# Lab J: Expansion of the Universe

Objective

In the 1920's when Hubble observed spectra of galaxies, he noticed that the spectral lines appeared red- shifted relative to spectra observed in the laboratory. The observed red-shift is due to the Doppler effect. Recall, that for objects moving away from us the wavelengths of emitted light are stretched so that we observe longer redder wavelengths. By measuring the amount of wavelength shift we can determine the speed at which the galaxies are receding. With today's lab, you are going to use the Doppler shift information from observed galaxies to determine the age of the universe.

What is the Doppler Effect?

Have you ever heard a police car or ambulance with its siren blaring go rushing by? Notice how the pitch of the siren is higher as it approaches you, then drops to a lower pitch as it recedes. This is due to the Doppler effect. To understand the Doppler effect, Imagine looking down onto a boat on a smooth lake traveling to the left. The waves the boat makes travel out as circles but the waves get compressed in the direction the boat is moving. Likewise, the waves get stretched out in the opposite direction. The compressed waves correspond to a shorter wavelength or higher frequency. The stretched out waves correspond to a longer wavelength or lower frequency. Thus, you can tell if the boat is moving towards or away from you by the wavelength of the waves. The same is true for light.

shorter
wavelength

longer
wavelength
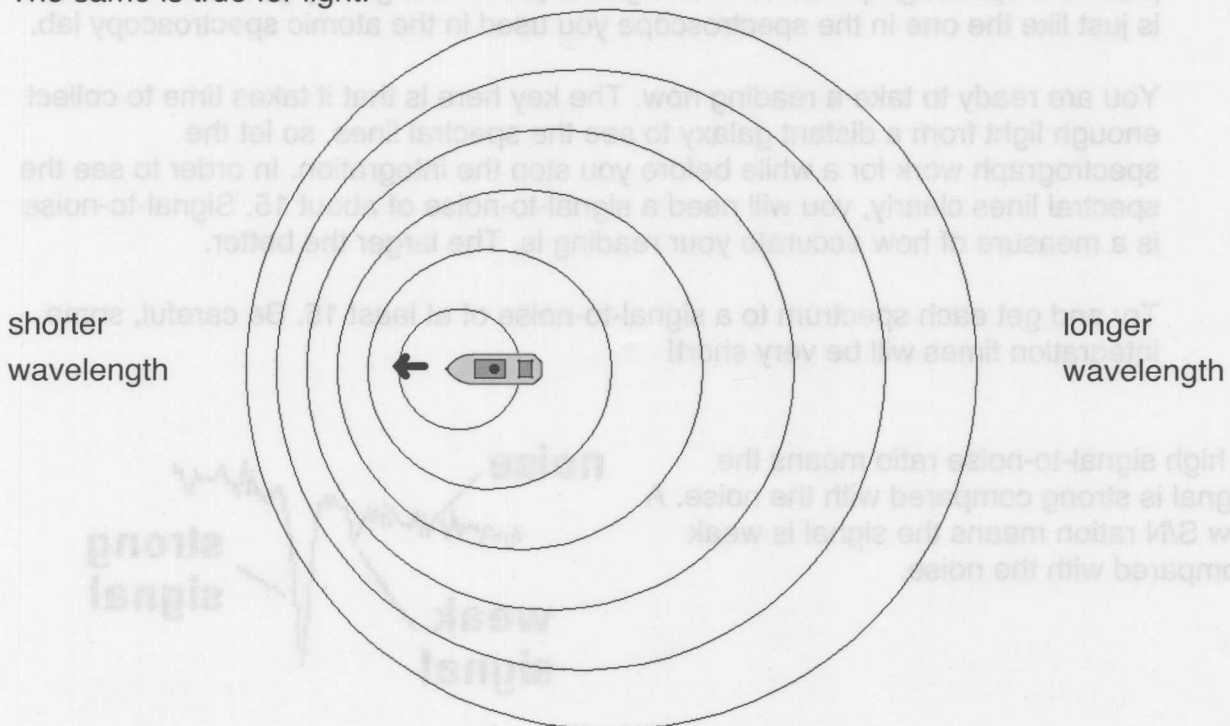
Part 1: Computer Observations

In order to explore the idea of Doppler shifted spectra we are going to use a computer program to simulate observing galaxies. Modern images and spectra of galaxies are obtained on electronic devices and computer processed. In this lab we will simulate such observations to determine galaxy distances and velocities.
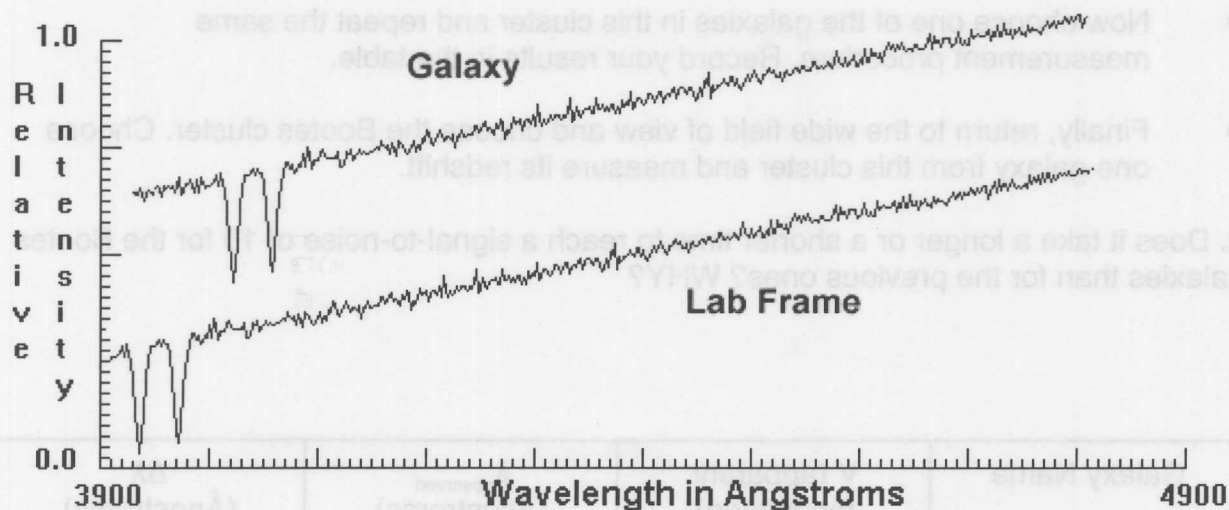
A. Taking the Data

- To start the program click on the button labeled **Part 1.** Click on **Log In** and enter any name on the first line. Click **OK** then click **Yes**. You are going to observe the H absorption lines of Calcium in the spectra of distant galaxies. You are going to use the Doppler shift of these lines to determine the Hubble constant.

- Make sure to open the dome (you should then see the sky slowly drifting past due to the rotation of the Earth).

- Set the telescope to track. This makes the telescope move so that the stars always stay in its field of view. You should also see the Coma I cluster of galaxies.

- Move the telescope using the **N**orth, **S**outh, **E**ast and **W**est buttons to place the cross hairs on one of the three galaxies. Now press the **Change View** button to zoom in on the entrance slit of the spectrograph. Use the **N, S, E, W** buttons to place the spectrograph slit on the brightest part of the galaxy you chose. This slit is just like the one in the spectroscope you used in the atomic spectroscopy lab.

- You are ready to take a reading now. The key here is that it takes time to collect enough light from a distant galaxy to see the spectral lines, so let the spectrograph work for a while before you stop the integration. In order to see the spectral lines clearly, you will need a signal-to-noise of about 15. Signal-to-noise is a measure of how accurate your reading is. The larger the better.

- Try and get each spectrum to a signal-to-noise of at least 15. Be careful, some integration times will be very short!

A high signal-to-noise ratio means the signal is strong compared with the noise. A low S/N ration means the signal is weak compared with the noise.

R e l a t i v e **I n t e n s i t y**

1.0

0.0

3900   **Wavelength in Angstroms**   4900
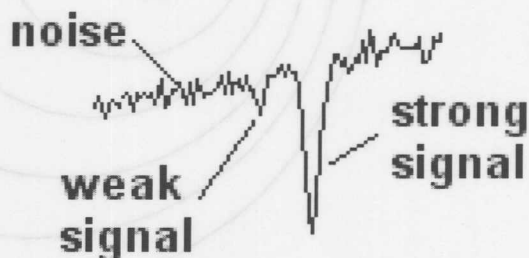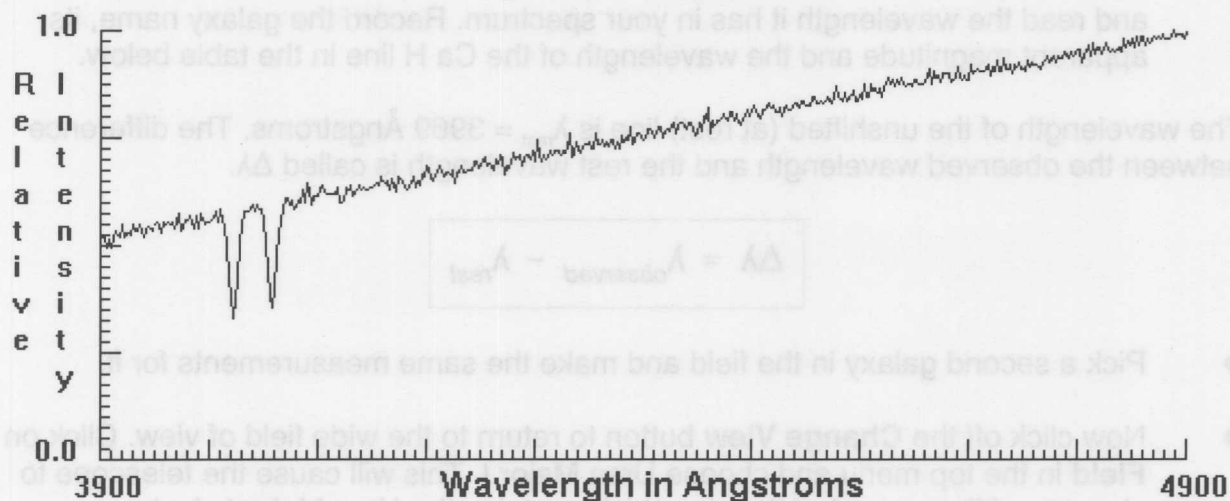
Your spectrum will look something like this. Notice the two absorption lines in the
spectrum. These are due to the element Calcium in the atmospheres of the stars that
make up the galaxy.

R e l a t i v e **I n t e n s i t y**

1.0

Galaxy

Lab Frame

0.0

3900   **Wavelength in Angstroms**   4900

Here we compare the spectrum of the galaxy with an absorption spectrum taken in the
lab here on Earth. Notice that the absorption lines in the galaxy are shifted to longer
wavelengths. This is due to the Doppler Effect which is caused by the motion of the
galaxy away from the Earth.

- Click on the Calcium H absorption line (the right hand of the two absorption lines) and read the wavelength it has in your spectrum. Record the galaxy name, its apparent magnitude and the wavelength of the Ca H line in the table below.

The wavelength of the unshifted (at rest) line is λ_{rest} = 3969 Ångstroms. The difference between the observed wavelength and the rest wavelength is called $\Delta\lambda$.

$$\Delta\lambda = \lambda_{observed} - \lambda_{rest}$$

- Pick a second galaxy in the field and make the same measurements for it.

- Now click off the **Change View** button to return to the wide field of view. Click on **Field** in the top menu and choose Ursa Major I. This will cause the telescope to slew to a different part of the sky which contains the Ursa Major I cluster.

1. Compare the image of the galaxies in the first field to the second. The galaxies in the second field are further away. What characteristics of their physical appearance would make you infer they are further away?

- Now choose one of the galaxies in this cluster and repeat the same measurement procedure. Record your results in the table.

- Finally, return to the wide field of view and choose the Bootes cluster. Choose one galaxy from this cluster and measure its redshift.

2. Does it take a longer or a shorter time to reach a signal-to-noise of 15 for the Bootes galaxies than for the previous ones? WHY?

Galaxy Name	V (apparent magnitude)	$\lambda_{observed}$ (Ångstroms)	$\Delta\lambda$ (Ångstroms)

B. Distances and Velocities

Now that you have the wavelength shifts, you need to figure out how far away the galaxies are. You would expect more distant galaxies to be fainter than nearby examples. Indeed this is the case and we can use this fact to find the distances to the galaxies you measured. If we assume all galaxies have the same intrinsic brightness of $M_V = -22$ magnitudes, we can compute the distance using the same formula you used in the HR Diagram lab.

$$distance \ (in \ pc) \ = \ 10^{(V-M_V+5)/5}$$

1. Compute the distances to your galaxies based on their apparent magnitude. Don't forget to divide your answer by 10^6 to get your results in Megaparsecs, not parsecs. Put your values in column 2 of the table below. **Check with the TA after your first Table 2 entry to be sure you are doing things correctly!**

2. Use your measured value for $\Delta\lambda$ to calculate the velocity of each galaxy. Use the Doppler shift relation

$$Velocity \ = \ \frac{\Delta\lambda}{\lambda_{rest}} c$$

where c is the speed of light, 3×10^5 km/s. Place these values into column 3 in the table below. Show your work !!

For column 4, convert the velocity from kilometers per second (km/s) to Megaparsecs per billion years (Mpc/Gyr) using

$$V \ (Mpc/Gyr) = V \ (km/s) \div 980$$

This is a measure of how many million parsecs a galaxy will travel in one billion years, which is more useful than kilometers and seconds for this lab. Refer back to page iv for the definition of terms such as mega (million) and giga (billion).

Galaxy Name	Distance (Mpc)	Velocity (km/s)	Velocity (Mpc/Gyr)	H (km/s/Mpc)	H (Mpc/Gyr/Mpc)

C. The Hubble Law:

Hubble was the first to discover that there was a relation between the velocity of a galaxy and its distance. He found that the velocity of a galaxy is proportional to its distance. Mathematically this can be written as

$$V = H \times D \quad \text{or} \quad H = \frac{V}{D}$$

1. Using this equation, calculate the value for the Hubble constant **H** based on your observations of each of the four galaxies. Put your answer in the columns 5 and 6 in the table above. Note: although we are going to use **H** in units of Mpc/Gyr/Mpc in this lab, astronomers usually measure **H** in units of km/s/Mpc. Now compute the average of the four values.

average **H** = _____(Mpc/Gyr/Mpc)

2. For each galaxy plot (page 110) its velocity in Mpc/Gyr on the y-axis and its distance on the x-axis. Draw a best fit straight line through the points making sure it passes through the origin at 0,0. Calculate the slope of the line in units of (Mpc/Gyr/Mpc). This is also **H**.

slope of best fit line **H** = _____

Why must the line pass through 0,0?

3. How does this compare with your value of **H** calculated by averaging the results of the four individual galaxies? Which do you think is a more accurate way to determine **H**?

Part 2: Computer Simulation of an Expanding Universe

In Part 1 you made measurements of the redshift of several galaxies in a manner very similar to what astronomers do at their telescopes. To develop a better visual picture of what an expanding universe is like, your group will now work with a computer

program that creates a hypothetical universe that you can move forward and backward in time and directly observe the movement of the galaxies.

- Click on **Quit** on the program for Part 1, exit the program and then click on the button labeled Part 2.

- Enter any four digit number that comes to mind. This number is the seed for the random generator that will create your universe of galaxies. Click on the Enter button.

Four Digit Number _____

- Along the top of the screen are your instructions and data. Choose a home galaxy near the center of the screen. Then choose three more galaxies, one nearby, one about an inch away, and one about two inches away. As you choose a galaxy, record in the table below how far away it is from your home galaxy.

- Now the Universe is at the current Epoch (right now). Send the universe into the future a few billion years by clicking several times the button labeled Go Forward 1 Gyr. Watch how the galaxies move apart. Now click Go Back 1 Gyr till you get back to the present. Repeat this a few times so that everyone in the group can see how the universe expands and contracts. The epoch is given at the top left of the screen.

- Now go forward in time to 8-10 or so billion years in the future. Record this time in the table. Click on each of your chosen galaxies. The computer will compute how many megaparsecs the galaxy has moved. Record these values in the table.

1. Compute the Velocity and record this in the table.

Velocity = (Distance Traveled) / (Time Elapsed)

Galaxy #	Starting Distance to Galaxy (Mpc)	Time Elapsed (Gyr)	Distance Traveled (Mpc)	Velocity (Mpc/Gyr)
1				
2				
3				

In an identical manner to Part 1, plot velocity on the y-axis and starting distance on the x-axis for your 'data'. Draw in your best fit straight line to the points (remember to make the line go through 0,0) and compute its slope. This is the Hubble constant **H**.

slope of best fit line **H** = _____

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2. Now click on the button 'START OVER'. Enter the EXACT same 4 digit number you used the first time and click on 'ENTER'. You should get the exact same distribution of galaxies you had before. This time, choose a DIFFERENT HOME GALAXY. Again, choose 3 other galaxies and then advance the age of the universe.

Compute the Velocity and record this in the table.

Velocity = (Distance Traveled) / (Time Elapsed)

Galaxy #	Starting Distance to Galaxy (Mpc)	Time Elapsed (Gyr)	Distance Traveled (Mpc)	Velocity (Mpc/Gyr)
1				
2				
3				

Using a different symbol, plot your results for this new home galaxy. Draw your best fit straight line to these new points and compute its slope (remember to make the line go through 0,0). Again, this is the Hubble constant.

Slope of best fit line for new home galaxy *H* = _____

3. How do your two values for the Hubble constant from PART 2 compare? Does it make any difference which galaxy you choose as your home galaxy?

4. Calculate the average values of the four Hubble Constant values (from part 1 and part 2) and the percent (%) difference between the minimum and the maximum.

%diff = (max - min)/average X 100%

5. Compare your results for Part 1 and Part 2? Did you get similar results, or very different results?

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Part 3. The Age of the Universe

If the galaxies in the Universe are all moving away from one another, then they should have been much closer together sometime in the past. In fact, at some time in the past, all the matter in the Universe must have been crushed together in an extremely dense and hot state. This is what astronomers call the Big Bang. Your group can now estimate how long ago the Big Bang took place using your value of the Hubble Constant. The Hubble constant tells us the current rate at which the Universe is expanding. The inverse of the Hubble constant tells us the time since the Universe began expanding (The Big Bang).

Age of the Universe ≈ 1/H

The units of H are Mpc/Gyr/Mpc, or 1/Gyr. So in your units, simply take the inverse of **H** from from the average you found to get the age of the Universe in billions of years.
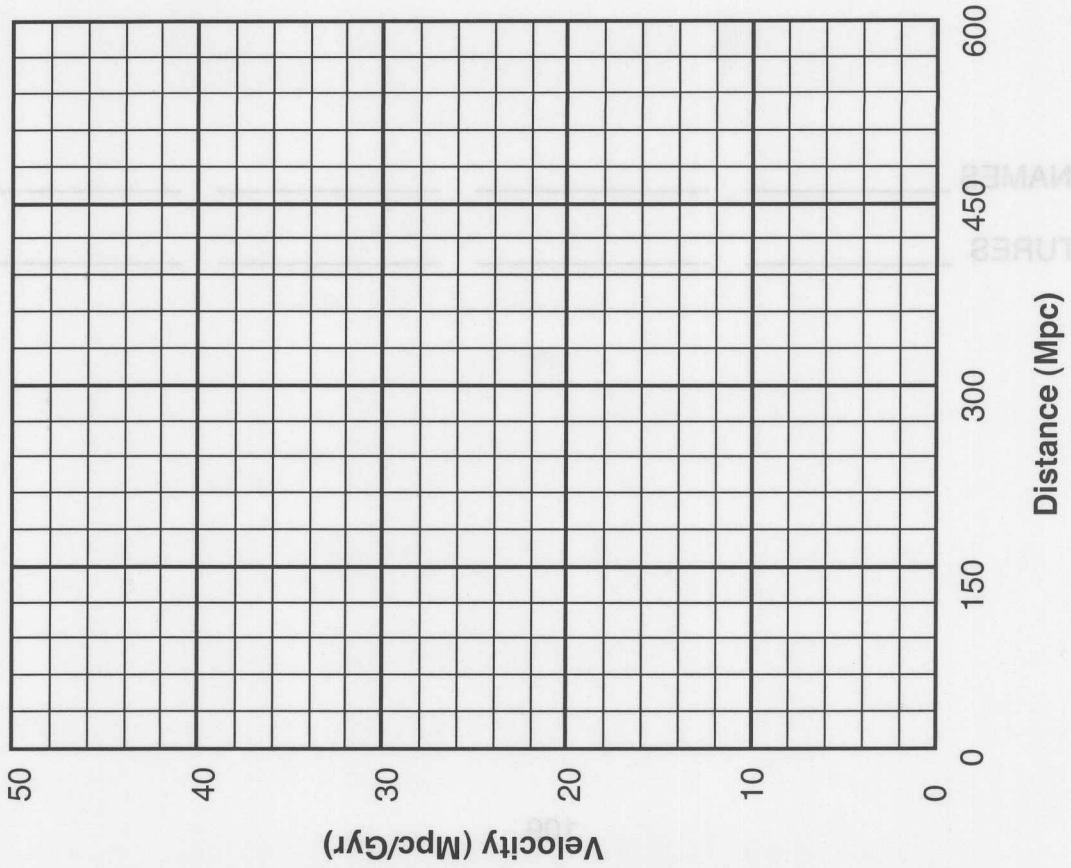
Age of the Universe _____ billion years.

Now, slowly click on the **Go Back 1 Billion years (1Gyr)** button on the screen the number of Gyrs you just calculated for the age of the Universe. Stop when you reach the age of the Universe you just calculated. How close to the Big Bang did you come?

PRINT NAMES _____ _____ _____ _____

SIGNATURES _____ _____ _____ _____

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Part 3. The Age of the Universe

If the galaxies in the Universe are moving away from one another, then they should have been much closer together in the past. In fact, at some time in the past, all the matter in the Universe might have been compressed together in an extremely dense and hot state. This small size or is called the Big Bang. Your group can now estimate how long ago the Big Bang took place using your value of the Hubble constant. The Hubble constant tells us the current rate at which the Universe is expanding. The inverse of the Hubble constant tells us the time since the Universe began expanding (The Big Bang).

$$\text{Age of the Universe} = 1/H$$

The units of H are in Mpc/Myr or ... , so if your form simply take the inverse of H from ... the average you found to get the age of the Universe in billions of years.

Age of the Universe = _____ billion years.

Now, slowly click on the red clock 1 billion years (1 Gyr) button on the screen. The number of Gyrs you just decreased for the age of the universe, stop when you reach the age of this universe you just calculated. How close to the big bang did you come?

Part 2

Velocity (Mpc/Gyr) vs. Starting Distance (Mpc)

Part 1

Velocity (Mpc/Gyr) vs. Distance (Mpc)