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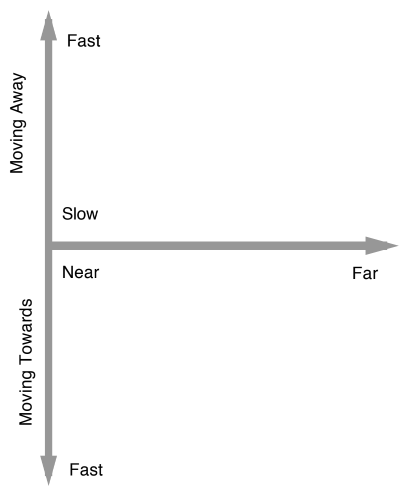
Edwin Hubble assembled a graph of galaxy velocities and distances determined through the Doppler Effect, and the cosmic distance ladder. The chart below shows the possible combinations of distance and speed.



1. Mark on the chart where nearby galaxies, moving away slowly would be.

2. Mark on the chart where distant galaxies, moving rapidly towards us would be.

In his first set of data, Hubble did not see all of these possibilities. You are going to simulate his discovery using data from the Hubble Space Telescope Science Institute.

3. In this activity, we are going to measure the diameter of galaxies and use a simplifying assumption that all galaxies are the same size. This isn't true, but it is close enough to make a good guess about how galaxies are actually distributed in speed and distance. For each of the following galaxies, follow these steps.

INSTRUCTIONS FOR EACH PICTURE

a. Measure the width of the **entire image** (not the galaxy, or the table, but the image in the table) in mm. Don't round.

b. Divide the first scale number in arc minutes (see the area to the right of each picture for this value) by the width of the image you found in a. This is the **plate scale** in arc minutes per mm.

c. Measure the **widest dimension** of the galaxy (see illustration below.) Measure in mm, and don't round. If it's tilted, then tilt your ruler.

d. Use the plate scale to find the size of the galaxy in arc minutes. Multiplying the answer to b (plate scale) by the answer to c (size of galaxy in mm) does this.

Write the answers in the boxes next to each image or on separate paper.

Then collect all this information in the table in the page that follows the images.

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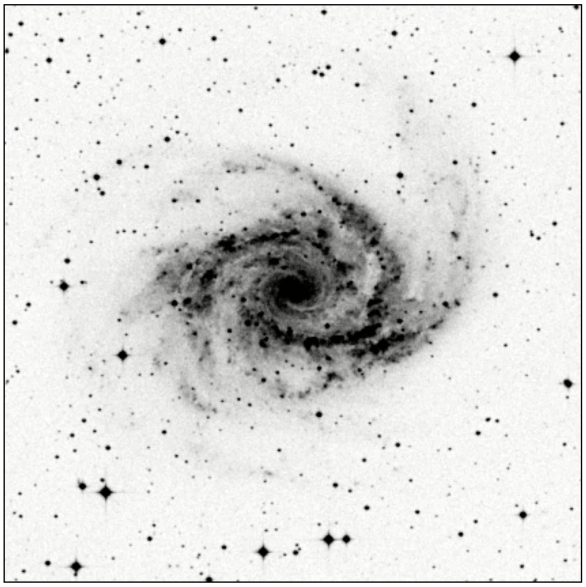
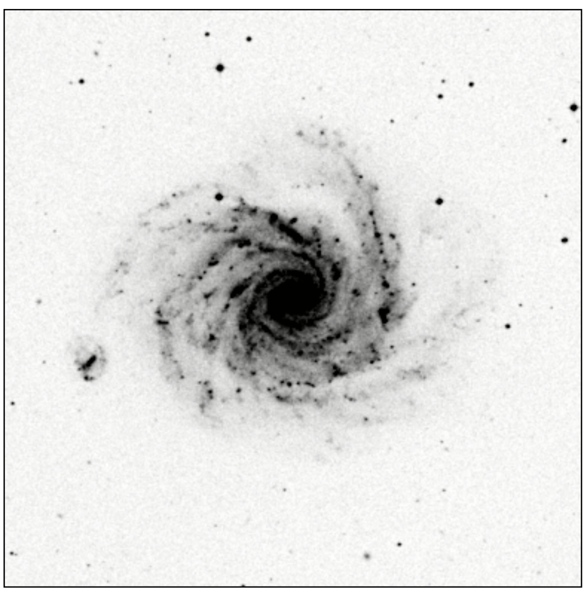


Name: NGC 2997
Velocity: 799
Scale: 27′x 27′
Source:http://ned.ipac.caltech.edu/cgi-bin/ex_refcode?ref-code=1994DSS...1...0000%3A
a. Width of image (mm):
b.Plate scale in arcmin/mm=scale/width:

c. Measure the widest dimension of the galaxy (mm):

d. Size of the galaxy in arcmin:



Name: NGC 3521
Velocity: 627
Scale: 9.3′x9.3′
Ref:http://ned.ipac.caltech.edu/cgi-bin/ex_refcode?ref-code=2007SINGS.5......0%3A
a. Width of image (mm):
b. Plate scale in arcmin/mm=scale/width:

c. Measure the widest dimension of the galaxy (mm):

d. Size of the galaxy in arcmin:

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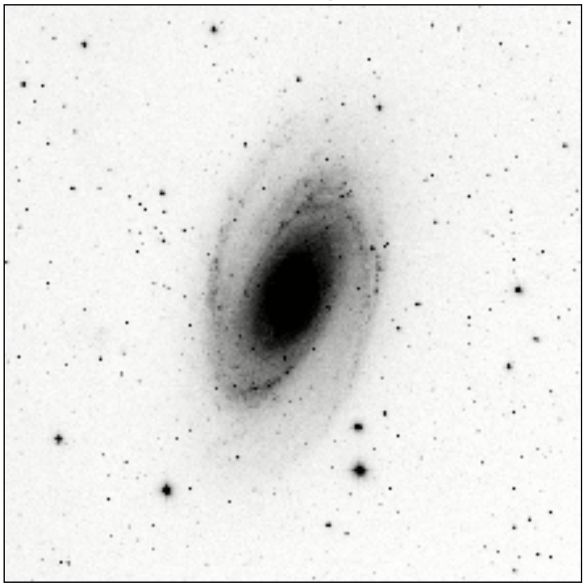
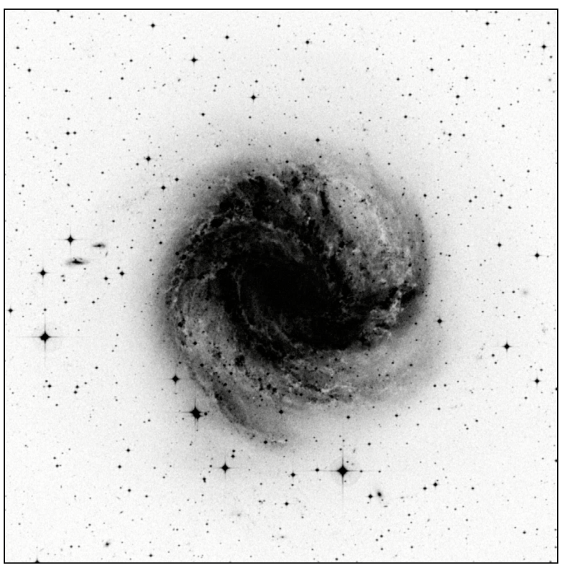


Object: M33
Velocity: 69
Scale: 60′x60′
Ref:http://ned.ipac.caltech.edu/cgi-bin/ex_refcode?refcode=1994DSS...1...0000%3A
a. Width of image (mm):
b. Plate scale in arcmin/mm=scale/width:

c. Measure the widest dimension of the galaxy (mm):

d. Size of the galaxy in arcmin:



Name: NGC 5236
Velocity: 275
Scale: 19′x19′
Source:http://ned.ipac.caltech.edu/cgi-bin/ex_refcode?refcode=1994DSS...1...0000%3A
a. Width of image (mm):
b. Plate scale in arcmin/mm=scale/width:

c. Measure the widest dimension of the galaxy (mm):

d. Size of the galaxy in arcmin:

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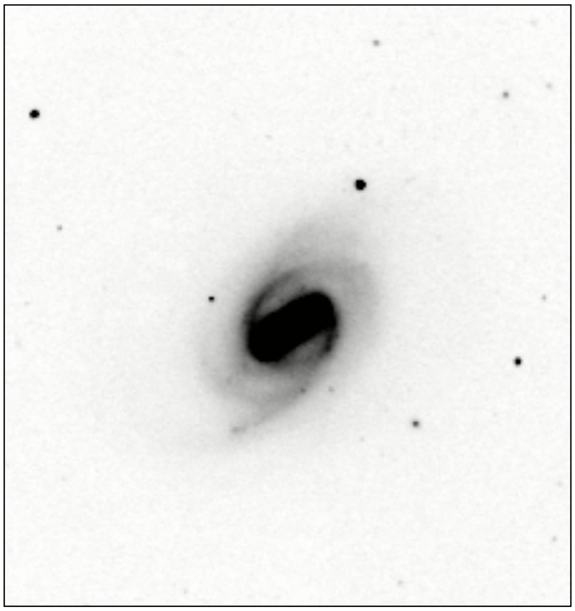


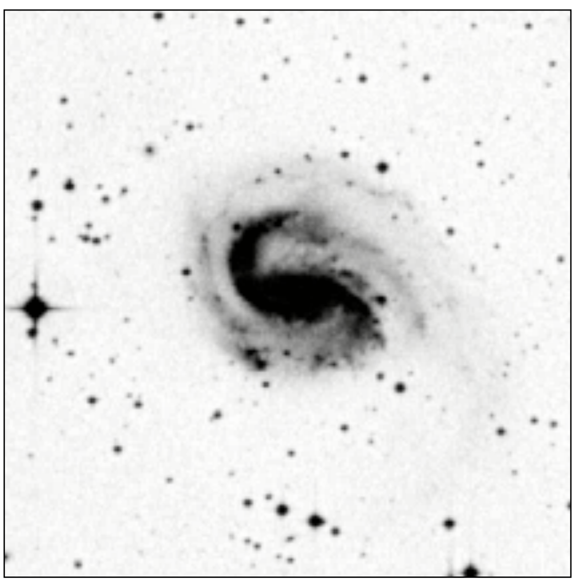
Name: NGC 289
Velocity: 1834
Scale: 4.4′ x4.7′
Ref:http://ned.ipac.caltech.edu/cgi-bin/ex_refcode?ref-code=2002ApJS..143...73E

a. Width of image (mm):

b. Plate scale in arcmin/mm=scale/width:

c. Measure the widest dimension of the galaxy (mm):

d. Size of the galaxy in arcmin:



Name: NGC 2907
Velocity: 3192
Scale: 6.0′x6.0′
Ref:http://ned.ipac.caltech.edu/cgi-bin/ex_refcode?ref-code=1994DSS...1...0000%3A

a. Width of image (mm):

b. Plate scale in arcmin/mm=scale/width:

c. Measure the widest dimension of the galaxy (mm):

d. Size of the galaxy in arcmin:

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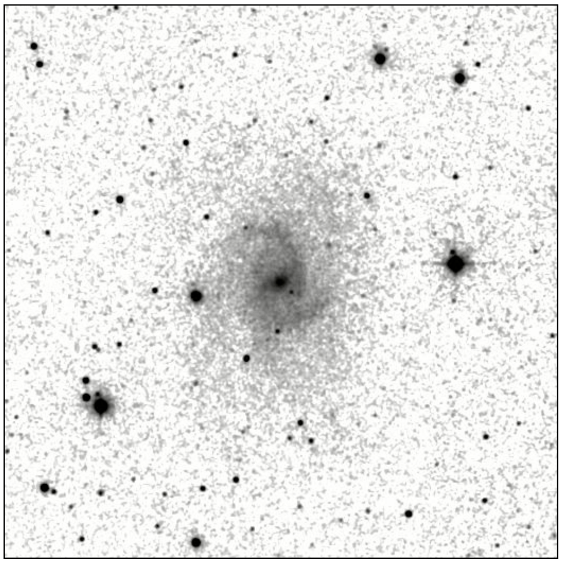
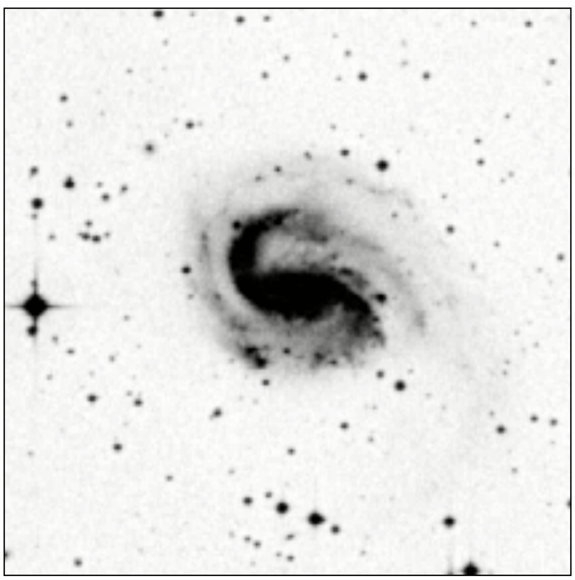


Name: NGC 2835
Velocity: 624
Scale: 8.7x8.7′
Ref:http://ned.ipac.caltech.edu/cgi-bin/ex_refcode?refcode=2003AJ....125..525J
a. Width of image (mm):
b. Plate scale in arcmin/mm=scale/width:

c. Measure the widest dimension of the galaxy (mm):

d. Size of the galaxy in arcmin:



Name: NGC 6907
Velocity: 3192
Scale: 6x6′
Ref:http://ned.ipac.caltech.edu/cgi-bin/ex_refcode?ref-code=1994DSS...1...0000%3A
a. Width of image (mm):
b. Plate scale in arcmin/mm=scale/width:

c. Measure the widest dimension of the galaxy (mm):

d. Size of the galaxy in arcmin:

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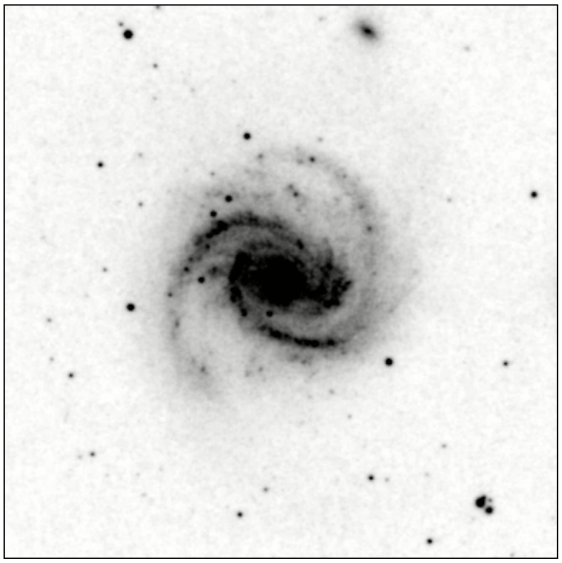
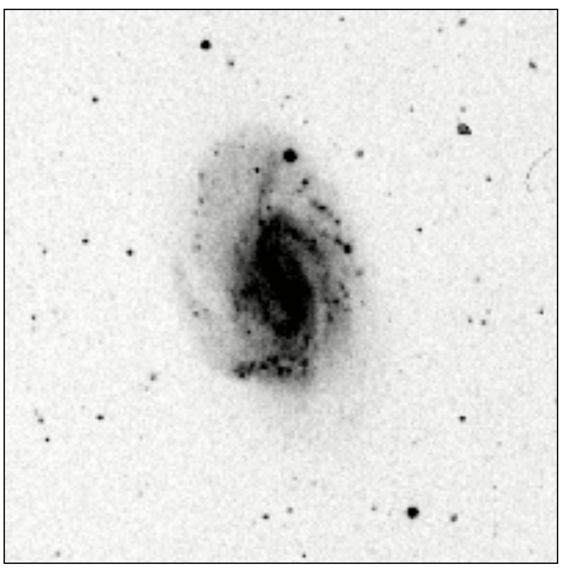


Name: NGC 4321
Velocity: 1464
Scale: 11′x11′
Ref:http://ned.ipac.caltech.edu/cgi-bin/ex_ref-code?refcode=1994DSS...1...0000%3A
a. Width of image (mm):
b. Plate scale in arcmin/mm=scale/width:

c. Measure the widest dimension of the galaxy (mm):

d. Size of the galaxy in arcmin:



Name: NGC 3726
Velocity: 909
Scale: 10′x10′
Ref:http://ned.ipac.caltech.edu/cgi-bin/ex_ref-code?refcode=1994DSS...1...0000%3A
a. Width of image (mm):
b. Plate scale in arcmin/mm=scale/width:

c. Measure the widest dimension of the galaxy (mm):

d. Size of the galaxy in arcmin:

References: Images are from NASA's NASA/IPAC Extragalactic Database as indicated by each image. Velocities are as published in The Atlas of Galaxies, NASA publication SP-496 by Allan Sandage and John Bedke, 1988.

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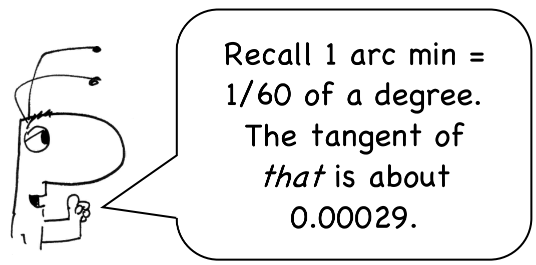
4. Copy the data from your measurements into the first two columns of the data table at the end of this activity. Also copy the recessional velocity into the last column.

5. Now convert these diameters to distances, using the following relationships. We assume (incorrectly, as it turns out, but it's not a bad first guess) that all galaxies are the same size, and they are all the same size as ours. Assume our galaxy is approximately 100,000 ly in diameter. If a galaxy the size of our own would appear to be 1 arc minute wide, it would be located at a distance of:

$$\tan(\text{angular size}) = \frac{100{,}000 \text{ ly}}{\text{distance}}$$

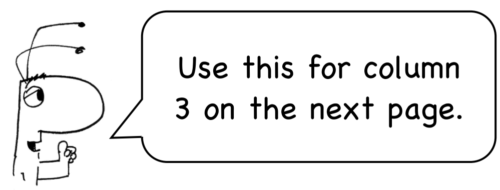
$$\text{distance} = \frac{100{,}000 \text{ ly}}{\tan(1 \text{ arcmin of angle})}$$

$$\text{distance} = \frac{100{,}000 \text{ ly}}{0.00029} = 344 \text{ million ly}$$



In this calculation we have converted 1 arc minute of angle into 1/60 of a degree before using the tangent function. If the galaxy were half the distance, it would appear twice as large, and if it were twice the distance, it would appear half as large. Thus the following ratio can be used to estimate distances of these galaxies:

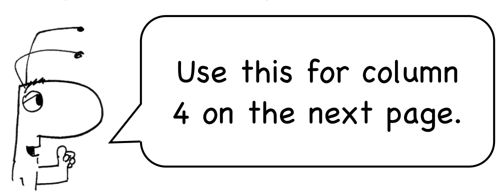
$$\text{distance to galaxy} = \frac{344 \text{ million ly}}{(\text{width of galaxy in arc minutes})}$$



Use this formula to estimate the distance to each galaxy. Enter these in the table.

6. Convert these distances in millions of light-years to mega-parsecs using this conversion.

$$\text{Distance in Mpc} = \text{Distance in Mly } \frac{1 \text{ pc}}{3.26 \text{ ly}}$$



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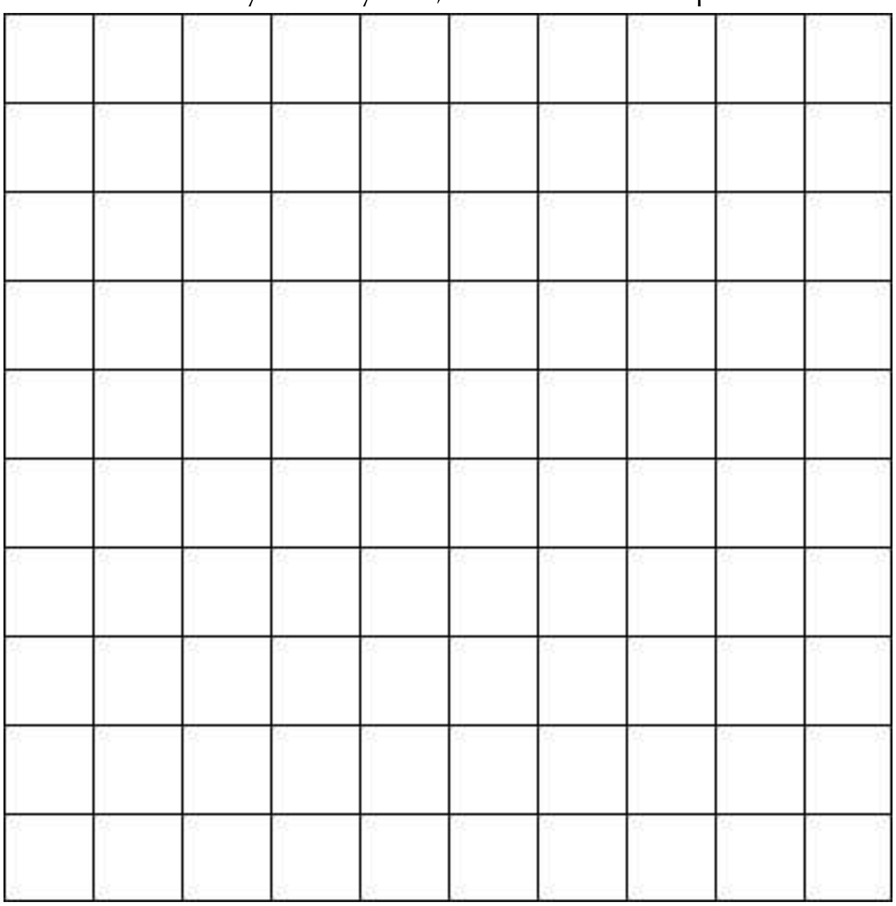
Data Table

1. Image name	2. Size of galaxy in arcmin	3. Estimated distance to galaxy (ly)	4. Estimated distance to galaxy (Mpc)	5.Recessional velocity

7. Now plot the redshift-determined speeds of these galaxies against the distance on the grid below. Put velocity on the y-axis, and distance in Mpc on the x-axis. Select a scale that allows the largest values to be plotted.



8. The points will not line up in a perfect line. Draw a line with a straightedge that passes through the origin (after all, we are in the Milky Way and we don't recede from ourselves) and then passes through as many of the plotted points as possible. Find the slope of this line. Remember slope is just rise over run. The units of this slope will be km/s per megaparsecs.

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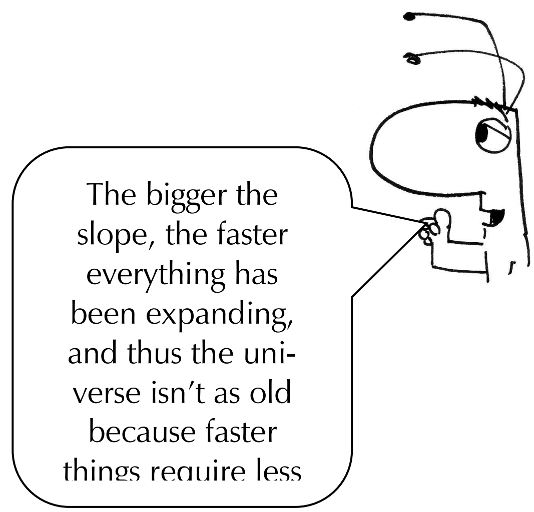
9. Use the chart below to estimate the age of the universe. How the slopes convert into the age of the universe will be explained at the end of this activity.

Slope of v vs. d graph ((km/s)/Mpc)	Age of Universe (years)
10	97,800,000,000
15	65,200,000,000
20	48,900,000,000
30	32,600,000,000
40	24,450,000,000
50	19,560,000,000
60	16,300,000,000
70	13,971,000,000
80	12,225,000,000
90	10,867,000,000
100	9,780,000,000
110	8,891,000,000
120	8,150,000,000
130	7,523,000,000



The answer you got probably differs quite a bit from typically accepted values. This is due to the imperfect method we used to measure distances, and the velocities were based on values published in 1988 by the Space Telescope Science Institute. Using more modern methods of measuring these values (such as Cepheid variables and Supernovas) the following data is currently available (2013) from NASA's Extragalactic Database:

Object	Distance in Mpc	Velocity in km/s
NGC 2997	10.77	1088
NGC 3521	12.078	801
M33	0.833	-179
NGC 5236	6.96	513
NGC 2903	9.058	550
NGC 4321	15.95	1571
NGC 3726	16.892	866
NGC 2835	10.824	886
NGC 289	22.767	1629
NGC 6907	37	3182

10. Plot these values on the same graph as before using a different symbol such as "x" instead of "•". Find the slope of this line as well, and write it here. What age does it imply?

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Recall from our speed, distance, and time analysis that a graph of this type will only be caused by everything traveling starting at the same time and from the same place.

The slope he got was a bit different than yours or the modern accepted value. Since then, we have refined the value. The modern accepted value is typically referred to as the **Hubble Constant** and its value is approximately 68 km/s/Mpc.

How the Hubble Constant generates the age of the universe, step by step
(This section is for advanced students. Ask your teacher if you need to read it.)

This discussion uses conclusions from the speed, distance, and time activity earlier in this workbook. We concluded earlier that the slope of a distance vs. speed graph (for constant speeds) is the travel time. We have plotted the speed vs. distance instead, which is reversed. (This is traditional with the Hubble diagram.) We will therefore not get the age of the universe unless we invert the slope first. We could simply state that 1/(68 km/s/Mpc) = 1 Mpc/(68 km/s) is the age of the universe and be done with it. Unfortunately the unit of measurement is unfamiliar. We would more typically say the age of something in *years*. Therefore our goal in the process below is to convert your slope into the age of the universe, and then do it again using the accepted value of the Hubble Constant.

11. First, *separate* the problem into numerator and denominator after you invert H.

____

____

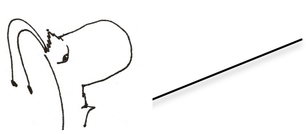
____

12. Next we have to make the distance unit match so they will cancel out. This means we have to convert the km/s to m/s, and the Mpc to meters.

Recall that 1 km = 1000 m, and convert as follows:

Your slope (H) x $\left(\frac{1000m}{1km}\right)=$ ____

This takes care of the denominator in the fraction. Now for the numerator.



Recall that the *numerator* is the top part of the fraction, and the *denominator* is the bottom.

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13. Next we must convert the Mega-parsecs (Mpc) into meters. Here are the conversion factors needed:
1 Mega pc = 1,000,000 pc
1 pc = 3.26 light years
1 light year = the distance light travels in a year = speed of light x time = 300,000,000 m/s x the number of seconds in a year

The distance light travels in a year is:

$$1 \text{ light year } = 300{,}000{,}000\left(\frac{m}{s}\right)\left(\frac{365.24\,days}{1\,year}\right)\left(\frac{24\,hours}{1\,day}\right)\left(\frac{60\,\text{min}}{1\,hour}\right)\left(\frac{60\,\text{sec}}{1\,\text{min}}\right)= \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

$$\text{Therefore 1 Mpc = (the answer above) x } \left(\frac{3.26\,ly}{pc}\right)\left(\frac{1{,}000{,}00\,pc}{Mpc}\right)= \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

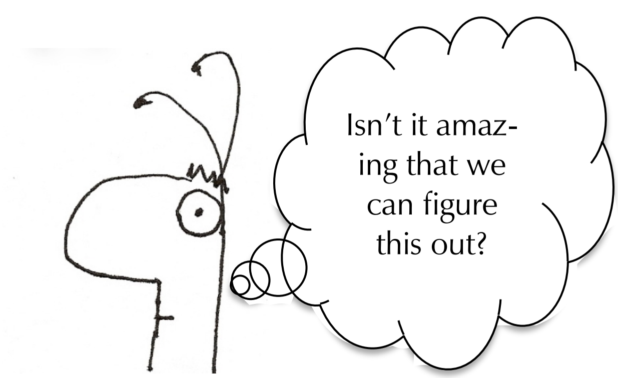
Now we have the numerator. Putting it all together we get…

14. The Age of the Universe

$$\text{The Age of the Universe is } = \left(\frac{\text{the answer to \#13}}{\text{the answer to \#12}}\right) =$$

15. This is of course inconvenient. So we will convert this to years to finish the problem. Use the conversion factors above in #3 to convert seconds back into years.

What is the age of the universe in years?



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Implications and Questions

This relatively simple calculation has led us to some conclusions that are intimidating to say the least. Yet the logic we have used is no more complex than figuring out the trip time when driving a car.

16. Like the driving cars example, the Hubble law graph implies that yesterday, the galaxies were a bit closer together; the day before that, still closer. If we traveled backward in time to the beginning that you calculated, where would all the galaxies be?

17. What does the fact that the Hubble graph is straight and not curved imply?

18. How will the universe be different in a billion years compared to now?

19. How does having a *larger* Hubble constant affect the estimated age of the universe?

20ß. Your teacher will have the age of the universe based on the accepted value of 68 km/s/Mpc. Compare this to your value.

There are some related questions like "*Where* did the universe begin?" and *"What was there before* the universe began?" Such questions are beyond the scope of this activity, but if you would like to know more you might consider the following books:

A Brief History of Time, by Stephen Hawking
The First Three Minutes, by Stephen Weinberg