access 0.4 meter telescope**.

11. Now that you have control of the telescope, click the switch on the right of the window to **Open** the dome of the telescope. Once the dome is open, turn on the **Telescope Control Panel**.

2.2 Steering the Telescope

1. You should now be at the telescope screen with the night sky displayed. This is the view through a smaller finder telescope, which would typically be mounted on the side of the telescope tube. Finder scopes are used to locate objects before they are observed at higher magnification through the main telescope. Notice that the display drifts slightly to the right. This is because the Earths rotation shifts the position of stars in the night sky. To compensate for this, turn on the tracking motor by clicking the **Tracking** button. The tracking motor is built into telescopes to compensate for the Earths rotation, so that an object can be observed for extended periods of time.

2. If you click on the directional buttons, you will notice that you can adjust the position of the telescope. However, if you want to move to a star that is very far from your current location, you will want to slew the telescope. Practice this by clicking the **Slew** button and selecting **Set Coordinates**. Enter the following coordinates: Right Ascension = 5^h 36^m 12.8^s, Declination = -1° 12′ 06″. Press **Ok**, then **Yes** to confirm. The telescope will rapidly slew to the target. This is Epsilon Orionis (Alnilam), the star which is in the middle of Orions Belt. You can see the other two stars in Orions Belt at the edges of the finder.

2.3 Star Hopping

1. One technique that is useful for locating objects is called star hopping. This involves using the locations of known bright objects to find fainter ones. Although this virtual telescope can perfectly slew to an object by its right ascension and declination, real telescopes are not so precise. In this example, you will use star hopping to move between bright objects.

2. If centered on Alnilam, you should be able to see the other two stars in Orions Belt. Begin by slewing to the upper right star so that it is in the centre of the screen. This is Mintaka, a binary star system.

3. Now, using Mintaka as a reference, slew so that Mintaka is at the upper left of the screen. As you do so, you should see a star that appears to be approximately as bright as Mintaka at the lower right corner. Once this star is in view, slew to it so that it is centered. This is Eta Orionis.

4. Now it is time to try a larger star hop. Slew so that Eta Orionis is at the top of the screen. Slew down until you find a reasonably bright star, 29 Orionis. You can use groups of faint stars to track how far you need to go. This star is roughly 2 and 1/3rd of a finder screen away from Eta Orionis if you start with Eta Orionis at the top of your screen. Since the finder scope is 2.5 degrees across, you will have to slew between 5.5 and 6 degrees. You will know you have found the correct star if you see a group of stars below and to the right of it in a roughly parabolic shape (parabola opening to the right).

5. From 29 Orionis, slew west and you should see a very bright star come into view from the right. Centre this star on the telescope, and write down its right ascension and declination.

6. Using the same technique, slew the telescope back to Epsilon Orionis.

2.4 Using the Photometer

1. In order to collect data, you must switch from the finder telescope to the main telescope. Do so by moving the slider on the **View** box to **Telescope**.

2. For this lab, the information on the brightness of stars is collected using a photometer, an instrument that counts all the photons from a source that fall into its aperture. A red circle in the telescope field of view represents the aperture. In this software, the photometer will automatically perform the conversion from count rate to flux to magnitude. Before these measurements can be taken, you will have to take a reading of the background counts in the sky so that they can be subtracted from the count rate of target stars.

3. Use the directional buttons to point the telescope away from Epsilon Orionis and towards an area of the blank sky. Then click on the Access button to open the photometer control.

4. To make a color-magnitude diagram, the magnitude of the star must be taken in both the B and V filters. This means a sky reading must be taken for both filters as well. Set the **Filter** to V, the **Integration Seconds** to 1.0, the **# of Integrations** to 3, and the **Reading** to Sky. Press **Start** and the photometer will collect photons for 3 seconds. Once the integration is finished, change the **Filter** to B and then press **Start** again.

5. Now that you have a background reading, slew the telescope back to the target star and open the photometer again. Using the same settings with switching **Reading** to Object, take a reading of the star. After measuring the counts in each filter, click on **File → Data → Record/Review** to record your magnitude measurement. A window will come up that shows you your measurements and all information about the star. Hit **Ok**. You must do this for each filter.

2.5 Collecting Measurements for the Cluster

1. Using the hot list generated earlier, you can slew to each target in the cluster without having to manually enter the coordinates. Click on **Slew** in the telescope control panel, and select **Observation Hot List**, clicking on **View/Select from list**. By double-clicking on each star in the list, its coordinates will automatically be entered into the telescope. Hit **Ok** and the telescope will slew to the target star.

2. Collect V and B readings for all the assigned stars in the cluster. You can improve the quality of your data by taking a fresh reading of the background every five stars or so.

3. **NOTE:** To ensure that your data is accurate, you want at least 10,000 counts so that your Signal/Noise ratio is approximately 100. Some faint stars on your list will not achieve this number of counts. You can correct this by doing a couple of things. First, you can set the integration time or number of integrations to be higher so that the telescope collects photons for a larger amount of time. Secondly, you can switch to a more powerful telescope by going to the main window and clicking the Telescopes button, selecting **Optical**, and then picking either the **1.0m** or **4.0m** telescope. These more powerful telescopes will collect more photons from the same source. A good strategy is to make a note of stars that are too faint for the 0.4m telescope and come back to them later with a more powerful telescope.

2.6 Making a Color-Magnitude Diagram

1. Once you have finished collecting data for every star in your cluster, you can turn off the telescope by turning off the **Telescope Control Panel**. To open the Color-Magnitude Diagram analysis select **Tools → HR Diagram Analysis** from the top menu. This will load a blue CMD plot. To load your observations onto the plot, choose **File → Load Plot → Data from Observations** from the menu bar and your measurements will automatically be plotted.

2. The first step in analyzing your data is to determine the distance to the cluster. You can do this by plotting a Zero Age Main Sequence line (ZAMS). To plot the ZAMS, select **Tools → Zero-Age Main Sequence** from the menu bar. You will see a green line appear on your diagram. Using the sliders at the side and bottom of the graph you can adjust the line. The right slider adjusts the distance modulus of the cluster (which in turn determines the distance) and the bottom slider adjusts the reddening of the cluster the cluster may appear redder than it actually is because interstellar dust between the cluster and us preferentially absorbs blue light more than red light. Try to fit the ZAMS line to the cluster. Your fit will not be exact, so it is best to fit to the middle of the main sequence because the upper stars on the CMD may be affected by the age of the cluster while the stars on the lower part of the CMD are affected more by observational noise. Determine a best value for reddening and distance modulus, as well as putting the ZAMS above, below, to the left, and to the right of the main sequence of the cluster to get an estimate on the uncertainty in your measurement. Record these values.

3. The second step is to estimate the age of the cluster. As the cluster ages, the shape of its CMD also changes. By selecting **Tools → Isochrones** you can add an isochrone on your CMD, which is a theoretical prediction of how the stars should be distributed at a certain age of the cluster. You can use the sliders in the isochrones window to adjust the age of the isochrones and the (B-V) value. To improve your fit, you can adjust the metallicity of the isochrone model. This may also improve your fit. As with the ZAMS, move both sliders above and below the plotted stars to estimate the uncertainty in your answer. Record your estimate for the age of the cluster. Make a printout (or email the plot to yourself for later printing) of your observed stars, and the best-fit isochrone.

3   Results and Post-Lab Analysis

Turn in your answers to these questions by Oct. 21, 2011, 5 pm, to the Astro 320 drop box on lower level 2, in front of L2-049.

1. What is the right ascension and declination of the star you slewed to in the star hopping section of the lab?

2. Include a printout of your observations of the cluster, with your best-fit isochrone.

3. Using the distance modulus determined, what is the approximate distance to the cluster?

4. What is the approximate age of the cluster?

5. Describe how the age and distance of the cluster are constrained, based on the parameters that affect each curve?

6. The VIREO software also contains pre-existing CMDs for other clusters. Access these CMDs from the HR Diagram Analysis window used in the last part of the lab. At this window, select **File → Load/Plot → Select Cluster Data** This will bring up a list of clusters for which the CMD is already available. By double clicking on a particular cluster, its CMD will be loaded onto the same graph used in the lab. **For each of the following clusters, use the Zero-Age Main Sequence and Isochrones to determine the distance modulus and age of each cluster.** (Note, if the clusters data does not load when selected, try opening the Zero-Age Main Sequence from the menu. This should load the data properly.) For these clusters, the extinction/reddening value on the ZAMS line is fixed.

   (a) M67 (NGC 2682)
   (b) NGC 752
   (c) M45 (Pleiades)

7. How do the curves of these clusters differ from each other and from the cluster you collected observations from?

8. Do you notice that the parameters in either the ZAMS or isochrones curves seem to be degenerate? That is, can you create reasonable fits for cluster observations using different combinations of the adjustable curve parameters? If so, which parameters are degenerate?

9. What are the relative numbers of un-evolved versus evolved stars observed in these clusters? Why might this be the case?