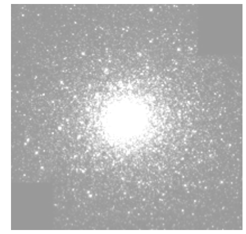
Name ____ Section ____________

Application Exercise: Determining Ages of Star Clusters Using Color Magnitude Diagrams



- ➢ The tutorial "Determining Cluster Ages Using CMDs" is a prerequisite for this exercise.

Learning Goals

- ❖Describe what is meant by a color-magnitude diagram (CMD).
- ❖List the information that can be inferred from a CMD.
- ❖Itemize the assumptions made when working with a CMD.
- ❖Qualitatively state the relationship between the color of a main-sequence star and its main-sequence lifetime.
- ❖Explain the fundamental basis for determining the age of a cluster given the cluster's "turn-off" B – V.
- ❖Determine cluster ages using their color-magnitude diagrams.
- ❖Summarize the complete process of how astronomers estimate the ages of star clusters.

Introduction

<u>Importance of determining the ages of star clusters</u>

Clusters are groupings of stars that were all born at roughly the same time. When we speak of the age of a cluster, we are equivalently asking the ages of the stars.

So why do we care how old clusters are? The age of a cluster can provide clues to the formation of galaxies and therefore the Universe. For example, stars in globular clusters appear to be the oldest in our galaxy. We can then infer that globular clusters were some of the first structures to evolve during the formation of our galaxy.

<u>Effect of cluster distance</u>

If one star in the sky looks brighter than another, can we say that star is more luminous?

When we look up to the sky at night, we see stars of varying brightness; that is, their **apparent magnitudes** are different. This difference is caused in part by the varying luminosities of the stars. But it could also be caused by the distance the star is from Earth. For example, the Sun appears brighter to us than Vega, but Vega is more than 50 times as luminous. Thus, we usually cannot use apparent magnitude of a star as an estimate of its luminosity.

In a cluster of stars, however, we *can* use the *apparent* magnitude of its constituent stars as a relative measure of their luminosities. Since a cluster is localized to one relatively small volume of space, all of the stars within a cluster are roughly at the same distance from Earth. Because the stars are at roughly the same distance, differences in apparent magnitudes are due only to differences in the stars' luminosities.

Clusters are three-dimensional objects, so there will still be *some* difference in distance between Earth and the individual stars in a cluster. However, since a cluster is localized to one (relatively) small volume of space, the differences in the distances to the stars is negligible. The following illustration, which is totally not to scale, may help.

To stress this point further, the apparent magnitudes of stars within a single cluster can be used to compare luminosities among those stars: The lower the apparent magnitude number of a star in a certain cluster, the greater the luminosity compared to all of the other stars. This is due to the fact that **the distance between individual stars in a cluster is much, much less than the distance the cluster is from Earth.** The distance between the front and back edges of the cluster simply does not significantly affect the apparent magnitudes of the stars of a cluster, making the differences in the luminosities of the stars the overriding cause of the different apparent magnitudes. If a star in a cluster *appears* brighter to us compared to another star in the same cluster, then the brighter star must have a higher luminosity.

Figure 1

Finding the turn-off color-index of a star cluster

We are finally ready to turn to the object of interest: color-magnitude diagrams, or CMDs for short. A CMD, such as the one to the right, is a plot of all of the stars in a cluster, but with a very specific set of axes. Along the horizontal axis is the color-index of each star, and along the vertical axis is the apparent magnitude of each star. Note that the vertical axis is reversed: the values for apparent magnitude get smaller as you go up. Pause a moment to look at the CMD to make sure you note each of these features.

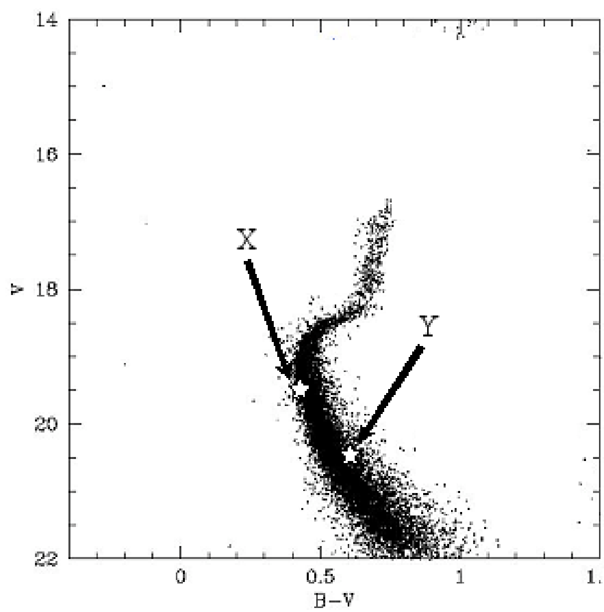


Figure 2

Every point on a CMD represents exactly one star. We can read off a star's B – V value by extending an imaginary vertical line down from the star to the horizontal axis. We can read off a star's apparent magnitude by extending an imaginary horizontal line left from the star toward the vertical axis.

For practice (be sure to check your results with your instructor to make sure you got them right):

A. Using the CMD in figure 2, estimate the B – V values of stars X and Y. Star X: ______ Star Y: ______

B. Which star is more luminous? ______

C. Assuming both X and Y are on the main sequence and were born at the same time, which star will leave the main sequence first? ______ Explain your answer.

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It's possible to visually identify the main sequence stars on a color-magnitude diagram. They lie within the long, relatively straight patch of stars that extends from the bottom right toward the top left of the CMD. Make sure this agrees with the labeled "Main sequence" on the CMD to the right (Fig. 3), where we've drawn a heavy dashed line to represent the lower edge of the main sequence.

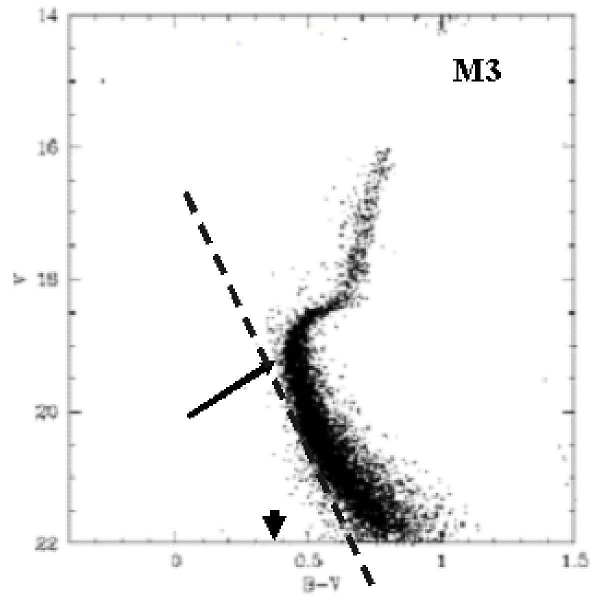

Figure 3

D. Put a <u>box</u> around the main sequence on the CMD to the right (this is meant to be easy). Put a <u>diamond</u> around the group of stars that have left the main sequence and thus are no longer "on it."

The stars you put a diamond around have run out of hydrogen fuel in their cores. That is, they have spent their lifetime on the main sequence and, in astronomer-speak, have "left it." The transition region between stars on the main sequence and those that are already off the main sequence is of importance to us. It is called the **turn-off point** or turn-off region. (The location of this point will vary from cluster to cluster, and will allow us to eventually determine the age of clusters.)

E. <u>Circle</u> the small region on the CMD shown in Fig. 3 above where stars are just beginning to "peel away" from the main sequence. This should lie close to the "turn-off point" label. The B – V value corresponding to this turn-off point is called the **B – V turn-off point.** What is the B – V turn-off point for this cluster? (You should come somewhere close to the arrow along the B – V axis.)

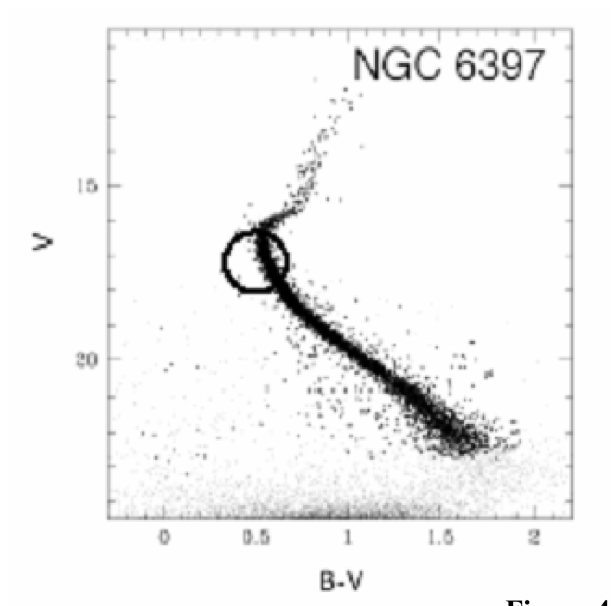

Figure 4

F. The approximate turn-off point for a different cluster, NGC 6397 (Fig. 4, shown to the right) has been circled for you. Draw a <u>diagonal line</u> that represents the lower edge of the main sequence stars. Estimate the B – V value for the turn-off point for this cluster: B – V = ______

You should now have a good idea of what a CMD plots and how to determine the B – V turn-off point. Be sure to let your instructor know if you are still a bit confused about this process. This method is something that many astronomers do in their careers today.

Procedure

<u>I. Estimating the ages of clusters</u>

Let us re-focus our attention to individual stars for a moment, instead of entire clusters. Thus far, we have been very *qualitative* in our descriptions; we know only that main sequence stars with a lower B – V value will spend less time on the main sequence. There is, however, a *quantitative* relationship between these two quantities (see Table 1 on the next page).

Table 1

Color-Index (B-V)	-0.4	-0.2	0.2	0.5	0.7	1.0	1.6
Main Sequence Lifetime (years)	$< 10^6$	3×10^7	4×10^8	4×10^9	1×10^{10}	6×10^{10}	$> 10^{11}$

Take a look at the main sequence lifetime for a star of color-index -0.2. The stated lifetime, 3×10^7 years, is the **time it will take a star, from when it first starts fusing hydrogen to helium in its core, to leave the main sequence.** Thus, if a star of color-index -0.2 started its fusion this morning, it will leave the main sequence in 3×10^7 = 30,000,000 = 30 million years. If a star of color-index -0.2 started its fusion 10 million years ago, it would leave the main sequence in 20 million years. If the star started its fusion 30 million years ago, it would just now be leaving the main sequence. (Of course, these are just approximate numbers!)

01. <1> An astronomer measures the visual magnitude of a main sequence star called Keid (located in the southern constellation of Eridanus) through a blue filter to be 5.4 and the corresponding visual apparent magnitude value to be 4.4. Once its core fusion starts , how long would it take Keid to leave the main sequence? ________________

02. <1> The same astronomer measures the color-index of a different star, Altair (located in the northern constellation of Aquila), to be 0.2. This astronomer knows that Altair is about 3×10^8 = 300,000,000 years old. Approximately how many years from now will the star leave the main sequence? ______________

It must be stressed that the listed main sequence lifetimes in the table above are not the current age of the main sequence star. Rather, they are the life expectancy of the star for remaining on the main sequence, regardless of how old the star actually is now. If humans were like stars, every person on Earth would have a lifetime expectancy "written" on them. This lifetime expectancy would not change, regardless of how old the person was. Likewise, the lifetime of a main-sequence star can be estimated from its B – V value.

There is one important property of clusters that allows us to determine the age of the cluster: **All of the stars in a given cluster were born at the same time.** This is due to the fact that stars in a cluster were formed from the same giant gas cloud that collapsed and condensed into stars at the same time.* So all of the stars in a cluster are of the same age. If we could determine the age of just *one* of the stars in that cluster, we would know how old *all* of the stars are. Therefore, we could *determine the age of a cluster if we just knew the age of one star. That star needs to be at or close to the turn-off point of the main sequence.*

03. <3> Keeping this in mind, take a look at the stars at the turn-off point in NGC 6397, reproduced to the right. Above, for Fig. 4, you estimated the B – V turn-off and should have gotten roughly 0.5.

- **a.** According to Table 1 above, how long do stars of B – V = 0.5 live on the main sequence? ________
- **b.** Are the stars at the turn-off point leaving the main sequence?_______
- **c.** Using this information, how old are the stars at the turnoff point?__________
- **d.** How old are all of the stars in this cluster?__________
- **e.** How old is NGC 6397?__________

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* We also assume that the stars all have the same composition. This leaves only the differences in masses that leads to the differences in stars as plotted on a CMD.

That's it. You have just determined the age of NGC 6397 using only one bit of information: the B – V value of the turn-off point.

04. <4> In your own words, list four of the steps that allow us to determine the age of a star cluster.

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II. Following ONE cluster through time

Stars within a cluster get older, just as everything else in the Universe does. If we are to believe that the B – V turn-off point can tell us the age of a cluster, then the B – V of the turn-off of a given cluster must change through time.

05. <1> You probably determined above that the age of NGC 6397 was around 4 billion years. In 6 billion years, the age of the cluster will be 10 billion = 1×10^{10} years old. What will the B – V turn-off value be for NGC 6397 in 6 billion years? __________

06. <2> Generalize your result from question 5: Suppose we you were able to witness the entire evolution of a cluster of birth. Describe how the B – V turn-off would change as time progressed.

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07. <2> Examine the four "simulated" CMDs that are shown on the next page. These CMDs all represent the **same cluster** of stars, but at different ages. (We would have to observe this cluster for billions of years in order to get the data to produce these CMDs. This, obviously, is impossible as humans live for only ~100 years, the high-tech astronomy we use today is less than 50 years old, while the age of the Universe and thus the oldest clusters would be around 13 billion years). Circle the turn-off point and measure the B – V turn-off value of each "snapshot in time" of the cluster. Rank the plots of the CMDs in terms of age of the cluster when the data was taken, from when the cluster was the youngest to when it was the oldest.

Cluster is youngest ________ ________ ________ ________ Oldest

Explain the logic you used.

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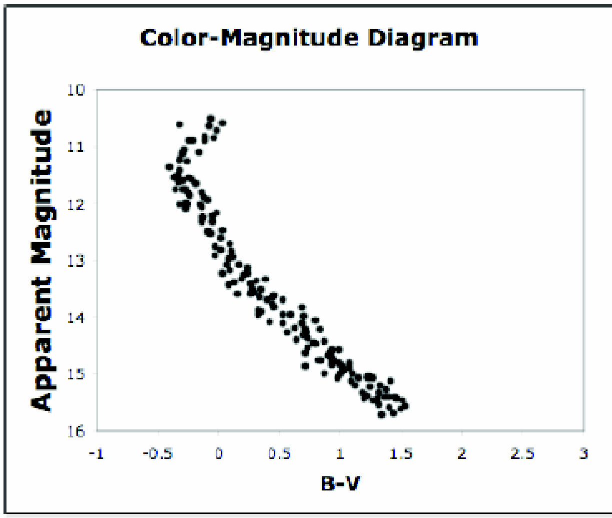

Figure A

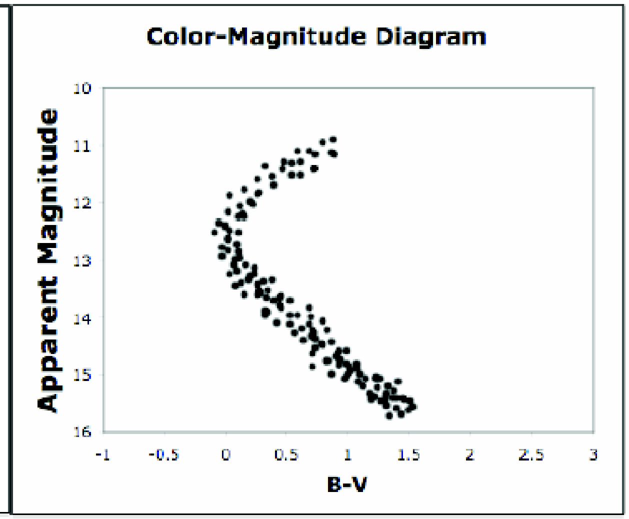

Figure B

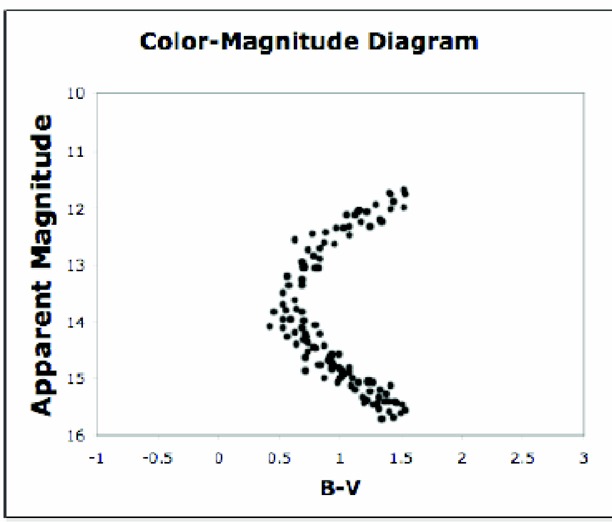

Figure C

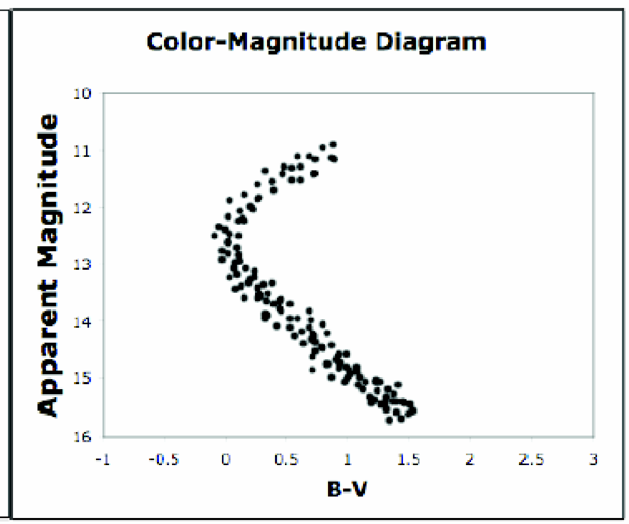

Figure D

08. <2> Instead of the four CMDs representing the same cluster as observed at different ages, suppose they are representing different clusters that we observed all last night. That is, these CMDs were plotted yesterday, and all are of different clusters in our galaxy. Rank the CMDs in terms of the ages of the different clusters shown, from youngest to oldest: Youngest cluster _______ ________ ________ ________ Oldest

Explain the logic you used.

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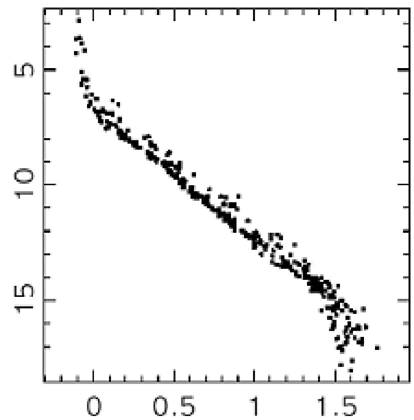
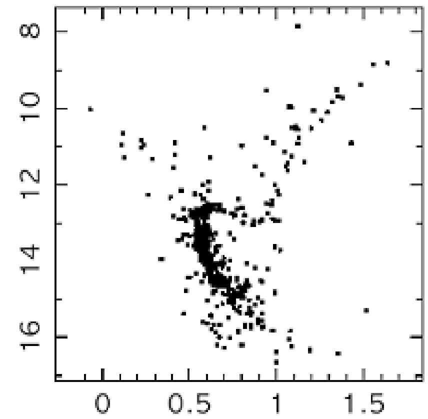
09. <2> Determine the B – V value of the turn-off (TO) and the age of each of the following open clusters.

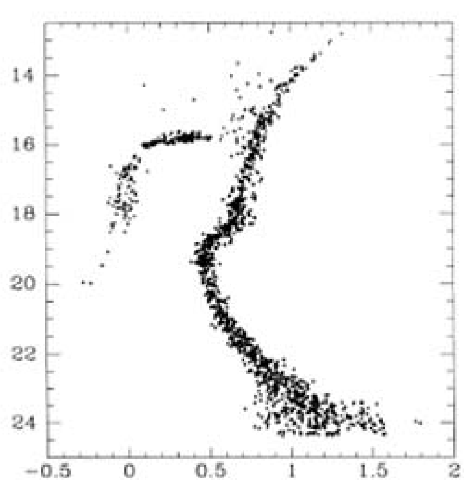


TO _____ Pleiades age: __________________

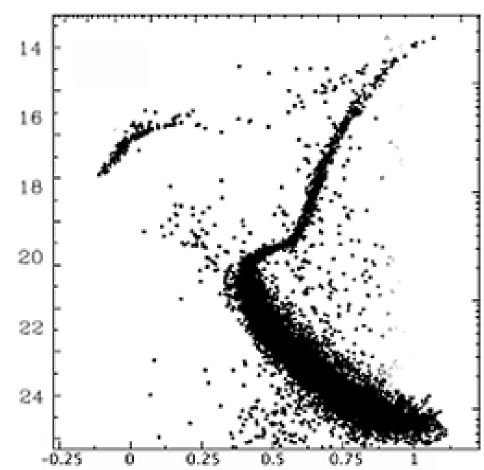


TO _____ M 67 age: _________________

10. <2> Determine the B – V value of the turn-off and the age of each of the following globular clusters.



TO _____ M 15 age: __________________



TO _____ M 55 age: _________________

11. <5> In your own words, explain why a color-magnitude diagram allows us to determine the age of a cluster. This should not be a step-by-step how-to (as in question 4). Rather, your response should incorporate ideas such as distance, luminosity, lifetime of stars, how clusters are formed, and similar concepts.

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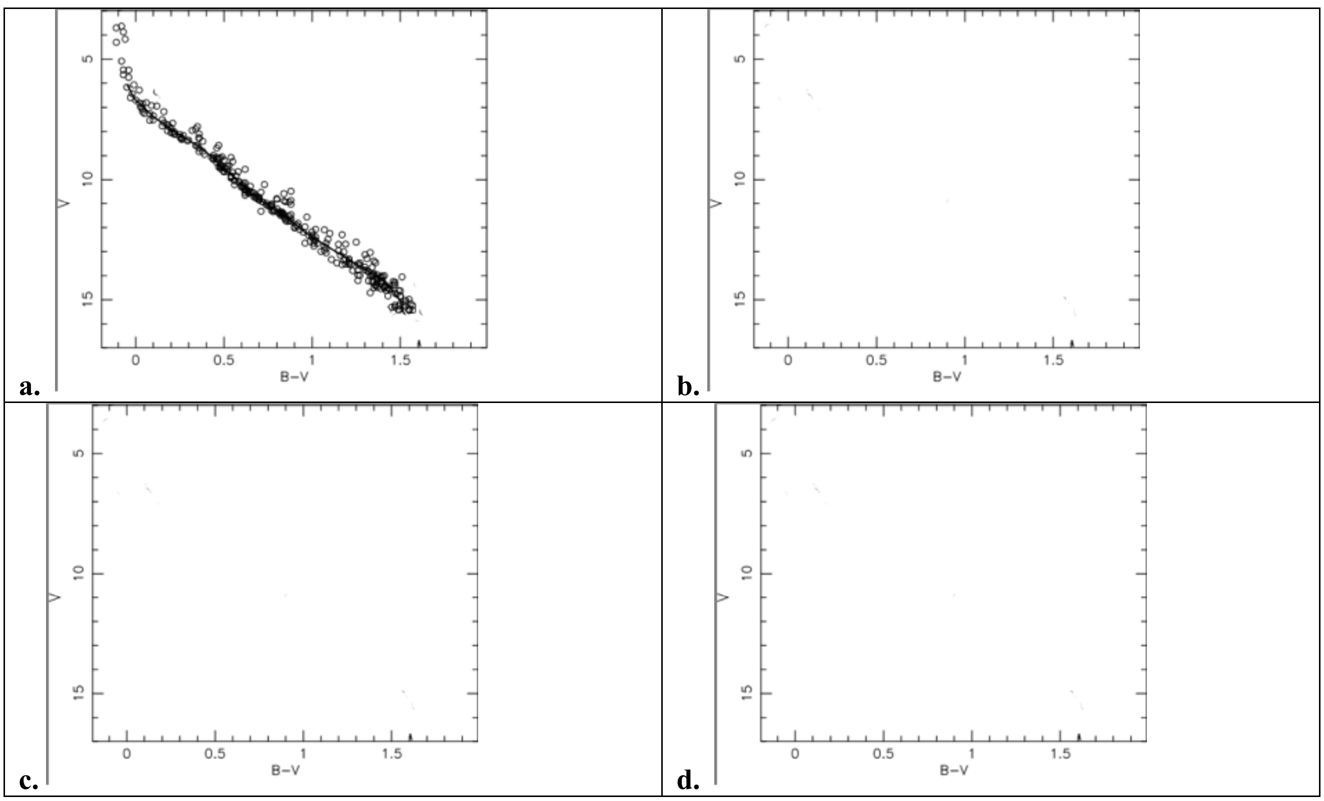
Critical Thinking

12. <2> In the footnote on page 5, we bring up the fact that it is the differences in the masses of the stars that are the primary reason that the main sequence stars in star clusters are at different apparent magnitudes and colors (B – V) on a CMD. For stars on the main sequence, what role does mass play in the life expectancy?

13. <3> Let's assume we are in a different universe where main-sequence stars that are the dimmest and have the largest B – V numbers actually have the shortest life expectancies, and those stars that are the brightest and have the smallest B – V numbers have the longest life expectancies. In the Fig. 6a below, we show the cluster with all of its stars still on the main sequence. For Fig. 6b - d, assuming that these stars get brighter and cooler as they age, plot how that cluster's CMD would look after, say, 1 billion years went by; then, 5 billion years; then, 10 billion years.



How might the data in Table 1 above be changed in this new universe?