Your Name: Credit: based on an Ana Larson lab

Homework 4 (AST1002)
The rotation of the Sun (and galaxy clusters)

Taking Data (/3):

Reducing Data (/6):

Analysis (/9):

Significant Figures (/1):

Units (/1):

Total (/20):

Introduction

This activity returns us to Galileo's discovery that the motion of sunspots strongly implies that the Sun rotates. He extended that observation to include the Earth: If the Sun rotates, then why not Earth? With a rotating Earth, there was a logical explanation for the rising and setting of the stars, and another nail was put into the coffin of a geocentric universe.

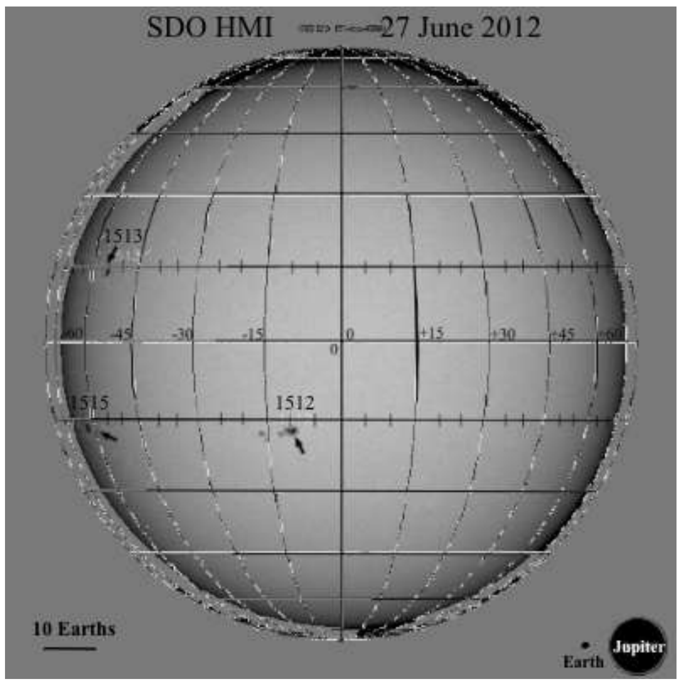
You will measure the apparent longitude of sunspots over a period of nine days, and then use this information to estimate the rotational period of the Sun.

You will learn:

- The best ways of combining data to get a measurement.
- How to use estimated errors to compare measurements.

Taking Data

We have provided a series of nine images of the Sun taken by the Solar Dynamics Observatory (SDO) using its Helioseismic and Magnetic Imager (HMI) instrument. The images were taken approximately 24 hours apart, except that we don't have an image for July 1st. This is the first image in this series.



Three sunspot groups (1512, 1513, and 1515) are present on the western hemisphere of the Sun. We've already measured their apparent longitudes using the overlaid grid (see table on next page). This grid is not "attached" to the Sun's surface as are the latitude and longitude lines on Earth, but rather is relative to our view of the Sun at that moment. However, both the grid and our view, are aligned with the Sun's rotation

1. Using the attached images, track these sunspots over as many days as possible, and enter their apparent longitudes into the table on the next page. If the longitude of a particular sunspot group is particularly difficult to estimate, put an asterisk by that number—you may want to avoid using that measurement later! *(3 points)*

Reducing Your Data

2. You'll calculate the number of degrees each sunspot group moves each day. To be more accurate we'll average three independent measurements. First choose three intervals for each sunspot (you can fill those in on the tables below). There are certainly several factors to weigh in choosing each date. In a sentence or two, explain which factors guided you to choose the dates you did. *(2 points for a clear explanation of why you chose them)*

Taking Data

Sunspot Group	Apparent Longitude								
	June 27	June 28	June 29	June 30	July 2	July 3	July 4	July 5	July 6
1512	-10								
1513	-55								
1515	-65								

Reducing Your Data

Group 1512	Beginning date	Ending date	Days between observations	Degrees per day
Interval #1				
Interval #2				
Interval #3				
Average degrees per day:				

Group 1513	Beginning date	Ending date	Days between observations	Degrees per day
Interval #1				
Interval #2				
Interval #3				
Average degrees per day:				

Group 1515	Beginning date	Ending date	Days between observations	Degrees per day
Interval #1				
Interval #2				
Interval #3				
Average degrees per day:				

Reducing Your Data (continued)

3. For each group, calculate the degrees the sunspot moved each day (remember that we're missing July 1st!). Then average the three numbers you just calculated to get (hopefully) a more accurate measurement of degrees moved each day. *(2 points)*

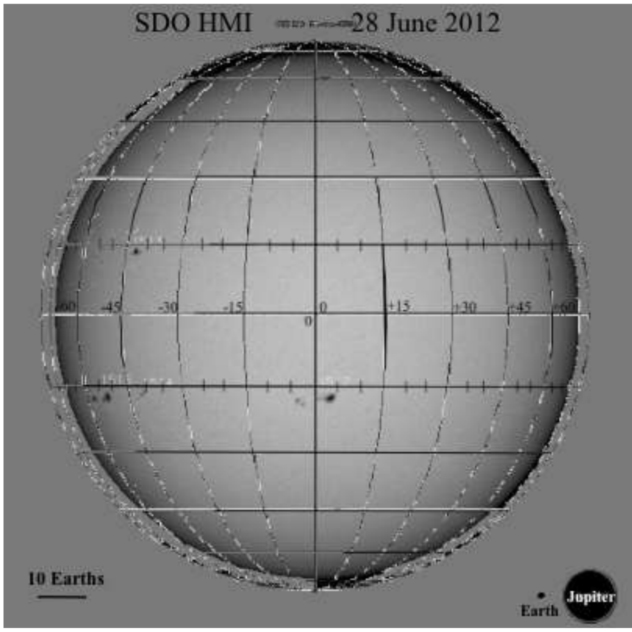
4. In physics class I learned how to propagate errors in a calculation, but in astronomy I learned how to estimate your error from the data itself. This can be useful to avoid just guessing! We'll do this by comparing two things that should be the same. Sunspot groups 1512 and 1515 lie at the same latitude on the Sun, they should have the same speed. Compare how many degrees sunspot groups 1512 and 1515 move each day. Since they probably actually move at the same rate, use any difference to estimate you're the error in your measurements. What is your error? *(2 points)*

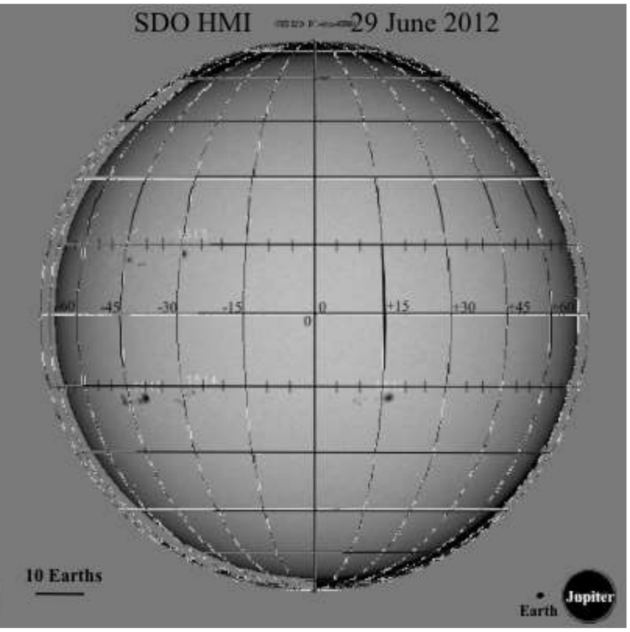
Analysis

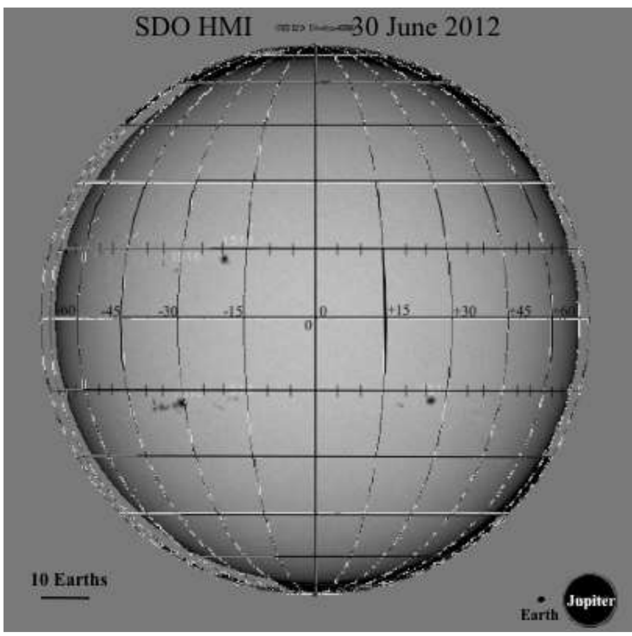
5. Using your results above, how long it takes the Sun to rotate one full turn? *(3 points)*

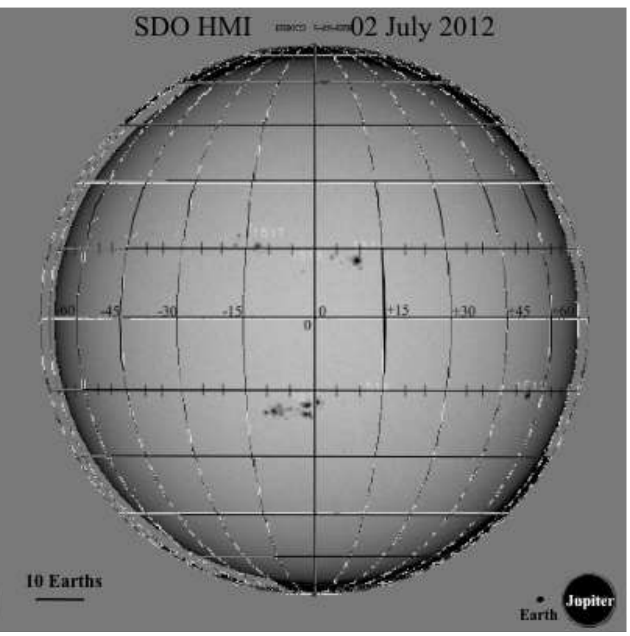
6. Unlike the Earth, the Sun is a ball of iridescent gas. As such, it doesn't have to turn as a single unit. Does your data show any evidence if differential rotation (different speeds at different latitudes)? Write a clear argument comparing the speed of sunspot group 1513 to the speed of the rest, taking into account the error that you estimated in step 4. *(3 points for a clear explanation of your reasoning + 3 points for using your numbers to support your reasoning)*

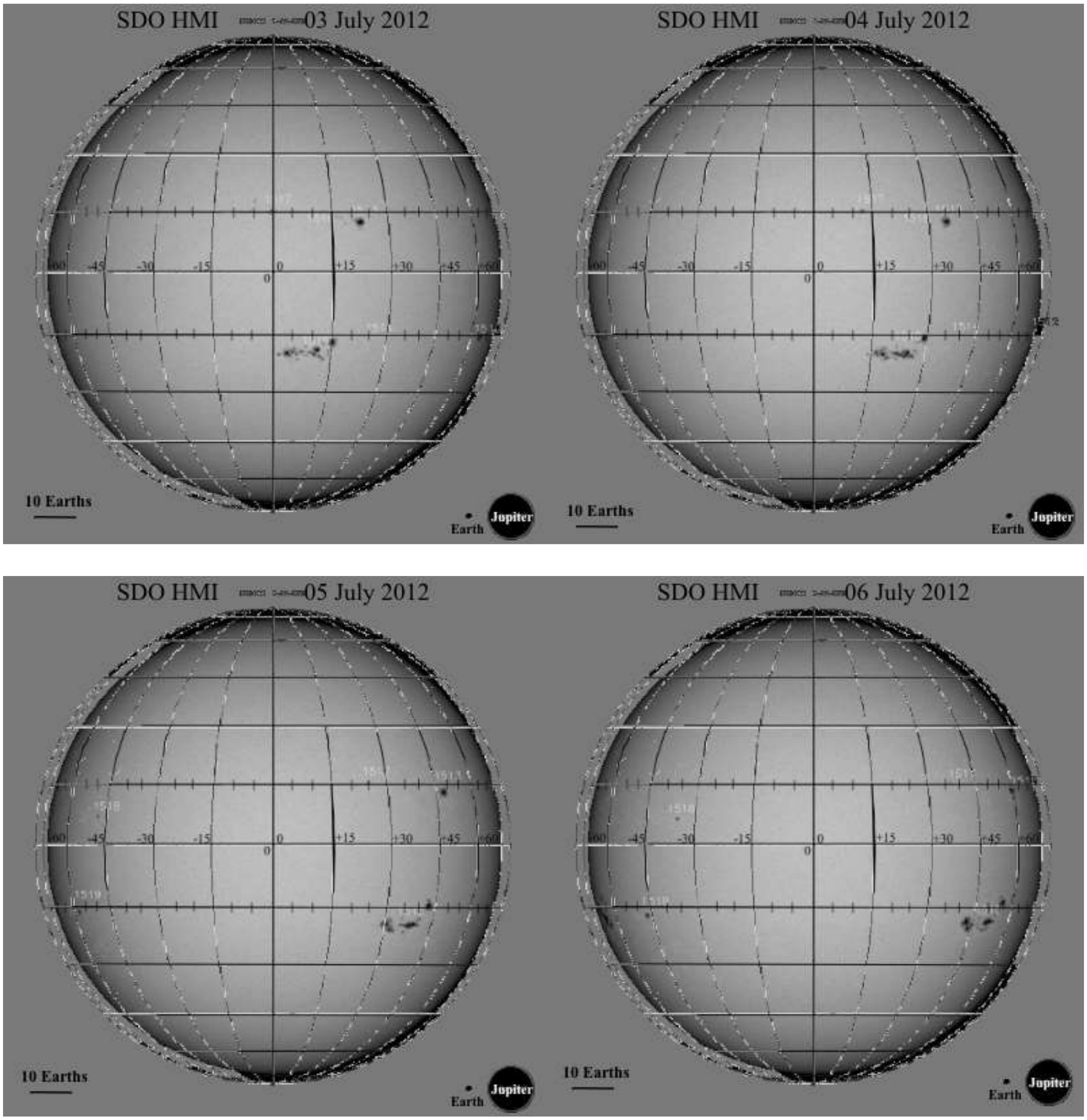
Images for the Rotation of the Sun









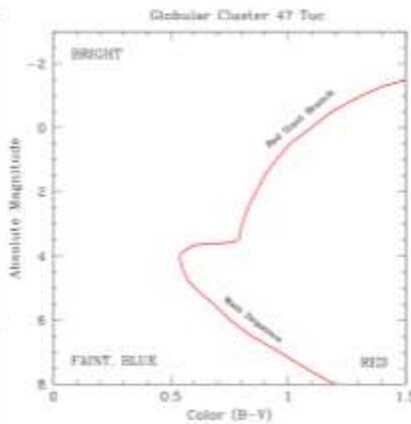


Images are courtesy of NASA's Solar Dynamics Observatory (SDO), taken with the Helioseismic and Magnetic Imager (HMI) instrument. Equatorial grid added by Ana Larson.

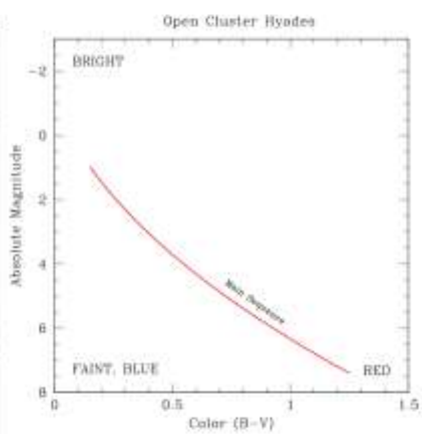
THE DISTANCES AND AGES OF STAR CLUSTERS
w/ HR Diagrams

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 homework, 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 lab you will use actual data to show how clusters can be used to measure the relative distances and ages of stars in the cluster.

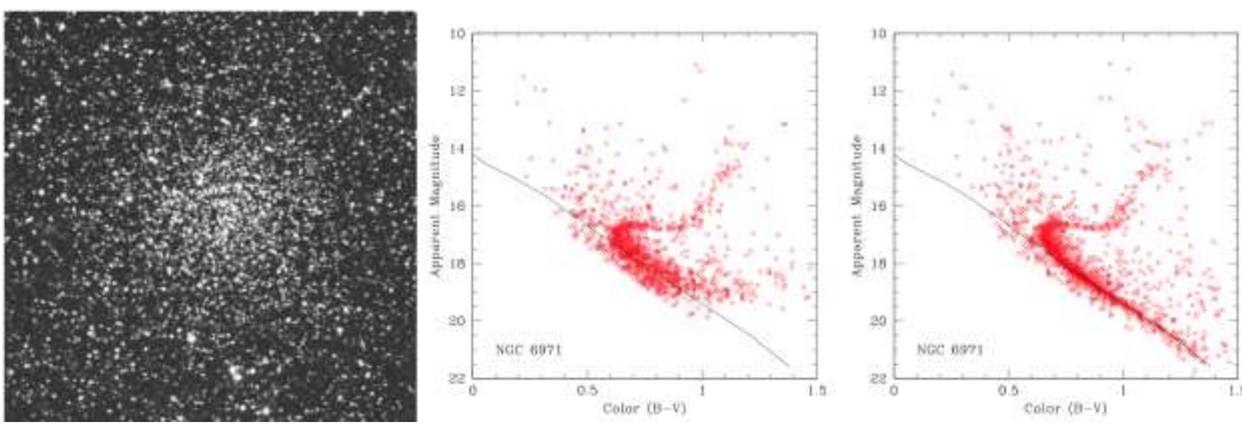
Getting Used To Stellar Data

For this lab, 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 simple 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 lab 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.



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. 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 these limitations, 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 this lab 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.

The Relative Distances of Clusters

Measuring distances is critical for deriving the luminosity of a star. Unfortunately, it is extremely dicult 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 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 1M main sequence star looks nearly identical to a young 1 M main sequence star, making it difficult to distinguish between them even if one is many gigayears (Gyr) 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 living on the main sequence. If the cluster were older, then all 2 M stars would have already used up the Hydrogen in their cores and evolved far from the main sequence.

Credit for this guide: UW Astronomy Education Clearinghouse.

Your Name: Your Section:

Color-Magnitude Diagrams of Clusters[1]

Introduction

The HR diagram, a plot of stellar luminosity versus color, has become the primary way we organize our thoughts about stars and stellar lifetimes. Unfortunately it’s very difficult to measure the luminosity of stars, so we have to take advantage of opportunities to use brightness instead. Since stars in clusters are all a similar distance from us, so we can compare the relative luminosities of clusters stars using their brightness. In this lab you will:

- Work with color-magnitude diagrams, and
- Estimate ages using stellar colors.

Color-Magnitude Diagrams (/5):

Main Sequence Lifetimes (/5):

Estimating Ages of Clusters (/8):

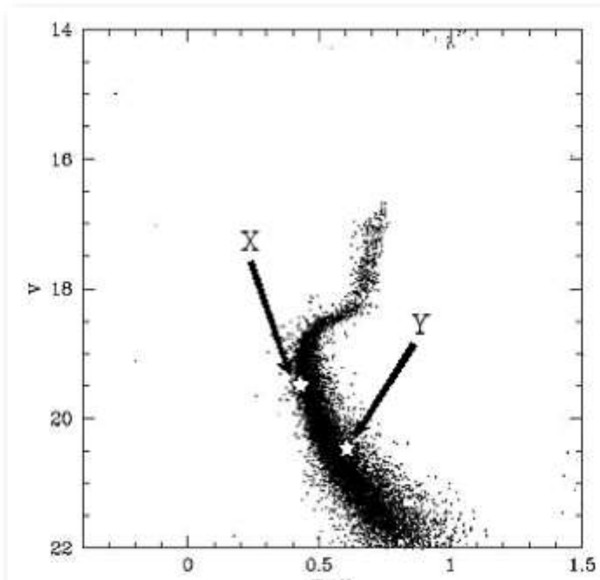
Units (/1):

Significant Figures (/1):

Total (/20):

Exploring Color-Magnitude Diagrams

Color-Magnitude diagrams (CMDs) plot the brightness and color of many stars from one cluster. The brightness of each star in the cluster is measured in two very specific colors, often *B* (blue) and *V* (“visual”, which is kind of greenish). In this CMD the *V* magnitudes are plotted along the brightness axis of a CMD. The numbers on this axis often increase downwards, because that’s how magnitudes work, *but brightness always increases upwards on a CMD.* The color axis of a CMD is found by taking the difference of the *B* and *V* magnitudes, because that’s a comparison of star’s brightness in *B* and *V*. Because the quantity *B-V* indicates the star’s color, we often refer to this specifically as *“a color”*. The Sun has a *B-V* of about 0.6, smaller (especially negative) numbers indicate bluer stars, larger numbers indicate redder stars.



Label the Main Sequence, Turn-off, and Giant Branch in this CMD. *(1 point)*

Estimate the B-V values of stars X and Y. Use checkmarks to indicate which of these stars is reddest, and which is the most luminous. *(2 points)*

	B-V	Check (✓) the one that is reddest	Check (✓) the one that is most luminous
Star X			
Star Y			

[1] Based closely on a lab from Ana Larson.

Consider the same two stars. Check (✓) the one that is the greatest for each quality. Note that a star's main sequence lifetime is the length of time it spends on the main sequence; it may also spend a

	Surface Temperature	Mass	Age	Main Sequence Lifetime
Star X				
Star Y				
Both are similar				

significant portion of its life as a giant. *(2 points)*

Estimating Main Sequence Lifetimes

The main sequence lifetime of a main sequence star can be estimated based on its *B-V* colors thanks to a great deal of theoretical and observational work in astronomy.

Sp. Type	O5	B0	A0	F0	G0	K0	M0
Mass (solar)	40	15	3.5	1.7	1.1	0.8	0.5
B – V	**-1.2**	**-0.3**	**0.0**	**0.3**	**0.6**	**0.8**	**1.4**
M.S. Lifetime (years)	1.0×10^6	1.1×10^7	4.4×10^8	3.0×10^9	8.0×10^9	1.7×10^{10}	5.6×10^{10}

Questions 4-7 concern a star with a *B-V* color of 0.8.

What is the main sequence lifetime of this star?

If this star was born this morning, how many years would it have until it left the main sequence? *(1 point)*

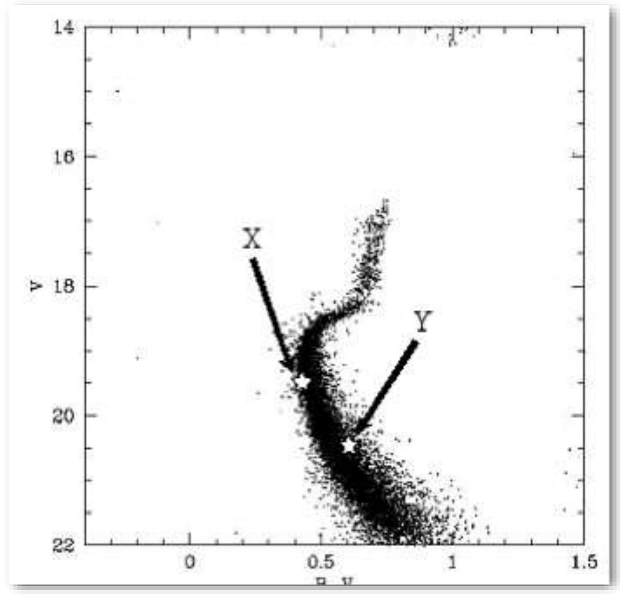
On the other hand, if this star was born 4.5 billion years ago with the Sun, how many years would it have until it left the main sequence? *(1 point)*

What if this star was in a cluster that was known to be 8 billion years old. Is it most likely to have evolved off the main sequence, be right at the turn-off, or sit low down on the main sequence? *(1 point)*

Altair, an naked-eye A7 star located in the northern constellation Aquila, has a *B-V* color of 0.2. If we believe that Altair is 3×10^8 years old, how many years from now will the star leave the main sequence? *Note that you'll have to estimate Altair's main sequence lifetime because we don't have a point of data for a B-V of 0.2. (2 points)*

Estimating the Ages of Clusters

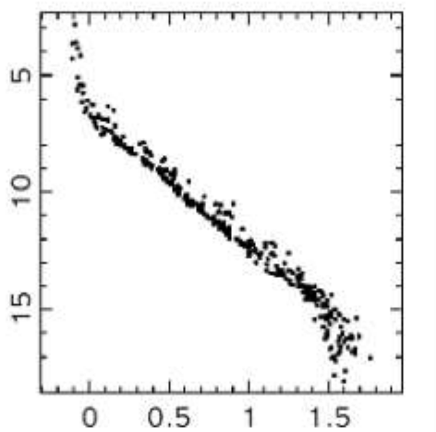
Consider the CMD to the right. What is the *B-V* of its turn-off stars? *(1 point)*



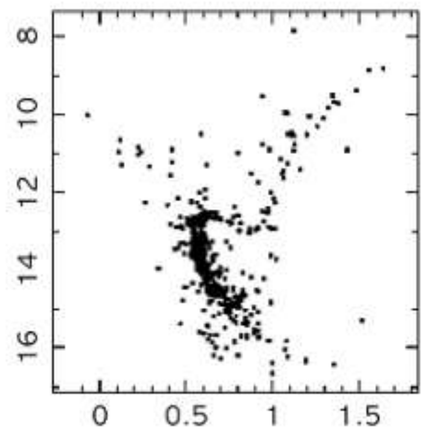
What is the main sequence lifetime of these turn-off stars? *(1 point)*

What is the age of this cluster? *(1 point)*

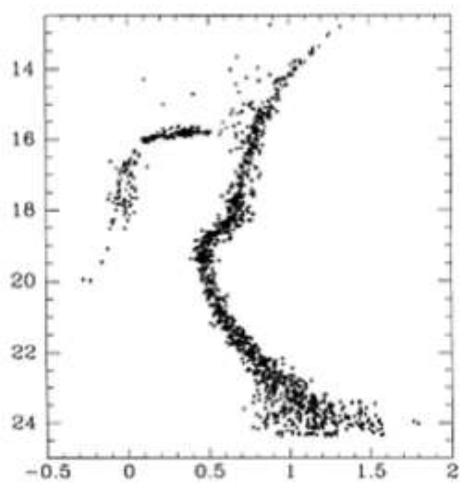
(over)



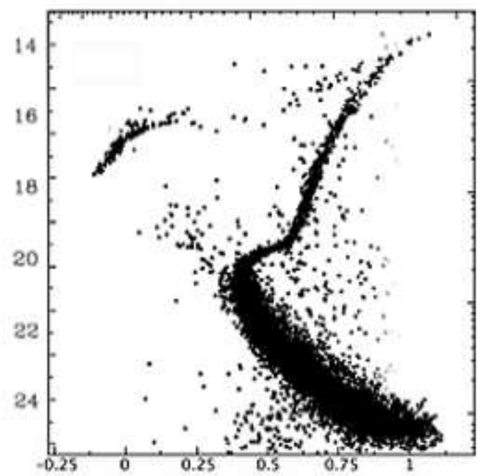
The Pleiades



M 67



M 15



M 55

For each of the these four clusters, measure the B-V of their turn-off, rank them by age, and estimate their age in years . (5 points)

Youngest Cluster	Turn-off Color (B-V)	Estimated Age (years)
Oldest Cluster		