# 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:

$$v = H_0 \times d$$

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 $H_0$ 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 on the [Galaxy Spectra Page](#) that we'll be working with. 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. Note that the image is inverted (light and dark are reversed).

<u>We divide galaxies by shape into **spiral** and **elliptical** categories.</u>

Notice in the diagram here that there are further classifications. When observing the galaxies given you can always search them by NGC number to find the specific category they are in.
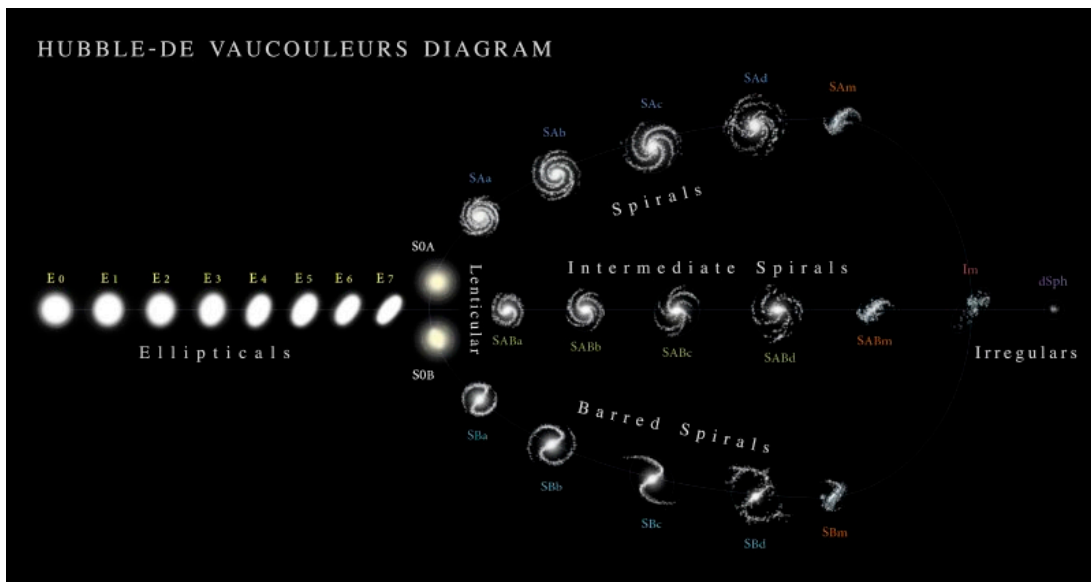


**Figure 1: <u>Hubble Vaucouleurs Diagram</u>**

For simplicity just focus on Ellipticals(Left) vs Spirals(Right)

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.

Take a look at the image for NGC1357. This is an example of a spiral galaxy.

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.

Take a look at the image for NGC3941.This is an example of an elliptical galaxy

1. Click through some other galaxies and find two other examples of clearly spiral galaxies and write their catalogue numbers here.

## We can also get information from their spectra

The spectra in the right column of the Galaxy Spectra Page plots 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.

Take a look at the spectra for NGC1357

- The full Spectrum is displayed on the top left of the page
- The bottom left graph specifically shows the Intensity of wavelengths around 3900 Angstroms to observe the absorption lines from Ca K and Ca H.
    - The black lines on the bottom tell you where the absorption dips should be (at 3933.7A and 3968.5A)
    - Notice the two dips for NGC1357 are slightly to the right. Click the first dip and confirm its around 3962A instead of 3933A.
- The bottom right graph is focused around the emission lines for hydrogen alpha.
    - Again the black line on the bottom tells you where it "should" be, at 6562.8A.
    - Click the emission peak and verify its actually at around 6608A.

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 this 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.


2. Open up NGC 4775's spectra and identify the absorption values for Ca K, and Ca H in Angstroms.



3. Also for NGC 4775 find the value for the Hydrogen alpha emission in Angstroms.

## 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.

4. 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?

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

You'll find a table on the next page with information about galaxies, some entries are already filled in to help you out.

Note that any galaxy with a "-" in front has easily identifiable spectral lines, be sure to pick a good number of these.

6. Pick 5 other galaxies that are currently blank and fill out their table entry on the next page by identifying their type and describing their spectrum.
   Specifically note in your 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 | Keep? |
|------|------|------------------------|-------|
| 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 | Keep? |
|---|---|---|---|
| 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 10 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 5 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 Hubble Law Links to Clickable Images and Spectra.

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 5 additional galaxies for your graph.

7. In the last column of the galaxy and spectra overview table, mark down your decision to keep or toss that particular galaxy. If you don't have at least 5 additional acceptable galaxies (10 total) then go back to 6 and find more until you do.

For this lab we'll give you the data for all the galaxies, you'll just work through a couple of examples then use the data for those you have chosen.

## Step 3: Calculating Recessional Velocities

### Method

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 $z$ according to the formula:

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

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 $\lambda_{true}$ is the wavelength that would be observed from an object at rest, such as in a lab, and $\lambda_{measured}$ is the wavelength measured from a moving object.

If we can find $z$ from the shift in wavelength we can then use that to find the recessional speed using some algebra:

$$v = z * c$$

### 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 in wavelength is

$$\lambda_{measured} - \lambda_{true} = 5050 \ \text{Å} - 5000 \ \text{Å} = \ 50 \ \text{Å}$$

The redshift is

$$z = \frac{\lambda_{measured} - \lambda_{true}}{\lambda_{true}} = \frac{50\text{Å}}{5000\text{Å}} = \ 0.01$$

Knowing the speed of light, we calculate that this galaxy is receding at

$$v = 0.01 * c = \ approximately \ 3000 \ km/s$$

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 Å and 3968.5 Å).

## Practice

Return to the page from earlier and practice this. [Hubble Law Links to Clickable Images and Spectra](Hubble Law Links to Clickable Images and Spectra)

Show your work for the following two example calculations.

8.  Calculate the z value and recessional speed for NGC 4775 using what you found in 2,3.

9.  Calculate the z value and recessional speed for any one of the other galaxies you kept from earlier.

# Step 4: Distance to each galaxy

## Method

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:

- Since the galaxy is so far away, we know the angle value $a$ in the diagram shown is extremely small.
- When the angle is extremely small $\sin a = a$
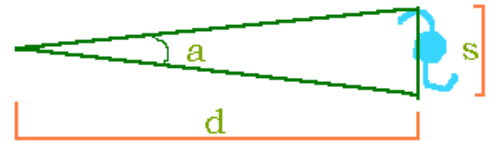
Using the right triangle relations $\sin a = \dfrac{opposite}{hypotenuse}$, and the small angle approximation

$$a = \frac{s}{d}, \qquad d = \frac{s}{a}$$

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 its longest part.
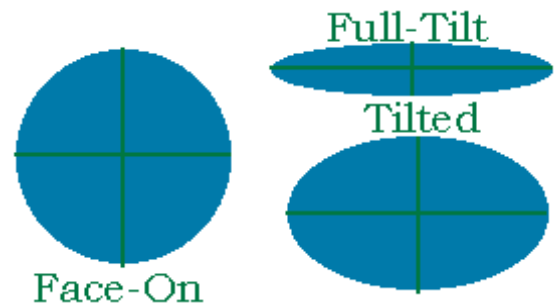
We calibrate the actual size by using a galaxy to which we know the true distance: the nearby spiral galaxy M31, the Andromeda galaxy. We know the distance to the Andromeda galaxy through observations of the Cepheid variables in it, and can thus use its angular size to determine that the Andromeda galaxy 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 Mega parsecs (Mpc), and dividing the right side by 0.001 (which is equivalent 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 Hubble Law Links to Clickable Images and Spectra

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.

## Practice
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

10. Measure the angular size of NGC 1832, which is a Spiral Galaxy. Then use that and the assumed size of 22 kpc to calculate the approximate distance to NGC 1832 in Mega Parsecs. Verify you get around 25 Mpc.

11. Measure the angular size of NGC 4775, which is a Spiral Galaxy. Then use that and the assumed size of 22 kpc to calculate the approximate distance to NGC 4775 in Mega Parsecs.

# Step 5: Analysis

## Hubble's constant

Now open the excel data sheet provided with the lab.

This sheet contains the approximate data for all the galaxies given on the web page.

Start by deleting the rows for all the galaxies you didn't take in 7. This should leave you with the data for at least 10 galaxies, the 5 given plus the 5 you selected. You should also have a 0, 0 value which will force our fit through the origin.

You can also include

12. Why must the line pass through the origin? What gives you this 0, 0 data point?

In Excel create a scatter chart of Recessional Velocity (km/s) versus Distance(Mpc) with your remaining data and add a linear trendline with a forced 0 y intercept.

It should look similar to the one shown here.

- See the Appendix E1 on the course webpage if you need help with this.
- Be sure to check the "Set Intercept" box and that 0.0 is entered in it.
- Note there's a largerpaper graph on the last page of this lab if your instructor prefers you do this by hand.
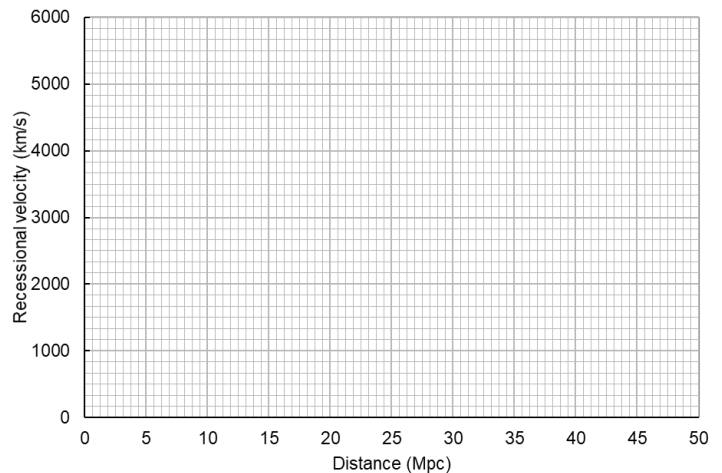
13. What is the slope of your linear fit? Write out the value with the units km/s/Mpc.
This is your value of the Hubble constant $H_0$ using just the data set you've selected

## Error Consideration

Hubble's Law predicts that galaxies should lie on a straight line when plotted on a graph of distance vs. velocity. The measured data you are given are rough estimates will not make a perfectly straight line, meaning there's some real error somewhere, so consider the following.

14. Consider your calculation of the recessional velocity in 8 and 9. What may have caused error in your values?

15. 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?

16. Another source of error is the assumption we made that all spiral galaxies have the same actual diameter. Consider 10 and 11 earlier, 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.

## Step 6: Calculate 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 get 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 x $10^{19}$ km per Mpc.
- Invert the result to get the age of the universe in seconds.
- Convert to years:
    - *divide* by 3.16 x $10^7$ sec/yr.

EXAMPLE:

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

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

The age of the Universe in seconds is:

$$1/ \, (2.4 \; x \; 10^{-18} \; 1/sec \,) \; = \; 4.1 \; x \; 10^{17} \; sec$$

The age of the Universe in years is:

$$(4.1 \; x \; 10^{17} \; sec) \, / \, (3.2 \; x \; 10^7 \; sec/year) \; = \; 1.3 \; x \; 10^{10} \; years$$

This is equivalent to $13 \; x \; 10^9 \; years$, or 13 billion years.

17. What age of the Universe is predicted by your Hubble Constant in billions of years to the nearest hundredth (two decimals)?

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.

Sample Data

| 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 | 3997.2 | 6608.6 | 0.0071 | 2100 | 0.982 | 22 |
| | 0.0071 | 0.0072 | 0.007 | | | | |
| 1832 | 3960.5 | 3994.8 | 6607 | 0.0066 | 2000 | 0.879 | 25 |
| | 0.0067 | 0.0066 | 0.0067 | | | | |
| 5548 | 4002.6 | 4040.9 | 6675.7 | 0.0176 | 5270 | 0.315 | 70 |
| | 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 | 4010.2 | 6612.1 | 0.0087 | 2623 | 0.782 | 28 |
| | 0.0082 | 0.0105 | 0.0075 | | | | |

Plot for hand tracing