

Project 1: Color-Magnitude Diagrams of Galactic Star Clusters

Parts A & B due Monday, Sept. 27

Parts C & D due Monday, Oct. 4

In this project you will be examining the color-magnitude diagrams of five star clusters located within the Milky Way galaxy. The five clusters are NGC 2420, NGC 2516, NGC 2682 (M 67), NGC 6397, and NGC 6838 (M 71). “NGC” stands for the New General Catalogue compiled in the late 19th century, while “M” is used for objects in the Messier catalog, compiled a century earlier. These clusters have a wide ranges of distance and ages.

I collected photometric data for individual stars in these clusters from published papers and online databases with the help of my friend and colleague Prof. Andrew West at Boston University. All data was taken over the last two decades using CCD cameras to take pictures with V ($\sim 5500\text{\AA}$) and I ($\sim 8000\text{\AA}$) band filters. The data has been cleaned up to remove as many non-cluster stars as possible, and corrected for the extinction caused by dust between us and the cluster (we’ll talk about dust more later).

Preparation

The first task is to use your UNIX skills to copy over the files you will need for this project. First make a sub-directory in your astro301 directory called `proj1`.

`cd` into this directory and copy the file `~aseth/proj1/data_proj1.tar` into it. This ‘tar’ file contains the files you will need for this assignment packed up. To unpack them type:

```
tar xvf data_proj1.tar
```

Now in your `proj1/` directory, you will find five files `cluster*_vi.dat`, these are the data files containing photometry for stars in each cluster. The names of the clusters have been anonymized. In addition there is a subdirectory `isochrones/` which contains theoretical models of stellar populations at different ages (and with different compositions).

Part A: Making Color-Magnitude Diagrams

The first task is to read in the data for each cluster and create a color-magnitude diagram.

Create an IDL program that you will put all your plotting commands in. Each data file has two columns containing the V and I band magnitudes of individual stars in the cluster. You can read each column into an array using the `READCOL` procedure.

```
READCOL,'filename', column1, column2, ... , FORMAT='F,F,...'
```

When plotting color-magnitude diagrams please follow these conventions: first, and most important, brighter stars with smaller magnitudes should be at the top of the plot and red stars should be to the right side. With the `PLOT` procedure you can achieve this using the `XRANGE & YRANGE` keywords to control the direction and range of the axes. Second, generally astronomers plot the redder of the two magnitudes on the Y-axis, so in this case, please plot $V - I$ vs. I . When first experimenting with the plots it is easiest to do it on the screen, but for making the final versions, make a postscript file containing all the plots. You’ll need to spend time learning about all the keywords `PLOT` uses; this page is useful for that:

http://idlastro.gsfc.nasa.gov/idl_html_help/Graphics_Keywords.html

1) Make a color-magnitude diagram of each individual cluster. Use a title with the name of the cluster and label the axes. To make points rather than a connected line use the `PSYM` keyword.

2) Make a color-magnitude diagram with all the clusters overplotted. You will need to use the `OPLOT` command for this. Use a different symbol (`PSYM`) and color (the `COLOR` keyword) for each cluster so they can be easily distinguished. To get different colors you need to load a color table using the command:

```
LOADCT, 12
```

The colors in a color table are distinguished using numbers ranging between 0 and 255. You can see what color corresponds to what color using the `xpalette` procedure. By using '12', we are loading the 12th pre-defined color table called `16 LEVEL`, which should work well for this assignment. The default color table is 0, and is grayscale.

Finally use the `LEGEND` command to label what symbols/colors correspond to what clusters.

What will you hand in? Include just the combined cluster plot in your project report (which each of you will hand in individually) and use all the plots to answer the following questions:

Question A1: What is the rank order of clusters in *distance* from closest to farthest? Explain how you know this.

Question A2: What are the colors of stars that are turning off the main sequence (or the brightest stars on the main sequence) in each cluster? Translate these colors into a spectral type using the $(V-I)_C$ column in the table at:

<http://www.stsci.edu/~inr/intrins.html>

Question A3: What is the rank order of clusters in *age* from youngest to oldest? Explain how you figured this out.

Question A4: The main sequence is not a thin line in these clusters. Some scatter comes from measurement error, but the width of the main sequence is also caused by another effect – what is it? (Hint: It is particularly visible in cluster 3, which appears to have an almost double main sequence.)

Part B: Measuring Distances

In this section, you will use a method known as *spectroscopic parallax* to measure the distances to each of the clusters. From both direct observations of nearby objects and models of stars we know the absolute magnitude of the main sequence as a function of color. To find the distance modulus to each cluster, you just need to compare these absolute magnitudes to the observed apparent magnitudes.

For the absolute magnitude of the main sequence as a function of color, we will use an *isochrone*; a set of stellar models for stars at a range of mass, all with the same age. We will use a young isochrone with an age of 4 million years so that all the stars in the isochrone are on the main sequence `isochrones/iso_4Myr_solar.dat`. All the isochrones we will use are from the stellar evolution modelers in Padova, Italy; these are the same isochrones I use in my research.

1) In an IDL program (a continuation of the old one, or start a new one) read in the 4 Myr isochrone using `READCOL`. The columns here are model stellar mass, *V* band absolute magnitude, *I* band absolute magnitude, $\log_{10}(\text{Luminosity [Solar Units]})$, $\log_{10}(\text{Effective Temperature [K]})$.

2) For each cluster, make a color-magnitude diagram and then overplot the isochrone as a line. Derive a distance modulus by adding the distance modulus to the isochrone until it falls on top of the clusters' main sequence. In deriving the distances, think carefully about what color range to fit and what to do about the width of the main sequence. You should be able to derive distances accurate to about 0.1 magnitudes or 10%.

What will you hand in? Make a table that lists each cluster’s distance modulus and distance in parsecs. Include a figure of one cluster where you have fitted the young isochrone to the data by adding the appropriate distance modulus. Then write a paragraph describing the details of any choices you made in the process of fitting the data and answer the question below.

Question B1: If we measure the color and apparent magnitude of a random star in our galaxy, why can’t we just use spectroscopic parallax to measure its distance?

Part C: Measuring Ages

You already determined the *relative* ages of the clusters in Part A. But to learn the actual ages of the clusters we need to use stellar models. In the `isochrones/` subdirectory there are a number of isochrones. For now, just look at the ones with solar in their name, we will talk about the others in Part D. The isochrone ages are specified in the filename and are given in megayears ($1 \text{ Myr} = 10^6 \text{ yr}$).

1) In a new IDL program, read in each isochrone and make a single color-magnitude diagram containing all the isochrones overplotted as lines. Remember, the isochrone magnitudes are absolute magnitudes.

2) For each isochrone determine the main sequence turn-off colors and masses (using the first column in the isochrone file) at each age. Plotting color vs. mass may be a good way of measuring the latter. Make a table of these values as a function of age.

3) Now you can find the age of each cluster! Plot each cluster’s color-magnitude diagram. Then add the cluster’s distance modulus to the isochrones to find the best fit isochrone or pair of isochrones that bracket the cluster. Estimate the age of each cluster.

What will you hand in? Include the plot of all the isochrones in your report, as well as the table of isochrone main sequence turn-off colors and ages. Then for each cluster include a plot with the best fitting isochrone(s) and give your best estimate of the age. Also, answer the following questions.

Question C1: Do all the clusters fit well to the isochrones? Which ones have the worst fit?

Question C2: Even for those clusters which are well fit by the isochrones, you will notice that the stars are not evenly distributed along the isochrone. At faint magnitudes this is because we don’t detect all the stars in the cluster. Apart from this observational affect, what what (two) factors affect how many stars are along each part of the isochrone?

Part D: The Effect of Stellar Composition

Age is the primary factor determining the appearance of a stellar population on the color-magnitude diagram, but it is not the only one. The composition of stars plays an important role as well. Of the three older clusters in this sample, one has only 20% of the metals we find in the sun, while the other is another order of magnitude more metal-poor. I have included corresponding isochrones in the `isochrones` directory. Metallicity is usually written using the “bracket” notation $[\text{Fe}/\text{H}]$. This notation is defined as the logarithmic ratio of the object’s Iron to Hydrogen ratio compared to the suns ratio:

$$[\text{Fe}/\text{H}] = \log_{10}\left(\frac{(N_{\text{Fe}}/N_{\text{H}})_{\text{object}}}{(N_{\text{Fe}}/N_{\text{H}})_{\text{Sun}}}\right)$$

Iron is often used as a proxy for all metals. Thus a star with $[\text{Fe}/\text{H}]=-1$ corresponds has 10% the metals in the sun. The non-solar isochrones I've included have $[\text{Fe}/\text{H}]=-0.7$ and -1.7 which roughly match the two oldest clusters in the sample.

1) Plot a color-magnitude diagram of the three isochrones with an age of 12.5 Gyr (`iso_12500Myr_solar.dat`, `iso_12500Myr_feh-0.7.dat`, `iso_12500Myr_feh-1.7.dat`), also include the 5000 Myr solar isochrone. Answer these questions before moving on.

Question D1: For the 12.5 Gyr old isochrones, how does the absolute magnitude of the main sequence and the color and mass of the main sequence turn-off change with stellar composition?

Question D2: The $[\text{Fe}/\text{H}]=-0.7$ isochrone and the solar metallicity 5000 Myr isochrone have a very similar main-sequence turn-off color. Describe the complications this introduces into our analysis in Part B and C. What features could you use to distinguish a younger population from an older metal-poor population?

2) For clusters 2 and 5, assume they have an age of 12.5 Gyr redetermine their distance and metallicity using the new isochrones.

Question D3: Do these fits look better than your original fits to these clusters?

What will you hand in? Include the plot you make in (1) as well as plots showing the best fit age and metallicity of the clusters 2 and 5. Also, include answers to questions D1-D3.