Student Name: *Lab TA Name:*
Lab Partner Name:

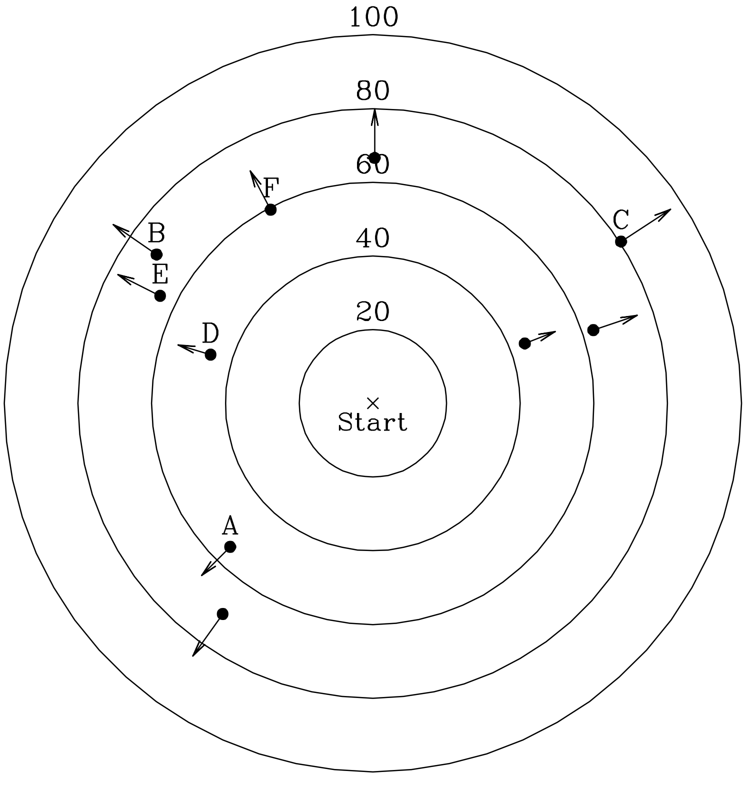
A1101, Lab 12: The Expanding Universe
Lab Worksheet

Part 1: A Desert Car Race

You are a journalist who has been assigned to cover an unusual car race in the desert. Cars start together, and the winner is the first one to get 100 miles from the starting point, in any direction (there are no roads).

You arrive above the scene in your helicopter at 11 am, which is the time you expected the race to start. To your horror, you encounter the scene depicted in the figure below, and you realize that you must have missed the start, by a lot. Large circles mark distances from the starting point in miles, and dots mark the locations of the ten cars in the race, with arrows to show that they are all racing away from the center. Using your super-powered Doppler radar gun, you measure the speeds of the cars labeled A-E, finding
A: 28 mi/hr B: 37 mi/hr C: 41 mi/hr D: 23 mi/hr E: 33 mi/hr

Measure the *distance* (in miles) that each car has traveled from the starting point. *Plot each of these points on Graph 1 of the handout, velocity vs. distance.*



Why do these points lie along a nearly straight line?
Why do they not lie exactly along a straight line?

When did the race start? How do you know?

What assumption did you make about the cars' speeds to figure out when the race started?

What do you expect the speed of car F would be if you measured it? Why?

Part 2: Hubble's Law

The velocity of a galaxy can be measured from the Doppler shift of its light, just as you have done in previous labs for stars. But measuring distance to astronomical objects is hard. To determine distances to far-off galaxies, we'll use white dwarf supernovae as "standard candles," taking advantage of the fact that all white dwarf supernovae have roughly the same peak luminosity. ("Peak luminosity" means the highest luminosity that the supernova attains, usually about two weeks after the explosion.) The apparent brightness of a supernova can be measured from images (like the ones from ASAS-SN that you analyzed in Lab 9), so with known luminosity you can solve for distance using the relation

$$\text{Brightness} = \text{Luminosity} \div (4\pi\, d^2)\ .$$

We're going to skip an important and challenging step, determining the peak luminosity of white dwarf supernovae using observations in galaxies whose distances have been determined using Cepheid variable stars. This step will be discussed in lecture, and here we will just use the result: the typical peak luminosity of a white dwarf supernova is about 3.6 billion solar luminosities ($3.6\times10^9\ L_{sun}$).

With this information in hand, we can use the apparent brightnesses of supernovae to infer their distances by employing our above equation in the form

$$(\text{Distance} / 1\ \text{AU}) = (\text{Luminosity} / L_{sun})^{1/2} \div (\text{Brightness} / B_{sun})^{1/2}$$

Remember that $X^{1/2}$ means the same thing as $\sqrt{X}$.

The table below lists the radial velocity (measured from Doppler shifts) and peak brightness of 10 white dwarf supernovae, which were observed by astronomer Mario Hamuy and his colleagues at Cerro Tololo observatory in Chile. In the table, the distances for five of the supernovae have been calculated for you. You should check that you get the same numbers for the first two cases so that you know you are using the formula correctly.

Compute the distances of these ten supernovae in AU and fill in column 4 of the table.

Supernova	**velocity [km/sec]**	**Brightness/B_{sun}**	**distance [AU]**	**distance [millions of Lyr]**
1990O	9,100	5.50×10^{-18}	2.56×10^{13}	406
1990Y	11,600	2.31×10^{-18}	3.95×10^{13}	627
1991S	16,700	1.51×10^{-18}		
1991U	9,800	5.71×10^{-18}		
1992J	13,700	2.52×10^{-18}	3.78×10^{13}	600
1992P	7,890	6.42×10^{-18}		
1992ag	7,780	6.57×10^{-18}	2.34×10^{13}	372
1992aq	30,300	4.61×10^{-19}		
1992bc	5,900	1.39×10^{-17}		
1992bk	17,400	1.56×10^{-18}	4.81×10^{13}	763

While the AU is a convenient unit for describing distances in the solar system, it's not well attuned to distances between galaxies. A more intuitive unit for galaxies is millions of light years, where 1 million Lyr = 6.3×10^{10} AU.
Convert all of your distances from AU to millions of light years and fill in column 5 of the table. ***(Check that you get the right numbers for the first two examples.)***

Plot velocity vs. distance for these 10 supernovae on Graph 2 of the handout.
Then draw a straight line on the graph that starts at v=0, d=0 and goes through the middle of the data points.

At a distance d = 500 million light years, what is v, in km/sec?

Compute the slope of your line by dividing *v* by *d*. This slope is Hubble's constant H_0, in the somewhat unusual units of km-per-second-per-million light years.

H_0 = ________________ km/sec/million Lyr.

When describing the distance to a galaxy, the unit that astronomers most often use is the megaparsec (Mpc). 1 Mpc = 1 million parsecs = 3.26 million light years. You can convert your value of H_0 to the conventional (though still somewhat unusual) units of km/sec/Mpc (km-per-second-per-Mpc) by just multiplying your previous number by 3.26. What do you get?

H_0 = ________________ km/sec/Mpc.

This is one of the most famous numbers in astronomy, and astronomers have spent many, many years using many, many telescopes to try to measure it accurately.

The strange combination of units in H_0 arises from the units that astronomers most often use to describe velocity (km/sec) and distances to galaxies (Mpc). It's notable that the reciprocal of this slope, $1/H_0$ has units of sec × (Mpc / km), and since Mpc and km are both measures of distance, the units of $1/H_0$ are really just time. Specifically, if you took $1/H_0$ using your number above and multiplied by the number of km in a Mpc, you would get approximately $1/H_0 = 4.4 \times 10^{17}$ seconds.

What do you think the physical significance of this time (usually referred to as the "Hubble time") might be?
Hint: To compute the slope of your line you divided velocity by distance. The reciprocal of that slope is therefore a distance divided by a velocity. What time does this give you?

Part 3: The Age of the Universe

Look back at your answer to Part 1, remembering how you determined the start time of the car race.

In Part 1, you had distances in miles and speeds in miles/hr, so you could just divide the distance by the speed to get the time in hours. Here we have speeds in km/sec, and we first need to convert distances from millions of Lyr to km so that dividing distance by speed will then give us time in sec.

To quite good accuracy, 1 million Lyr = 10^{19} km.

For the three supernovae listed below, convert the distance you listed in the table of Part 2 from millions of Lyr to km, by multiplying your earlier number by 10^{19}. Fill in column 3 of the table.

Supernova	**v in km/sec**	**distance in km**	**(d/v) in sec**	**(d/v) in yrs**
1990O	9,100			
1991S	16,700			
1992aq	30,300			

To calculate how long it takes to go a distance *d* at a speed *v*, you divide distance by velocity, just like you did for the cars in Part 1.

Do this calculation for each of the 3 supernovae and fill in the 4th column of the table.

Then convert your answer from seconds to years by dividing the number in column 4 by 3.16×10^{7} sec/yr, and fill in column 5.

According to your results, when did the expansion of the universe begin?
Are the ages you calculate from the three supernovae similar?

What assumption did you make about the speed of galaxies in order to calculate the age of the universe?

In Lab 8 you estimated the ages of star clusters. The oldest known star clusters have estimated ages of 12 – 13 billion years. Is the age of the universe that you calculated from your measurements of Hubble's law:

(a) Much larger than the age of the oldest star clusters
(b) Slightly larger than the age of the oldest star clusters
(c) Slightly less than the age of the oldest star clusters
(d) Much less than the age of the oldest star clusters

Suppose that you discovered a new star cluster with an age of 25 billion years. Why would this be a puzzle?

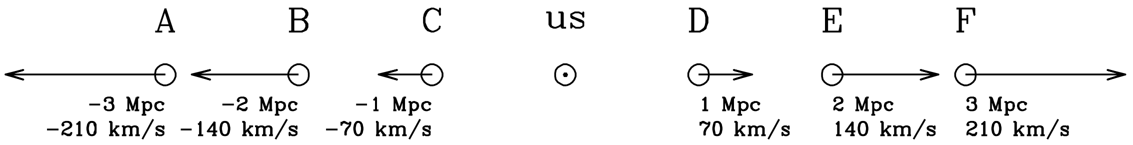
Part 4: The Center is Everywhere

Hubble's law may give you a queasy non-Copernican feeling: does the fact that everything in the distant universe is moving away from *us* require the Milky Way to be at the center of the cosmos? We will now address this conundrum.

The diagram below shows a simple illustration of Hubble's law $v = H_0 d$, where distances are now indicated in megaparsecs (Mpc). The circle in the middle represents the Milky Way galaxy, and the other circles mark the positions of six other galaxies. The distances of these galaxies from the Milky Way are listed below the points. Positions to the left of the page have negative values and positions to the right of the page have positive values.

Arrows illustrate the velocities of the galaxies relative to the Milky Way, and the velocity values are listed below the points, in km/sec. Galaxies moving to the right have positive velocities and galaxies moving to the left have negative velocities.

These positions and velocities follow Hubble's law with a Hubble constant H_0 = 70 km/sec/Mpc. For example, the galaxy with position d = 3 Mpc has velocity v = 210 km/sec, and the galaxy with d = -2 Mpc has velocity v = -140 km/sec.



(a) You are driving on the German autobahn at a respectable speed of 110 km/hour. A reckless driver barrels past you in the left lane traveling at 160 km/hour. *What is the speed of the reckless driver's car* <u>*relative*</u> *to your car?*

(b) Suppose that you were an astronomer living in Galaxy E, instead of in the Milky Way, and you measured the positions and velocities of the other galaxies shown in the diagram. *As seen from Galaxy E:*

What is the position (in Mpc) and velocity (in km/sec) of galaxy F?

What is the position and velocity of galaxy D?

What is the position and velocity of galaxy A?

Important: Use positive numbers for the position of galaxies to the right of Galaxy E and negative numbers for the position of galaxies to the left of Galaxy E. Use positive numbers for the velocity of galaxies that are moving to the right <u>relative</u> to Galaxy E, and negative numbers for the velocity of galaxies that are moving to the left relative to Galaxy E.

(c) Now suppose you are an astronomer living in Galaxy A. As seen from Galaxy A:

What is the position and velocity of galaxy B?

What is the position and velocity of galaxy D?

What is the position and velocity of galaxy E?

(d) *On the basis of what you found in (b) and (c), explain (in 2-4 sentences) why the following statement is incorrect:*

> Hubble's law shows that other galaxies are moving away from the Milky Way, with a velocity that is proportional to distance. From this we can conclude that the Milky Way is at the center of the universe, since observers in other galaxies would not see the same kind of regular expansion.