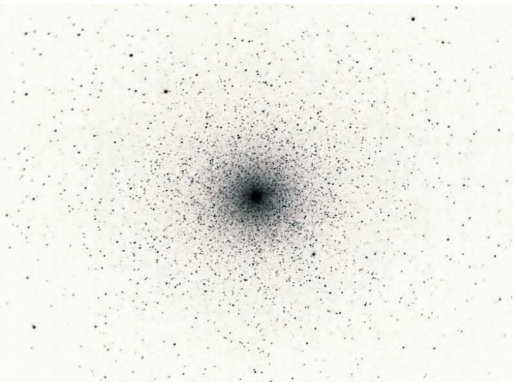
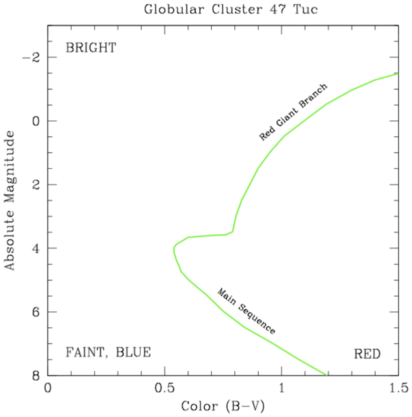
Project C:
The Distances and Ages of Star Clusters

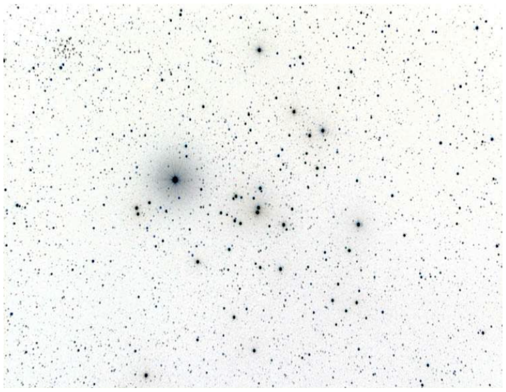
Very few stars are born isolated. Instead, most stars form in small groups, known as clusters. The stars in a cluster form when a single cloud of cold gas collapses to form many individual stars with a wide range of masses. Because all the cluster stars form from the same gas cloud, they all have a common age and distance. As you will see in this project, the common age and distance of their stars make stellar clusters particularly useful for studies of the ages and luminosities of stars.

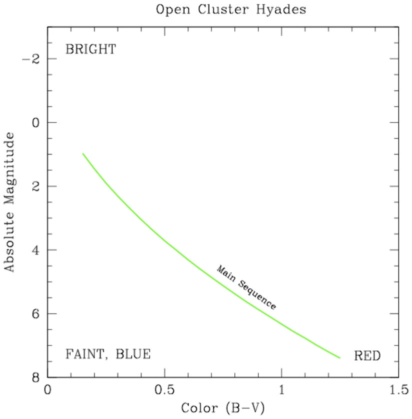
There are two classes of clusters. The first are known as “globular clusters”. Globular clusters are very dense, and can host millions of stars in the space of only a few parsecs. The majority of the globular clusters in the Milky Way are very old. Thus, they have few massive main sequence stars, and a large population of red giant branch stars, as can be seen in the schematic H-R diagram below.





The second class of clusters are “open clusters”. These clusters are more diffuse than globular clusters, and have only hundreds or thousands of stars. Open clusters are easily destroyed, and thus the majority of open clusters are young. The figure below shows the nearest open cluster, the “Hyades”, along with a schematic H-R diagram showing the location of the main sequence of this young cluster. Compared with the globular cluster 47 Tuc above, there are many more young main sequence stars, and no significant population of old red giants.





In this project you will use actual data to show how clusters can be used to measure the relative distances and ages of stars in the cluster.

Getting Used to Stellar Data

For this project, you will be using “H-R” (or equivalently, “Hertzsprung-Russell”) diagrams to observe the temperature and brightness of stars in several globular and open clusters. As you have seen in class, the H-R diagram plots temperature along the horizontal x-axis, and luminosity on the vertical axis. Unfortunately, it is relatively complicated to derive accurate temperatures and luminosities for large numbers of stars. Instead, astronomers use the equivalent “color-magnitude” diagram, which is much easier to construct. In a color-magnitude diagram, the astronomical “color” (which is sensitive to temperature) is plotted along the x-axis, and the apparent or absolute magnitude is plotted along the y-axis.

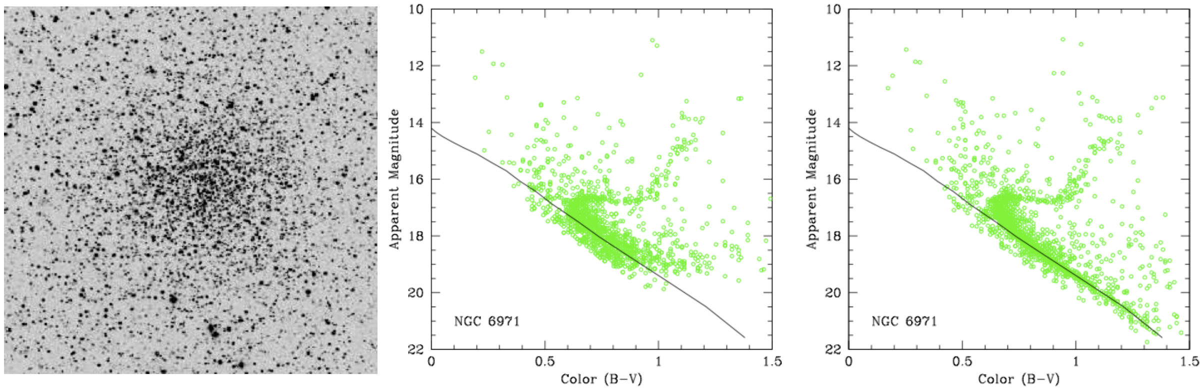
For historical reasons, color-magnitude and H-R diagrams obey a few rules:

- Brighter stars are found towards the top of the plot.
- If apparent or absolute magnitudes are used to measure the brightness, then smaller numbers will be at the top of the plot. Remember that the magnitude system is “backwards”, such that brighter objects have smaller magnitudes.
- Redder colors and cooler temperatures are found towards the right side of the plot
- Astronomers derive a numerical value for a star’s color by measuring the difference between a star’s apparent magnitude when it is viewed through a blue filter and then through a redder filter. With this system, larger numbers for the color indicate redder colors and lower temperatures.

The data in this project uses the blue “B” filter and greenish-yellow “V” filter to measure a color referred to as “B-V”.

The plots below show actual data for stars in an old stellar cluster named “NGC 6791”. The left hand figure shows an image of the cluster. The two right hand figures show the color-magnitude diagrams that result from two different observations of the same cluster. Superimposed on each diagram is a diagonal line that indicates where main sequence stars should lie.

Different Observations of the Same Cluster (NGC 6791)



As you can see, the real color-magnitude diagram looks different from the schematic diagrams shown on the first page. Most notably, not every star lies exactly along a well-defined locus[1]. There are two main reasons for this. First, there are many stars in the diagram that are not actually located in the cluster. They are foreground and background stars in the Milky Way, that just happen to lie along the line of sight to the cluster. Second, the brightnesses and colors of the stars are not measured perfectly, and thus there is some "scatter" of stars away from the true locus you would have seen if you had had perfect measurements. The scatter due to measurement errors tends to decrease for brighter stars, since their colors and brightnesses can be measured more accurately than for faint stars. Third, stars are not plotted all the way to the bottom of the graph, since not every observation can detect the very faintest stars. Thus, some observations (like the one in the middle) are missing data on faint stars that are visible in much longer exposures on larger telescopes (like the observations on the right, for the same cluster).

Even with the limitations above, however, you should be able to see that the majority of the stars lie on a well-defined locus. For this cluster, you can see:

1. *A main sequence, which roughly follows the solid diagonal line*: This sequence contains only stars that are fusing Hydrogen into Helium in their cores.

2. *A red giant branch, to the upper right of the main sequence:* This sequence includes stars that are reaching the end of their lifetimes. They have evolved off the main sequence as they've run out of Hydrogen in their cores.

3. *Turn-off stars:* These stars are the brightest stars still remaining on the main sequence. They are slightly more massive than the most massive stars that are still burning Hydrogen in their cores. Thus, these stars are in the process of "turning off" the main sequence.

In the following two sections you will use these features to derive the relative distances and ages of several clusters. First, you will measure the relative distances of two different globular clusters using the relative brightnesses of their main sequence stars. Since all main sequence stars have similar luminosities regardless of which cluster they're in, differences in the apparent brightnesses of the main sequence will indicate which cluster is more distant. Second, you will derive the ages of several different open clusters by identifying the mass of their turn-off stars. There is a unique relationship between the mass of a star and the duration of the time it spends on the main sequence. Thus, you can derive the age of a cluster from the mass of the turn-off stars that are just now leaving the main sequence.

---

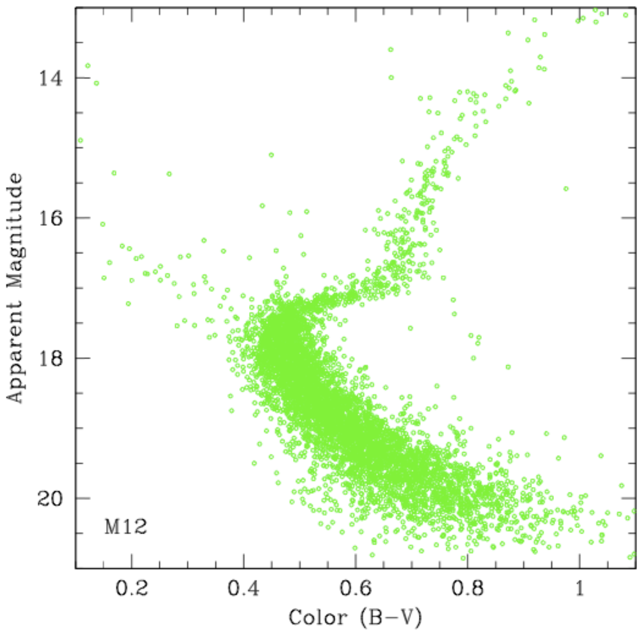
[1] "Locus" refers in this case to the curve which most of the points follow

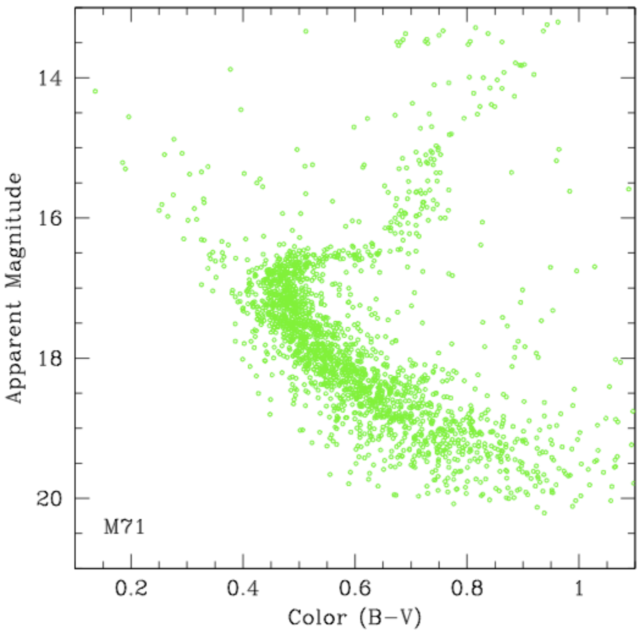
The Relative Distances of Clusters

Measuring distances is critical for deriving the luminosity of a star. Unfortunately, it is extremely difficult to judge the distance to an individual star, particularly for stars that are far enough away that they do not exhibit a measurable parallax shift. A distant red giant can appear to be identical to a faint, cool main sequence star nearby. Both will have the colors and spectra of M-stars, in spite of their very different luminosities and distances. Measuring distances for isolated stars is therefore challenging.

It is far simpler to measure distances to stars that happen to form within a cluster. Main sequence stars can be easily identified from the cluster's color-magnitude diagram, removing the ambiguity between red giants and cool main sequence stars. By assuming that the main sequence stars in the cluster have the same intrinsic luminosity as other main sequence stars whose luminosities are known, one can derive the distance to the cluster. Any difference in the apparent brightness of the main sequence stars be due solely to differences in distance.

The plots below show the color-magnitude diagrams of stars in two different globular clusters. The one on the left is the globular cluster M12, and the one on the right is the globular cluster M71. These two clusters have similar ages, yet their main sequences are shifted with respect to each other. This offset occurs because all the stars in one cluster are much further than the stars in the other cluster. Thus, main sequence stars of the same mass appear fainter in the more distant cluster. However, because the stars in these two clusters are otherwise similar, you can assume that the stars in one cluster's main sequence are just as luminous as stars of similar colors in the other cluster.





Distance Questions

1. In which cluster does the main sequence appear brighter, for stars of a fixed color? [M12/M71]

2. Which cluster is more distant? [M12/M71]

3. Use a ruler to draw a line through the main sequence stars in each cluster. Do your best to keep the slope (i.e. the angle) of your line the same in each diagram. Try to aim your line through the center of the sequence rather than along the upper or lower edge.

4. Using your line as a guide, estimate the apparent magnitude of main sequence stars with colors of B – V = 0.5, 0.6, &0.7, and enter your answers in the table below.

Color	Apparent Magnitude of Main Sequence		Difference in
$(B-V)$	M12	M71	Magnitudes
0.5			
0.6			
0.7			

5. Using the results in your table, what is the average difference in the apparent magnitudes of stars with similar B – V colors in each cluster?

Main sequence stars in __________ [M12/M71] are ___________ magnitudes fainter than the main sequence stars in the nearer cluster.

6. Using the difference in apparent magnitudes, how many times fainter is the luminosity of the stars in the more distant cluster with respect to the nearer one?

The stars in ________ [M12/M71] appear to be _____________ times fainter than the stars in the nearer cluster.

7. Using this result compute how many times more distant is one cluster with respect to the other.

The stars in ___________ [M12/M71] are ____________ times further away than the stars in the nearer cluster.

8. Your work above demonstrated how to derive the relative distance between two clusters. However, you did not derive an absolute distance to either cluster (i.e. in parsecs). Assuming that you have a large sample of nearby main sequence stars with well measured colors, apparent brightnesses and distances, describe how you could use your data on nearby stars to derive the true distance to one of the clusters. Please give a clear numbered list of the steps you would take, starting with:

    a) Calculate the luminosities of the nearby main sequence stars from their measured apparent brightness and distance.
    b) ...

The Ages of Clusters

To understand how stars evolve and change throughout their lifetimes, it is critical to know the properties of stars of different ages. Unfortunately, it is extremely difficult to determine the age of any random star. An old 1$M_\odot$ main sequence star looks nearly identical to a young 1 $M_\odot$ main sequence star, making it difficult to distinguish between them even if one is many gigayears older than the other.

While it is difficult to measure the age of an individual star, it is relatively straightforward to measure the ages of a cluster of stars. If all of the stars in a cluster were born at the same time, then they share a common age. Thus, if the age of just one of the stars can be determined, then the age of all the stars will be known.

Fortunately, there is one class of stars for which it is quite easy to determine an age. Stars that have just used up the Hydrogen in their cores will begin to brighten, and will pull off the main sequence to higher luminosities. These stars are known as “turnoff” stars, because they are in the process of turning off the main sequence. Stars of different masses leave the main sequence at different times, because the main sequence lifetime of a star depends sensitively on the mass of the star. Thus, for a cluster of stars with similar ages, stars of only one particular mass will have just the right lifetime to be leaving the main sequence at the time the cluster is observed. Stars that are more massive than the “turnoff mass” will have already evolved into red giants or supergiants, and stars that are less massive will still be sitting comfortably on the main sequence.

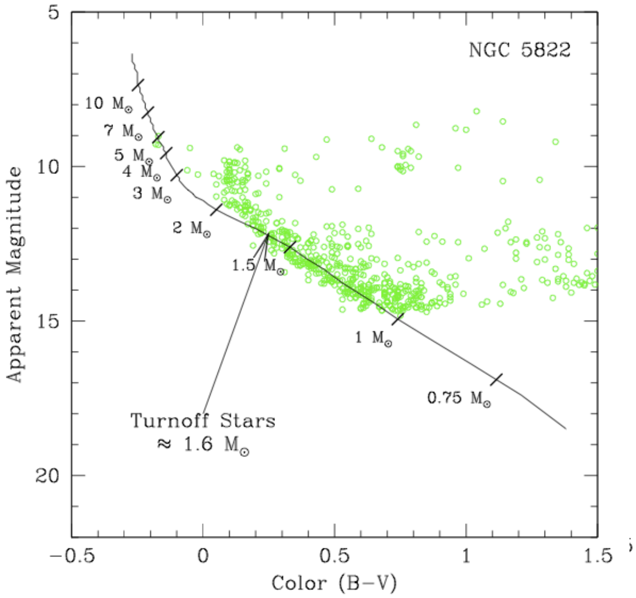
To find the age of stars in a cluster, one therefore must identify the turn-off stars, and then estimate their masses. Identifying the turnoff stars is relatively straightforward. If one can find the main sequence stars in a cluster, the turnoff stars will be those that are just a bit brighter than the brightest stars that still lie firmly on the main sequence. To find the masses of the turnoff stars, one can use the fact that main sequence stars of a particular mass always have a particular temperature, and thus appear to have a particular color. Therefore, by measuring the color of the stars that are just now leaving the main sequence, one can estimate the mass of the turnoff stars. Since we know how long stars of any mass can live on the main sequence, we can therefore calculate how old the stars in a cluster might be.

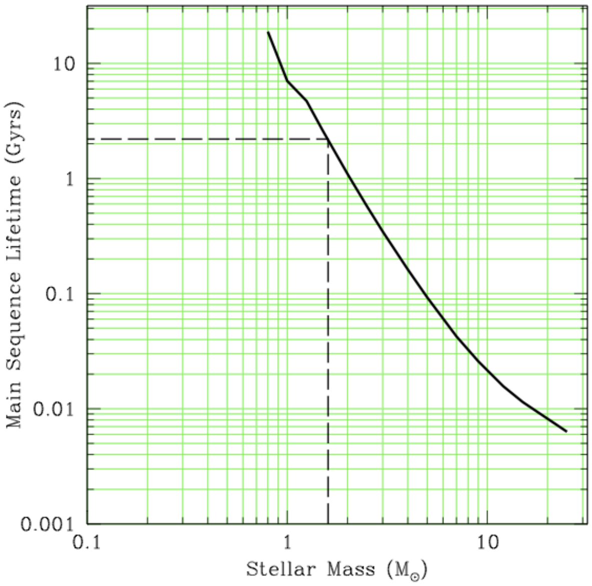
For example, suppose the turnoff stars in a cluster had the color of an A-star, which has a mass of 2 solar masses. A 2 solar mass star lives on the main sequence for roughly 1 Gyr and thus the cluster must be around 1 Gyr old. If the cluster were younger than 1 Gyr, then there would still be stars more massive than 2 $M_\odot$ living on the main sequence. If the cluster were older, then all 2 $M_\odot$ stars would have already used up the Hydrogen in their cores and evolved far from the main sequence.

Procedure

At the end of this text are color-magnitude diagrams for four open clusters of different ages. Superimposed on each plot is a diagonal line showing where main sequence stars lie. The tick marks along the line indicate where main sequence stars of different masses lie. You will identify the turnoff stars in each diagram, and use the main sequence locus to estimate the mass of the turnoff stars. You will then use the lifetimes of the turnoff stars to estimate the ages of the clusters.

As an example, below is the color-magnitude diagram for the young open cluster NGC 5822. On the diagram, an arrow points to the location of the turnoff stars. These stars must have a mass of ~1.6M⊙, based on comparing the location of the arrow to the tick marks on the diagonal line that indicates where main sequence stars of different masses lie. Note that while the turnoff stars don't lie exactly at a tick mark, you can estimate the mass from the adjacent tick marks. In this case, the turnoff stars are much closer to the tickmark at 1.5 M⊙ than to the tickmark at 2.0M⊙, so we estimate a mass of ~1.6M⊙. The lifetime of the stars of this mass can be estimated from the plot on the right, which shows a logarithmic plot of a star's mass versus its main sequence lifetime. The dashed line shows that a star with a mass of ~1.6M⊙ has a lifetime of ~2 Gyr. Thus, NGC 5822 is probably around 2 Gyr old.





1. In each cluster, identify the brightest stars that are still on the main sequence. Draw a circle around these, which are the turnoff stars.

2. Comparing the location of the turnoff stars to the main sequence locus in the plot, estimate the masses of the turnoff stars. Record your answers in the table below.

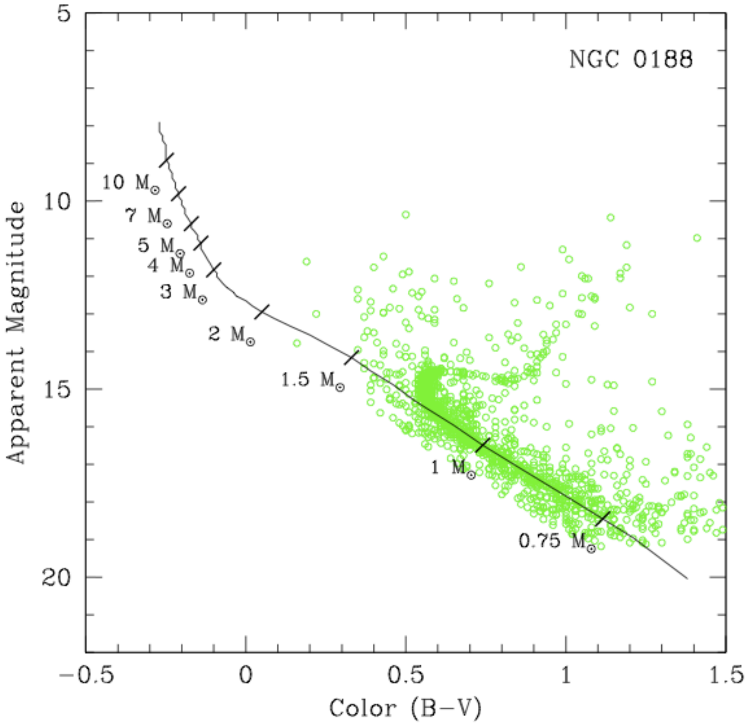
3. Use the plot on the previous page of the main sequence lifetimes of stars as a function of their mass to estimate the ages of the clusters. Please record your answers in the table below.

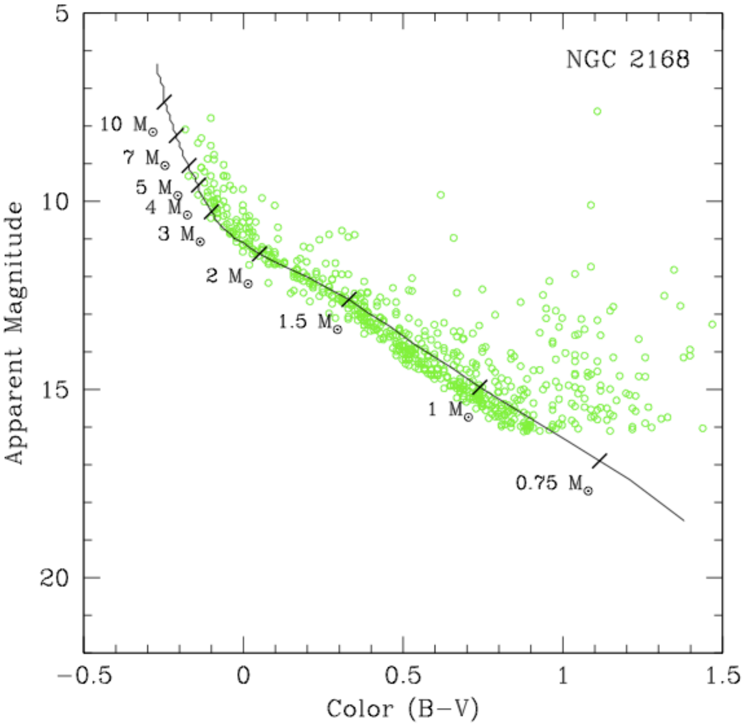
Cluster	Mass of Turnoff Stars	Age
NGC 0188		
NGC 2168		
NGC 2682		
NGC 5822	$1.6\,M_\odot$	2 Gyr
NGC 6791		

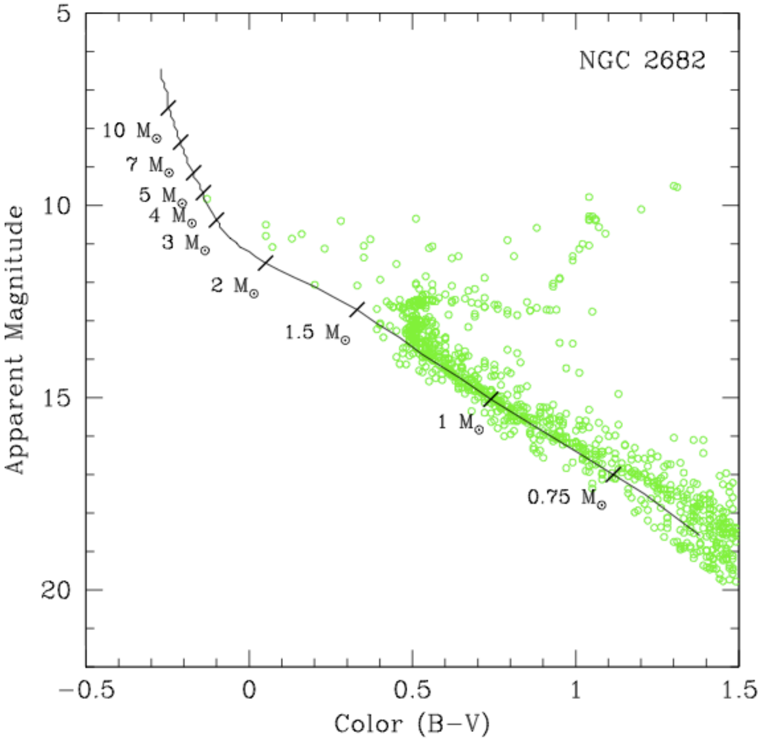
Age Questions

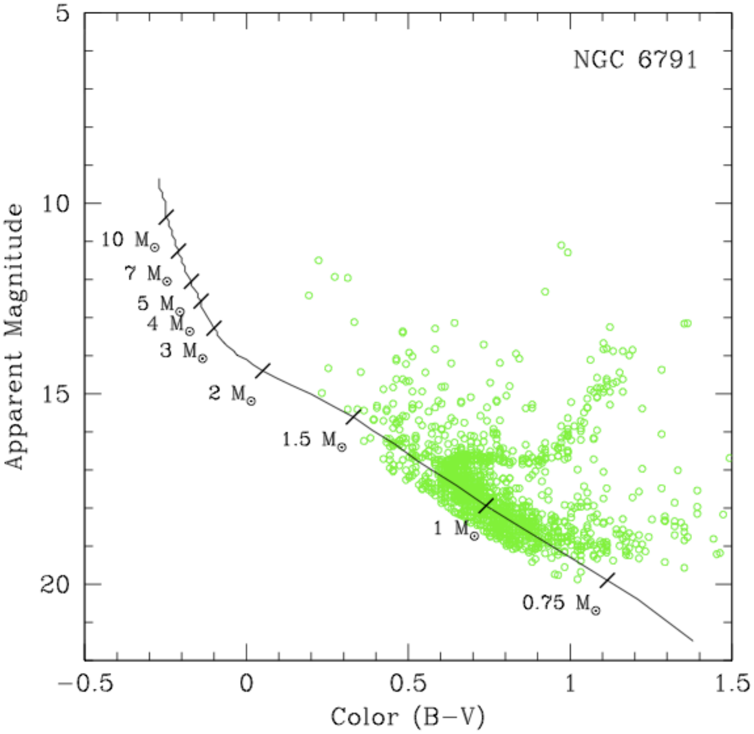
8. Stars with masses between $1.25M_\odot$ and $1.5M_\odot$ take less than a Gigayear to reach the top of the red giant branch after consuming the Hydrogen in their cores. For the cluster NGC 6791, do you think that the stars currently on the red giant branch were originally 5 $M_\odot$ main sequence stars or 1.5 $M_\odot$ main sequence stars? [1.5 $M_\odot$/5 $M_\odot$] Please explain your reasoning.

9. Are the open clusters all at the same distance? _________ [Yes/No]. Please explain your reasoning.


NGC 0188
Apparent Magnitude
Color (B−V)
5
10
15
20
−0.5
0
0.5
1
1.5
10 M⊙
7 M⊙
5 M⊙
4 M⊙
3 M⊙
2 M⊙
1.5 M⊙
1 M⊙
0.75 M⊙


NGC 2168
Apparent Magnitude
Color (B−V)
5
10
15
20
−0.5
0
0.5
1
1.5
10 M⊙
7 M⊙
5 M⊙
4 M⊙
3 M⊙
2 M⊙
1.5 M⊙
1 M⊙
0.75 M⊙


NGC 2682
Apparent Magnitude
Color (B−V)
5
10
15
20
−0.5
0
0.5
1
1.5
10 M⊙
7 M⊙
5 M⊙
4 M⊙
3 M⊙
2 M⊙
1.5 M⊙
1 M⊙
0.75 M⊙


NGC 6791
Apparent Magnitude
Color (B−V)
5
10
15
20
−0.5
0
0.5
1
1.5
10 M⊙
7 M⊙
5 M⊙
4 M⊙
3 M⊙
2 M⊙
1.5 M⊙
1 M⊙
0.75 M⊙