The Expanding Universe

Introduction

In this lab you will estimate the expansion rate of the universe (the Hubble constant) and the age of the universe.

In the 1920's, Edwin P. Hubble discovered that distant galaxies were all moving away from the Milky Way. Not only that, the farther away he observed, the faster the galaxies were receding. He found the relationship that is now known as Hubble's Law: the recessional velocity of a galaxy is proportional to its distance from us. The equation is:

$$v = H_o \times d,$$

where v is the galaxy's velocity (in km/sec), d is the distance to the galaxy (in megaparsecs; 1 Mpc = 1 million parsecs), and H_o is the proportionality constant, called "The Hubble constant."

The value for the Hubble constant, which gives the age of the Universe, has been an area of ongoing debate since Hubble's first measurement. Different methods often give conflicting estimates. However, the Hubble Constant is one of the most important numbers in cosmology because it is a measure of the age of the universe. This long-sought-after number indicates the rate at which the universe is expanding, the velocity stemming from the primordial "Big Bang." The Hubble Constant can be used to determine the intrinsic brightness and masses of stars in nearby galaxies, examine those same properties in more distant galaxies and galaxy clusters, deduce the amount of dark matter present in the Universe, obtain the scale size of faraway galaxy clusters, and serve as a test for theoretical cosmological models.

In the last lab or the semester, we will determine our value for the Hubble constant and get from it the age of the Universe. You will need to decide which galaxies to use for your calculation, then move to finding the recessional velocity for each galaxy and its distance. Your data analysis will lead to your value for the Hubble constant, the uncertainty in the value, and the age of the Universe. This lab uses much of the knowledge you have gained over the past semester.

Procedure

Step 1: Getting to Know the Galaxies

Our first step will be to become familiar with the images and the spectra of the galaxies with which we will be working. These images and spectra are real data, and were obtained using a CCD (charge-coupled device) on a couple of large (2 - 4 meter), ground-based telescopes.

Look through the 27 galaxy spectra shown on the galaxy spectra page.
You can click on a galaxy image at left to zoom in on the image - note that the image is inverted (light and dark are reversed). Look at the general shapes of the different galaxy images.

We divide galaxies by shape into *spiral* and *elliptical* categories. The primary objects found in spiral galaxies are stars of all ages, masses, and composition; dust; and hydrogen gas. We see star formation from regions of gas in spiral galaxies, and spiral galaxies contain younger stars. The bright hydrogen gas regions and massive but short-lived stars will dominate the light of a spiral galaxy, both producing strong emission lines of hydrogen.

On the other hand, most elliptical galaxies contain old, cool stars. There is little or no free dust and gas in ellipticals, and no massive star formation. We expect to see absorption lines dominating the spectra of elliptical galaxies, especially lines of ionized calcium (CaII H & K) and hydrogen.

The spectra to the right of the images plot the relative intensity of the total light radiated from each galaxy as a function of wavelength. The underlying shape or curve of each spectrum is due to the continuous spectra from those stars that dominate the light coming from the galaxy (thermal radiation). Where you see dips in the spectrum of a galaxy, particular wavelengths of radiation are being absorbed. Where you see sharp spikes in the spectrum of a galaxy, radiation is being emitted. The spectra from these galaxies reflect the combined light from all of the objects in them.

There are a couple of features you should especially note when trying to decipher these spectra:

- Not all of the "jiggly" lines come from the light of the galaxy. Each spectrum contains noise; we just cannot get away from it. Some of the spectra are much "noisier" than other spectra. This noise tends to hamper accurate identification of some of the lines.

- Many of the spectra show strong hydrogen emission lines along with some absorption lines. Note that the "relative intensity" axes are not all at the same scale. Some spectra will look "flat" because the scaling had to be adjusted to accommodate an intense hydrogen emission line, usually at 656.28 nm = 6562.8 Angstroms. The relative intensity for some spectra ranges from 0 to 1.2; for others, from 0 to 15.
- Some spectra show only absorption lines, or absorption lines with very weak hydrogen emission lines.

What these spectra tell us

These plots of "jiggly lines" are telling us all about these galaxies, just as stellar spectra tell us all about stars. The spectrum of a galaxy will represent the total light coming from those objects that are contributing the most to the light of the galaxy. These objects will be those that far outnumber other objects, or are the most luminous (red giants), or both.

1. Most of the emission lines readily apparent in most of these spectra are due to hydrogen. What kind(s) of galactic objects might produce hydrogen emission lines?

2. Which type(s) of galaxies do you expect would show only absorption lines?

Fill out the table on the next page with data about the different galaxies. Some entries are filled in. Note in the description of the spectrum:

- Which galaxies show emission lines? (Look specifically around the wavelength regions of 6600, 4900, and 4200 Angstroms.)
- Which galaxies show primarily absorption lines including strong H and K lines? (Look specifically around the wavelength region of 4000 Angstroms.)

NGC#	Type	Description of spectrum	
1357	Spiral	Emission spike around 6600 Å, some absorption lines too.	Y
1832	Spiral	Huge spike at around 6600 Å, plus other spikes.	Y
2276			
2775	Elliptical	Strong absorption (deep dips), not much emission.	N
2903			
3034			
3147			
3227			
3245			
3310	Spiral (a bit wonky)	GIGANTIC emission spikes compared to continuous part.	N
3368			
3471			
3516			
3263			

NGC#	Type	Description of spectrum	
3627			
3941	Elliptical	Deep absorption lines, no emission spikes.	N
4472			
4631			
4775			
5248			
5548	Spiral	Huge spike around 5100 Å and a fat spike around 6600 Å.	Y
5866			
6181			
6217	Spiral	Huge spike around 6600 Å, small spike around 4900 Å.	Y
6643			
6764	Spiral	Large spike around 6600 Å and small spikes at 4900, 5100 Å.	Y
7469	Spiral	Emission spikes at 4900, 5100, and 6700 Å, minimal absorption	N

Step 2: Selecting Your Galaxies

We will select a sample of about 15 galaxies for further study. To make this task a bit faster, 5 galaxies have already been selected, and a few already eliminated. You will need to choose about 10 more galaxies and eliminate the rest.

Criteria:

We will later use to use the size of galaxies in the sky to estimate how far away they are. We need to assume galaxies of a similar type are similar in actual size. In this lab, we choose to work only with spiral galaxies.

A secondary criterion is similar spectral characteristics. As you review your classifications of the galaxies and your descriptions of the spectra, do you see any pattern or correlation?

You will be looking for absorption lines of ionized calcium, lines designated by "H" and "K" [rest wavelengths of 396.85 and 393.37 nm (3968.5 and 3933.7 Angstroms)] and the emission of the H-alpha line of hydrogen [rest wavelength of 656.28 nm (6562.8 Angstroms)]. But remember: these spectra are of galaxies that are moving away from us and so the lines are going to be redshifted (shifted towards longer wavelengths); some, you will find out, by a large amount.

The galaxies with clear lines are marked with ' - ' on this page: http://www.astro.washington.edu/courses/labs/clearinghouse/labs/HubbleLaw/galaxies.html. It is entirely acceptable to eliminate galaxies if spectra are "ugly" and lines are hard to identify - for example, NGC 3310 is ruled out because it has a weird spectrum - or if the angular size of the galaxy looks hard to estimate. Just make sure you choose a minimum of 10 additional galaxies for your graph.

In the last column of the galaxy and spectra overview table, mark down your decision to keep or toss that particular galaxy.

Step 3: Recessional velocities

The velocity of a galaxy is measured using the Doppler effect. The radiation coming from a moving object is shifted in wavelength, producing a redshift according to the formula:

$$\frac{v}{c} = z = \frac{\lambda_{\text{measured}} - \lambda_{\text{true}}}{\lambda_{\text{true}}}$$

Here v is the recessional velocity of the galaxy and c is the speed of light, which is about 300,000 km/sec. The ratio v/c is called the redshift, or z. The wavelength λ_{true} is the wavelength that would be observed from an object at rest, such as in a lab, and $\lambda_{\text{measured}}$ is the wavelength measured from a moving object.

Example: An absorption line is measured in the lab at 5000 Å. When analyzing the spectrum of a certain galaxy, the same line is found at 5050 Å. The shift is 50 Å. The redshift is $z = 50/5000 = 0.01$. Knowing the speed of light, we calculate that this galaxy is receding at $v = 0.01$ c or approximately 3000 km/s.

We consider three common spectral lines: the hydrogen-alpha emission line (656.28 nm, or 6562.8 Å), as well as the "K and H" absorption lines of ionized calcium (393.37 and 396.85 nm, or 3933.7 and 3968.5 Å).

The following page links to zoomed-in portions of the spectra for different galaxies, focusing on the regions where the above lines are found: http://www.astro.washington.edu/courses/labs/clearinghouse/labs/HubbleLaw/galaxies.html

Fill in the Spectra and Velocity parts of the data table at the end of the lab.

Note that for each galaxy there are two entries in each spectral line column. The top entry is the measured wavelength. The bottom entry contains the calculated redshift. To find the average redshift, sum your three redshifts and divide by three. Then multiply by 300,000 km/sec to find the recessional velocity.

Start with NGC 1357 and NGC 1832 to see if you can duplicate or come close to the values discussed under the analysis. Note how the data table has been filled in and make sure you understand what data goes where and what calculations are being done.

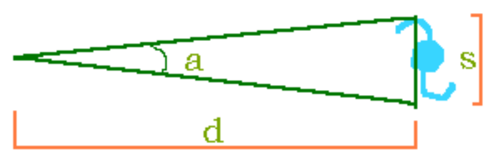
Step 4: Distance to each galaxy

A trickier task is to determine the distances to galaxies. For nearby galaxies, we can use standard candles such as Cepheid variables or Type I supernovae. But, for very distant galaxies, we must rely on more indirect methods. The key assumption for this lab is that galaxies of similar Hubble type are, in fact, of similar actual size, no matter how far away they are. This is known as "the standard ruler" assumption.

We can relate the distance and size of galaxies using the small-angle approximation:

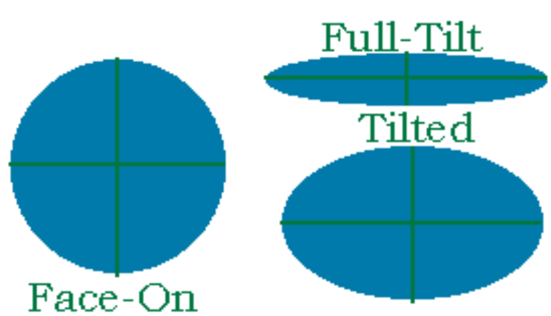
$$a = s / d$$

$$d = s / a$$



where a is the measured angular size (in radians), s is the galaxy's true size (diameter), and d is the distance to the galaxy.

We also have to be careful about how we measure size. The schematic below shows a galaxy viewed from three different angles. We assume that the spirals are all round disks, and that their different shapes are simply because we are viewing them from different angles. So we will always want to measure the size of the galaxy along it's longest part.



We calibrate the actual size by using a galaxy to which we know the true distance: the nearby spiral galaxy M31, the Andromeda galaxy. We know the distance to the Andromeda galaxy through observations of the Cepheid variables in it, and can thus use it's angular size to determine that the Andromeda galaxy is 22 kpc (1 kiloparsec = 1000 pc) across.

We could find the distance to the galaxies using lengths measured in kiloparsecs:

distance (kpc) = size (kpc) / angle (rad)

But given the enormous distances involved, we multiply the left side by 1000, producing a distance in Mpc, and dividing the right side by 0.001 (which is eqivalent mathematically), producing an angular size in milliradians or mrad:

distance (Mpc) = size (kpc) / angle (mrad)

The angular size of the galaxy is measured by using its image link on

http://www.astro.washington.edu/courses/labs/clearinghouse/labs/HubbleLaw/galaxies.html

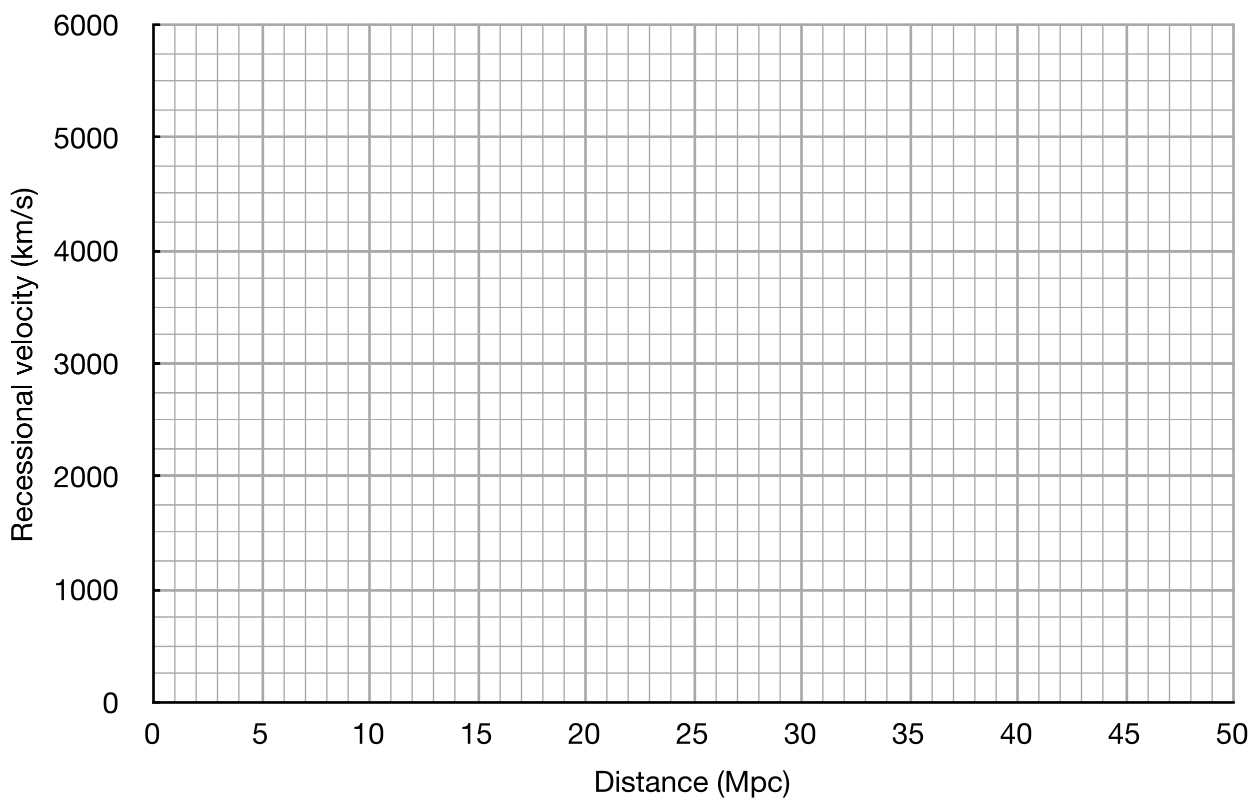
- Note that the images used in this lab are negatives, so that bright objects -- such as stars and galaxies -- appear dark. There may be more than one galaxy in the image; the galaxy of interest is always the one closest to the center.
- To measure the size, simply move the mouse and click on opposite ends of the galaxy, along its longest part. (You will need to make a total of two clicks, hit try again if you mess up.) **Try to include all of the fuzzy disk surrounding the bright core.**
- The angular size of the galaxy (in milliradians; 1 mrad = 0.057 degrees = 206 arcseconds) will be displayed
- Make a few measurements to make sure your results are consistent with each other. This measurement involves some judgement calls as to where exactly the disk ends, so expect some variation.
- Write your best estimate of the galaxy size down on your data table given in the student answer sheets, under "Galaxy Size."
- **Check that you get roughly similar values to the filled-in entries before continuing with the rest of the galaxies.**
- Calculate the distance in Mpc using

  distance (Mpc) = size (kpc) / a (mrad)

  with the assumed size of each galaxy being 22 kpc.

NGC	Line: Ca K 3933.7Å	Line: Ca H 3968.5Å	Line: H-alpha 6562.8Å	Avg. redshift	Velocity (km/sec)	Galaxy size (mrad)	Distance (Mpc)
1357	3962.0	3997.2	6608.6	0.0071	2100	0.982	22
	0.0071	0.0072	0.0070				
1832	3960.5	3994.8	6607.0	0.0066	2000	0.879	25
	0.0067	0.0066	0.0067				
5548	4002.6	4040.9	6675.7	0.0176	5270	0.507	43
	0.0173	0.0183	0.0172				
6217	3950.3	3985.6	6590.7	0.0042	1260	0.724	30
	0.0042	0.0043	0.0042				
6764	3966.0	4010.2	6612.1	0.0087	2623	0.782	28
	0.0082	0.0105	0.0075				

NGC	Line: Ca K 3933.7Å	Line: Ca H 3968.5Å	Line: H-alpha 6562.8Å	Avg. redshift	Velocity (km/sec)	Galaxy size (mrad)	Distance (Mpc)



Analysis

Hubble's constant

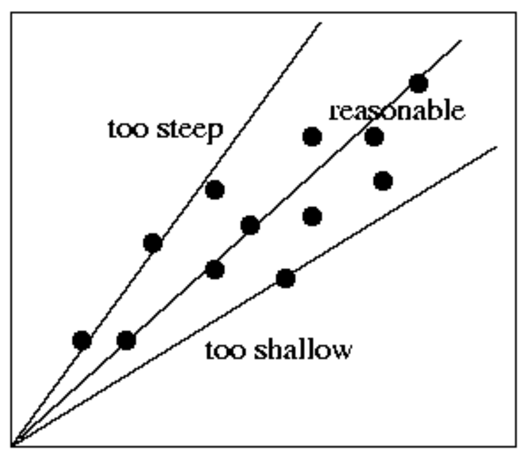
Using the graph at the end of this answer sheet, plot your data with distance in megaparsecs (Mpc) on the x-axis, and velocity in kilometers per second (km/s) on the y-axis.

Draw a straight line that you estimate to best fit the data in the graph; remember that this line must pass through the origin (the 0,0 point).

3. Why must the line pass through the origin? What gives you this data point?

4. Calculate the slope of the line (rise/run). This is your value of the Hubble constant, in the units of km/sec/Mpc. Show your calculation:

Hubble's Law predicts that galaxies should lie on a straight line when plotted on a graph of distance vs. velocity. The measured data will not make a perfectly straight line, so you had to make a guess as to where to draw your best fit line. One simple way to estimate the uncertainty in the value of Ho is to draw the steepest reasonable line and the shallowest reasonable line on the graph.



5. What are the slopes of the steepest and shallowest reasonable lines on your plot?

6. Half of the difference between these two slopes is the estimated error in your measurement. What is the uncertainty in your value of H_o?

Sources of error

7. One obvious source of error is the assumption we made that all spiral galaxies have the same actual diameter. How would an over-estimate or an under-estimate of the size of a galaxy affect your estimate of the distance to it? Explain. Draw a diagram if you want.

8. Quantitatively (give some numbers) how precise do you believe your measurements to be for the wavelengths? For the angular sizes?

9. What was an example of something that affected the precision of your measurements?

10. Another consideration is the fact that galaxies are found in groups or clusters. The motion of these galaxies through space as they orbit in their cluster is called peculiar motion, and it adds to the overall motion from the Hubble expansion: some galaxies will be receding more slowly than others in the cluster while others will be receding more quickly. How does this peculiar motion affect your velocity measurements?

The Age of the Universe

We see galaxies receding from us at velocities proportional to their distance. How long has it taken the galaxies to to that distance? Distance is velocity multiplied by the time spent traveling. The time spent traveling - the age of the universe - would be galactic distance divided by galactic velocity. Hubble's constant is galactic velocity divided by galactic distance, so the universe's age is $1/H_o$. (This assumes the universe expands at a constant rate.) To find the age of the Universe:

- Convert your H_o from km/sec/Mpc to inverse seconds (s^{-1}) by converting units: *divide* by 3.1×10^{19} km per Mpc.
- Invert the result to get the age of the universe in seconds.
- Convert to years: *divide* by 3.16×10^{7} sec/yr.
-

EXAMPLE:
Your Hubble constant is 75 km/sec/Mpc, which is equivalent to

$$(75 \text{ km/sec/Mpc}) / (3.1 \times 10^{19} \text{ km/Mpc}) = 2.4 \times 10^{-18} \text{ s}^{-1}$$

The age of the Universe in seconds is:

$$1/ (2.4 \times 10^{-18} \text{ s}^{-1}) = 4.1 \times 10^{17} \text{ s}$$

The age of the Universe in years is:

$$(4.1 \times 10^{17} \text{ s}) / (3.2 \times 10^{7} \text{ s/year}) = 1.3 \times 10^{10} \text{ years}$$

This is equivalent to 13×10^{9} years, or 13 billion years.

11. What age of the Universe is predicted by your Hubble Constant?

This age represents a very simple model for the expansion of the universe, with a constant rate of expansion; we now know (from looking at even more distant galaxies) that the speed of the universe expansion has changed over its history.

The current best estimate of the age of the universe is from the Planck satellite observations of relic radiation from the hot early universe: 13.82 billion years. Planck data suggests a Hubble Constant of 67.3 ± 1.4 km/s/Mpc. However, recent estimates of the Hubble constant from supernovae measurements are 74.2 ± 3.6 km/s/Mpc. While the difference between these values isn't extreme, we still have more to learn about the history of our universe.