# Lab #5:
# Cluster H-R Diagrams

March 5, 2012

Due March 9, 2012

Objectives:

- To generate two Hertzsprung-Russell diagrams, each of a different star cluster.
- To determine the approximate ages of these clusters using model isochrones.
- To determine the distance to these clusters.

Equipment:

- Data from SIMBAD
- MATLAB

## Introduction

In lecture, you saw Hertzsprung-Russell (or H-R) diagrams of a general collection of stars, using the luminosity and temperature as the axes. But the H-R diagram is most useful when plotting stars that are all in the same cluster; the diagram can tell us not only the age of the cluster, but also its distance from us. How, you might ask? We rely on the fact that stars in a single cluster are all approximately the same age and approximately the same distance from us.

Since the effects of distance are the same for every star in the cluster, we can plot their *apparent* magnitudes in a single filter (such as V) as a stand-in for the luminosities. Observationally, it is the apparent magnitude (which is related to flux) that we measure, while determining the luminosity requires some assumptions or other data. We also easily measure the colors of stars, which are the differences in magnitude between two filters (such as B-V), while determining the temperature would require more work. By plotting the stars of a single cluster using apparent magnitude and color, you can locate the main sequence on this H-R diagram.

Once you know where the main sequence is, you can determine where the main sequence turn-off occurs. The turn-off is where the main sequence ends; stars with masses greater than the turn-off have already evolved off the main sequence. Since the length of time that a star lives on the main sequence is determined almost exclusively by mass, you know that clusters which are missing the top of the main sequence must be at least as old as the longest main sequence life-time of the missing massive stars. But how do we know the life-times of stars?

Astronomers have a fairly good understanding of the big picture of how main sequence stars work these days, as well as the giants and supergiants. We have stellar evolution models that take a population of stars of the same age with a wide range of masses and evolve the whole population through time, giving the absolute magnitude (which is based on luminosity) and the colors (derived from the temperatures) of all the stars in the population at each snapshot in time. This sounds something like our H-R diagram of the star cluster, doesn't it? These snapshots in time are called "isochrones", from the Greek *isos* + *chronos*, meaning "equal time". If you take the set of isochrones and find which specific isochrone is shaped the most like your cluster H-R diagram, you have found the age of the cluster!

But wait! You will notice that the isochrones are much brighter in V than your cluster, because the isochrones are created by plotting *absolute* magnitude, while the cluster H-R diagram is plotting *apparent* magnitude. If you shift the isochrones down (by adding to the absolute magnitude, since the magnitude scale is backwards, and fainter stars have larger values of absolute magnitude), you can line up the isochrones with your observations. If you know the difference between absolute magnitude and apparent magnitude, you've found the distance! Apparent magnitude minus absolute magnitude (m-M) is known as the "distance modulus", and you get the distance to the cluster from the equation:

$$m - M = 5log\frac{D}{10\text{ pc}} \tag{1}$$

or, rewritten to solve for D, the equation becomes:

$$D = 10^{0.2(m-M+5)} \tag{2}$$

where D is given in parsecs (pc).

Remember that it is key that the stars are all at the same distance and of the same age. If you plotted the apparent magnitude of random stars that were not at the same distance, the main sequence would be washed out. A B7 V star like Regulus would appear about 8 magnitudes fainter at a distance of 1000 pc than it does at Regulus's distance of 23.8 pc. If you then assumed on the diagram that the main sequence ran through Regulus, that same B7 V star at 1000 pc would then appear on the diagram as a white dwarf, which it is not! Furthermore, if the stars plotted are not all of the same age, the presence or absence of a high mass, short life-time star on the main sequence tells you nothing about the age of other, unrelated stars.

## Procedure

You will be using data compiled by the SIMBAD astronomical database and the Sloan Digital Sky Survey (SDSS) to find the magnitudes of stars in a star cluster in different filters. You will then plot the V magnitude of these stars vs. the B-V in order to create H-R diagrams of the star clusters. Then you can compare the main sequence of the clusters to the main sequence of the isochrones to determine the age and distance modulus ($m$ - $M$) of the clusters.

(1) Make a single folder with the initials of each lab partner and the lab number in the "A121" folder on the desktop. Then open Firefox and go to the website for this lab, `http://www.astro.umd.edu/~cychen/MATLAB/ASTR121/labHR/`, and download the file called "m41.txt". Then click on the link for the SIMBAD astronomical database.

(2) Click on the "by identifier" link (under the red box labeled "Queries"). Enter "M67" (without the quotes) in the "Identifier" bar, and hit "submit ID". The M stands for Messier, as in Charles Messier, who put together a list of fuzzy objects that were not comets back in the late 1700s. This will bring up the page for the open cluster M67. Scroll down the page, and click on the icon for the Aladin applet. This will open a new tab, which might take a few seconds to finish loading.

(3) Once the page loads, you should see an image with lots of red labels plotted over it. These red labels are all the objects in the field for which SIMBAD has data. Fortunately, we do not need all of them. Previously, we have made students click on 60 of the stars and record the B and V information by hand, but no more! There's an easier way to narrow down the data. First, zoom out (the drop-down menu on the right side of the applet) to 1/4x so that all of the cluster is visible.

(4) Now, in the search box at the lower right of the image, type "incl" (without the quotes) and hit "Go". This will highlight all of the stars which have a type of *incl, which means "star in cluster". It will also list all of the stars below the image. Go to the "Catalog" menu, and select "Create new plane with selected sources...", and "in one homogeneous table". A new plane will pop up in the box at the upper right, with the incredibly creative name of "Select.src". Select this plane by clicking on it once. It should now be highlighted in blue.

(5) Now go to the "File" menu, and select "Export planes (FITS, VOTable,...)..." A window will appear, asking you to select the planes you want to export and where to export it to. Make sure only the "Select.src" plane is selected (with a check mark), and give it a file name like "m67.txt", instead of the "Select.src.txt". Also select "TSV" as the format for the catalog. Now, for the Directory, give it the path to the folder you created in step (1) (`C:\Users\Student\Desktop\A121\yourfolder\`), and click "Export".

(6) Now repeat steps (4) and (5), searching instead for "rgb" and "wd", and put the results in files called "m67rgb.txt" and "m67wd.txt".

(7) We need one last file before we continue. Go to the lab's website, and, under "Procedure 3: The HR Diagrams", download the file isochrones.mat to your folder. This file contains a set of isochrones which I have downloaded from `http://stev.oapd.inaf.it/cgi-bin/cmd_2.3` and read into MATLAB previously. The .mat file format means that MATLAB will read the file in exactly as I had the data stored in my MATLAB session. (If you feel like playing around with the isochrones website later, you might care to know that I used the following settings to get the isochrones we'll be using: $A_V = 0$, IMF was the Chabrier (2001) lognormal, single isochrone of t=1.0e8 to 1.1e10 yrs and Z=0.020 - essentially solar, output as isochrone tables.)

(8) Open MATLAB and give the command

**>> cd yourdirectory**

where yourdirectory is the path of the folder in which you saved your files (which is `C:\Users\Student\Desktop\A121\yourfolder`). Before we start loading files, let's edit the M67 files to put them together into one file. Give MATLAB the command

**>> edit m67.txt**

which will open the file in MATLAB's editor program. You can also issue this command to open m67wd.txt and m67rgb.txt, or just use the "File", "Open" menu in the editor. These steps are very important to make sure the file is read into MATLAB properly. In m67.txt, delete just the row of dashes separating the column names from the data. In m67rgb.txt and m67wd.txt, copy the data only (i.e. everything below the dashes) and paste into the bottom of the data in m67.txt, so that all the data is now contained in m67.txt. Save your changes to m67.txt. The file for M41 (m41.txt) does not need to be edited.

(9) Let's explore the isochrone data. Issue the command

**>> load isochrones.mat**

to load the isochrones. In your workspace, you will see that a new variable, a 1x1 struct, called "isoc" exists. Give the command

**>> isoc**

which will tell you that isoc is composed of two more structs called "e8" and "e9". Now type

**>> isoc.e8**

and you'll see that isoc.e8 is further composed of 9 more structs, called "one", "two", and so on. If you look at isoc.e9, you'll see that it is composed of 20 structs. Now look at

**>> isoc.e8.one**

which is composed of 3 arrays of double precision numbers, called "B", "V", and "logage". These arrays contain the B magnitudes and V magnitudes of every star in the model, and the $\log_{10}$ of the age of the stars in years.

The reason I constructed it this way is to try to make clear what age each isochrone represents. Calling it "isoc" reminds you that these are isochrones. Breaking it into "e8" and "e9" is to separate the isochrones for hundreds of millions of years (hence e8) from the billions of years (e9). Then isoc.e8 and isoc.e9 are further broken down, separating each isochrone from each other. Thus isoc.e8.one represents the data necessary for the 100 millions years isochrone, while isoc.e9.ten represents the 10 billion years isochrone. You'll also notice names like isoc.e9.sevenpt5, which represents 7.5 billion years.

To make sense of the isochrones data, let's plot isoc.e9.five. We'll be plotting V (y-axis) vs. B-V (x-axis), just like we'll do for the stellar data from SIMBAD in a few moments. Plot the five billion years isochrone, and remember to flip the y-axis, since the magnitude system is backwards:

**>> plot(isoc.e9.five.B - isoc.e9.five.V, isoc.e9.five.V, 'b+')**

**>> set(gca, 'YDir', 'reverse')**
which will change the direction of the y-axis labels. (Remember, if you use "gca", which stands for "get current axes", you do not need the **hold on** command to make it work, but if you use "axes", then you do need **hold on**.)

Let's break down that **plot** command a little. The first part, "isoc.e9.five.B - isoc.e9.five.V", subtracts the V magnitude from the corresponding B magnitude for all the stars in the model, and tells **plot** to make this result the values on the x-axis. The second part, "isoc.e9.five.V", tells **plot** that these will be the values on the y-axis. The last part, "b+", tells **plot** that it should make each data point a blue plus sign. If you want a reminder of what colors and symbols can be used, use the **help plot** command.

Let's add a title and labels to the plot, because plots are meaningless if you don't know what is being plotted.
**>> xlabel('B - V')**
**>> ylabel('V')**
**>> title('5 billion years isochrone')**

Let's do one last thing to this plot before we move on to the stellar data. See what happens when you do
**>> hold on**
**>> plot(isoc.e9.five.B - isoc.e9.five.V, isoc.e9.five.V + 5, 'ro')**
**>> legend('5e9 isochrone','5e9 isochrone + 5','Location','SouthWest')**
**>> hold off**

You will need to shift the isochrones in this way, since they are in *absolute* magnitude, in order to scale them to the distance of your cluster data.

If you'd like to save a copy of this plot, you can either use the "File", "Save as" menu in the figure window, or just type
**>> print('-djpeg','5billion')**
which will create a jpeg file of your plot. Other file formats are possible; see **help print** for more options.

(10) Open a blank m-file (from the "File" menu either in the editor or in the main MATLAB window) to create a script m-file. In this file:
(a) Write the commands to load the "isochrones.mat" file and one of your cluster data files.

The command to open the cluster data files is a new one, **tdfread**, which reads tab-delimited files, and is used as such:
**>> m41 = tdfread('m41.txt')**
This will read in m41.txt and create a struct named "m41", with separate arrays for each column in the file. The arrays are named according to the column titles in the file, which you hopefully did not delete in step (8), when removing the line of dashes below it. The important arrays within these structs are "m41.B" and "m41.V". These are the B and V magnitudes of the stars in each cluster.

(b) Now write the commands to clear the figure and plot the H-R diagram of M41, remembering to reverse the y-axis. Does it look young or old?

(c) Pick an isochrone and overplot it, using a different symbol than for the M41 data. Don't forget to use **hold on** and **hold off**.

(d) Add axes labels, a title, and a legend. The legend should state what cluster you are plotting and the age of the isochrone that you are overplotting. It should also include the amount you added to the V values of the isochrone to account for the distance to the cluster.

(e) Include a command to save the file as a jpeg.

(11) Now for the science! Like you did in the last lab with the classification of stellar spectra, use the script file you just created and edit it, in order to try isochrones of different ages and different vertical shifts. Look for the isochrone which has its main sequence turnoff at the same B - V value as your data. You may want to overplot a second isochrone, so that you can more easily tell if the next older or younger isochrone isn't a better match. Make sure you pick the isochrone that matches the shape the BEST. Change the age of the isochrone to "shift" the main sequence turnoff left or right.

Play with the amount that you shift the isochrone vertically (i.e. play with the distance of the cluster) by adding to the V values (only on the y-axis: leave B - V alone) in your **plot** command.

When you've decided on the isochrone and the amount that you need to shift by (accuracy to within +/- 0.5 magnitudes is good), make sure your legend reflects the name of the cluster and the final age and vertical shift you used. It should show the M41 data and the best isochrone (or two isochrones, if it's between 2 ages), shifted to match your data, and it should have appropriate labels for the axes. Print out a copy of the plot for each lab partner.

(12) Repeat (11) for M67 by changing the file name you use in the script m-file. Make sure you change the cluster name in the legend! You don't have to change the array names. Print out a copy for each partner of the m-file you used to create the plot, as well as the plot for M67. Since these plots are easier to see in color, email me the jpeg file for both clusters (one email per lab group, with both lab partners' names included in the email), too.

## Questions

Each lab partner should hand in a print-out of the plots for M41 and M67, and a print-out of the last version of the m-file, which should reproduce the plot for M67. Email me the jpeg file for each cluster plot (one email per lab group, including both partners' names somewhere in the email). Then, either on the back of one of the plots or on a separate sheet of paper, answer the following questions **in your own words**. NOTE: For this lab, it's OK that your plots, as printed from MATLAB, and your m-files are identical to your lab partner's. The answers to the questions, including anything sketched later onto the plots, should be your own work. You can discuss the answers with your partner (or anyone else in the lab), but you should not copy their answers nor allow anyone to copy yours.

1) On the H-R diagram for each cluster, label the main sequence and any other features you can identify. Refer to the diagrams in your text. (You don't have to do this part in MATLAB; You can write on your plot after you print it out.)

2) Using the distance modulus (m-M, the value by which you had to shift your isochrones), calculate the distance to each cluster. If you do the calculations in MATLAB, make sure you either write down your

answer or publish the file, so that the result is visible. If you publish, include a comment (using the % symbol) on the line with the calculation to note what the units are.

3) Let's make sure your ages make sense. What color are the brightest stars on the main sequence in each cluster (i.e. are they more toward the blue side or the red side)? What does this tell you about the age of the clusters? Do the ages you found from the isochrones agree with this?

4) Why does this technique only work for clusters, and not for, say, all of the stars within 100 pc from us?