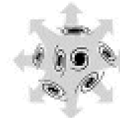
The Hubble Law:

An Introductory Astronomy Lab



Edwin Hubble Discovers the Universe

Credit: Mt. Wilson Archive, Carnegie Institution of Washington Explanation: No person in history has had greater impact in determining the extent of our universe than Edwin Hubble. From proving that other galaxies existed to proving that galaxies move apart from one another, Hubble's work defined our place in the cosmos. Hubble lived from 1889 to 1953 and is shown above posing with the 48-inch telescope on Palomar Mountain and his famous pipe. In memory of his great work, the Orbiting Space Telescope was named after him. Today a great controversy rages on the rate of the universe's expansion, parameterized by a quantity known as Hubble's constant.

Picture and caption from Astronomy Picture of the Day, February 17, 1996. Corner animation adapted from an illustration at STScI public information site.

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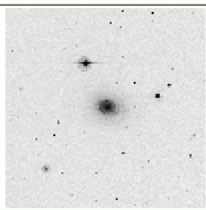
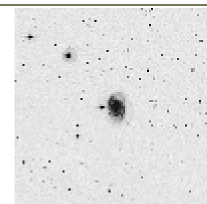
What you will be handing in:
Galaxy and Spectra Overview Sheet
Data Table Sheet
Table of Results and Questions Sheet

This lab represents modifications and additions made by Ana Larson, to the original Hubble Law Lab developed by members of the Astronomy Department at the University of Washington. The real credit goes to the people involved in the original package. The list of the cohorts and information regarding the images and spectra may be found in the credits.

THE HUBBLE LAW

Gallery of Galaxies

	On-line: click on the picture of the galaxy to view the enlarged image.			
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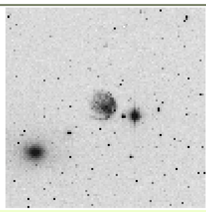	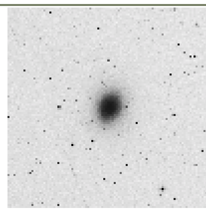	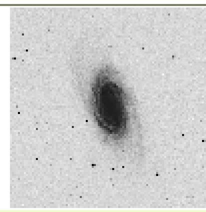	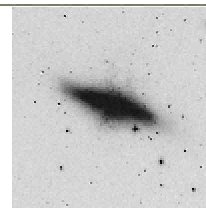	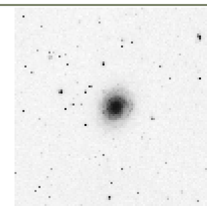
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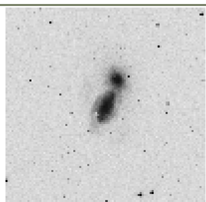	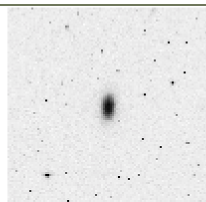	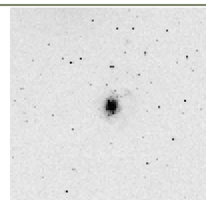	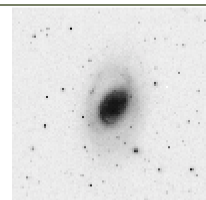	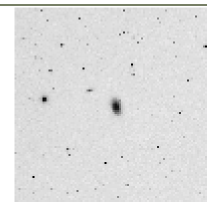
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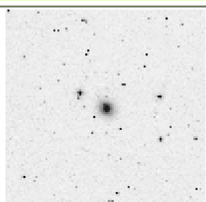	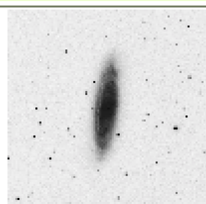	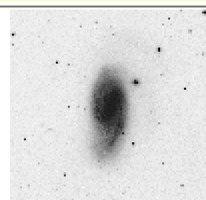	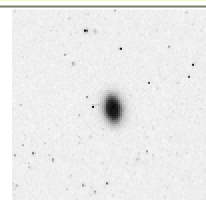	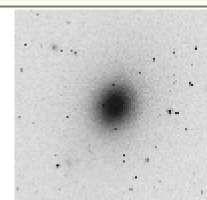
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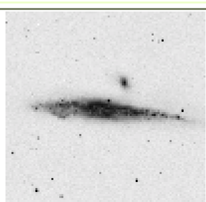	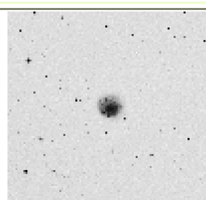	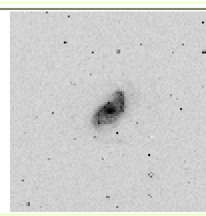	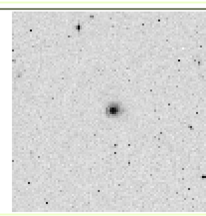	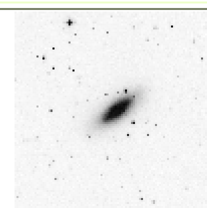
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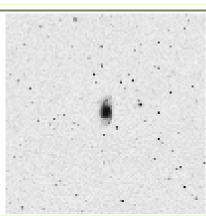
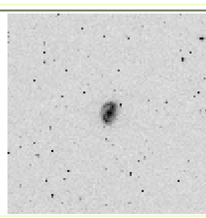
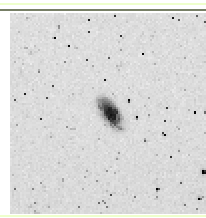
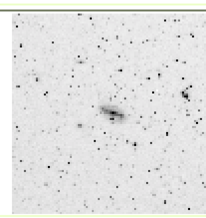
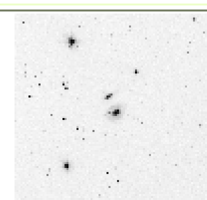
				
NGC 6181	NGC 6217	NGC 6643	NGC 6764	NGC 7469

Objective

To derive a value for the Hubble constant and the age of the universe.

Introduction and Overview

In the 1920's, Edwin P. Hubble discovered that distant galaxies were all moving away from the Milky Way (and the Local Group). 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 looks like this:

$$\mathbf{v = H_o * d}$$

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 $\mathbf{H_o}$ is the proportionality constant, called "The Hubble constant." This equation is telling us that a galaxy moving away from us twice as fast as another galaxy will be twice as far away.

The size of the Universe, as measured by the Hubble constant, continues to be an area of fierce debate. Even the most recent observations of the Hubble space telescope have not silenced the feuding sides. Before the HST observations, one group insisted the value was close to 100 km/sec/Mpc while the other group claimed a value of 50 km/sec/Mpc. Although the sides are now closer, 80 km/sec/Mpc versus 60 km/sec/Mpc, both groups insist that their value is, in fact, the correct value.

Why such a heated debate over a single number? The Hubble Constant is one of the most important numbers in cosmology because it is needed to estimate the size and age of the universe. This long-sought number indicates the rate at which the universe is expanding, 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 short time we have remaining in this quarter, we will enter this debate as we work to determine **our** value for the Hubble constant. Read through the following summary of the steps to be taken and get an overview of what is involved. You won't need to stay up all night making the observations, but you will need to decide which galaxies to use. Once your galaxies are chosen, you will 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 and size of the Universe. This lab uses much of the knowledge you have gained over the past few weeks. Ready? Let's begin.

The Steps Towards the Hubble Constant and the Age of the Universe

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. You will be sketching, classifying, and describing each galaxy

Step 2: Selecting Your Galaxies

Out of the 27 images and spectra of galaxies that are available for analysis, you will need to choose 15 to analyze. We want to use galaxies that have similar looks and characteristics so that we can be relatively sure we are using galaxies that are all the same actual size. We do this by seeing how they **look** and what their **spectra** are like. We want spiral galaxies; we do not want elliptical galaxies.

Step 3: Finding the velocity of each galaxy

The velocity is relatively easy for us to measure using the Doppler effect. An object in motion (in this case, being carried along by the expansion of space itself) will have its radiation (light) shifted in wavelength. For velocities much smaller than the speed of light, we can use the regular Doppler formula:

$$\frac{(\lambda - \lambda_o)}{\lambda_o} = \frac{v}{c}$$

λ **measured wavelength**
λ_o rest (laboratory) wavelength
v velocity
c speed of light

The quantity on the left side of this equation is usually called the **redshift**, and is denoted by the letter **z**. The **velocity** of the galaxy is determined by measuring the redshift of spectral lines in the **spectrum** of the galaxy. The full optical spectrum of the galaxy is shown at the top of the web page containing the spectrum of the galaxy being measured. Below it are enlarged portions of the same spectrum, in the vicinity of some common galaxy spectral features: the "K and H" lines of ionized calcium and the *H-alpha* line of hydrogen.

Step 4: Finding the distance to each galaxy

The next step is to determine the distances to galaxies. For nearby galaxies, we can use standard candles such as Cepheid variables or white-dwarf supernovae. But, for very distant galaxies, we must rely on more indirect methods. **The key assumption for this lab is that we are measuring galaxies of similar Hubble type**. We then assume that they are all the same physical size, no matter where they are. This is known as "the standard ruler" assumption. We must first calibrate the actual size by using a galaxy to which we know the true distance. We are looking for galaxies in the sample that are spiral galaxies, as we would use the nearby spiral galaxy, M31 the Andromeda galaxy, to calibrate the distances. We **know** the distance to the Andromeda galaxy through observations of the Cepheid variables in it. Then, to determine the distance to more distant, similar galaxies, one would only need to measure their **apparent** (angular) sizes, and use the small-angle formula.

Step 5: Data Analysis

Here is the step where you determine the Hubble constant and the uncertainty in that constant. You will be graphing the distance to each galaxy in megaparsecs (*x-axis*) versus the recessional velocity of that galaxy in kilometers per second (*y-axis*) and calculating the slope of the data -- your Hubble constant. The uncertainty in your constant is the uncertainty in the slope: what is the steepest your slope could be (highest value for the Hubble constant) and what is the shallowest (lowest value)?

With your value for the Hubble constant in hand, you are ready to calculate the age and size of the Universe using both a simple model for the expansion and a more realistic model that includes gravity.

Step 6: Questions

Your final step: Do you understand what you have just completed? What do some of the errors in your measurements mean? Could they have been prevented or minimized? Within your errors, do you agree with the pundits? Are you ready to challenge them?

Additional Information Available On-Line:

- Firming Up a Hubble Constant
- Cepheids in NGC1365
- Supernovae in NGC4639
- HST on Track for Measuring the Expansion Rate of the Universe (press release)
- Measuring the Expansion Rate of the Universe (background information)
- Cosmic Yardsticks
- The Hubble Constant

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.

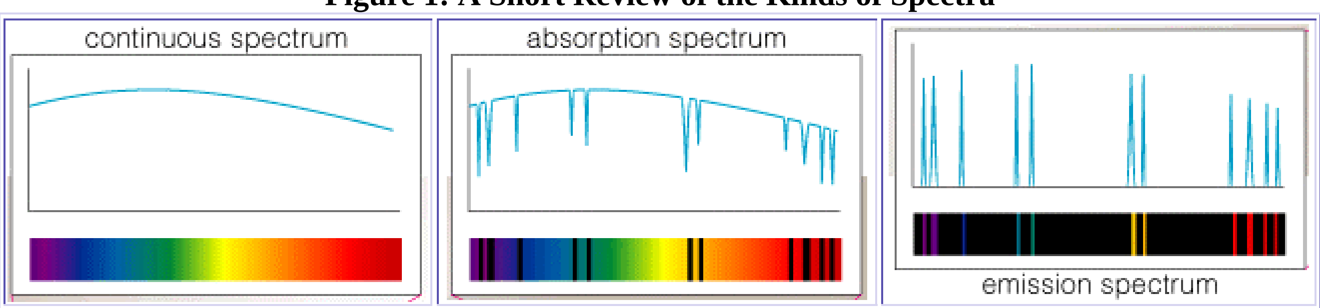
The Images

Examine closely the 27 galaxies linked from the pages showing each galaxy and its spectrum. Note any substructure, irregularities, or other defining characteristics for each galaxy. These features may be difficult to see for the more distant galaxies. On the galaxy overview sheet, **sketch each galaxy**, and give your best guess of its general Hubble type (spiral, barred spiral, elliptical, irregular).

The Spectra

Examine closely the 27 spectra shown on these full spectra pages. You are looking at the **relative intensity** of the total light radiated from each galaxy as a function of wavelength. The overall shape or curve of each spectrum is due to the continuous spectra from the stars (thermal radiation). Where you see dips in the spectrum of a galaxy, that is where radiation is being absorbed. Where you see sharp spikes in the spectrum of a galaxy, that is where radiation is being emitted. Unlike our "idealized" spectra of earlier in the quarter where we examined individual stars, the spectra from these galaxies reflect the total of all of the light from all of the objects in them.

Figure 1: A Short Review of the Kinds of Spectra



Continuous spectrum of thermal radiation	Spectrum showing absorption of light from thermal radiation passing through a cooler, thin gas.	Emission spectrum of hot, thin gas seen against a cooler background.

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

1. Not all of the "jiggly" lines come from the light of the galaxy. Each spectrum contains noise; we just cannot get away from it. You should notice that some of the spectra are much "noisier" than other spectra. This noise tends to hamper accurate identification of some of the lines.
2. Most 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", when, in fact, the scaling had to be adjusted to accommodate an intense, hydrogen emission line, usually the one 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.
3. Some spectra show **only** absorption lines, or absorption lines with very weak hydrogen emission lines.
4. What you should be looking for are 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)]. **Remember**: these spectra are of galaxies that are moving away from us and so the lines are going to be **redshifted**, some, you will find out, by a large amount.

After looking closely at the corresponding spectrum for each galaxy, write a short description of the spectrum in the space provided on the galaxy overview sheet. You will be using these sketches, classifications and descriptions shortly to eliminate some of the galaxies from further consideration.

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. Remember the primary objects found in spiral galaxies: stars of all ages, masses, and composition; dust; and HII regions. We expect, because the bright HII regions and massive OB stars will dominate the light of a spiral galaxy, to see 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 certainly 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 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, or both.

Step 2: Selecting Your Galaxies

The critical assumption

We want to **work only with spiral galaxies** (barred spirals will also be okay), and not elliptical galaxies. Why? Recall that if we see a galaxy that is 1/2 or 1/3 the angular (apparent) size of another galaxy, we would like to be able to state that that galaxy is 2 times or 3 times farther away. To do this, we must assume that if galaxies resemble each other, then they are approximately the same actual size.

We also want to choose galaxies that have 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 should use this pattern or correlation in your decision to "keep or toss."

Selecting the Galaxies

In the last column of the galaxy and spectra overview table, mark down your decision to keep or toss that particular galaxy. You may toss up to 12 of the galaxies out of further consideration. You should plan to keep 15 galaxies to give you enough galaxies to work with in deriving the Hubble constant. **Once you eliminate a galaxy, you do not need to do anything more with that galaxy.**

Note: to make this task a bit faster, 5 galaxies have already been selected, and a few already eliminated. You will need to choose 10 more galaxies and eliminate the rest.

After your selection process is complete, answer this question for yourself: "Based upon these images, what do I foresee as possible problems in measuring the angular diameters of the galaxies?"

THE HUBBLE LAW Measurements of Velocities and Distances

Step 3: Finding the velocity of each galaxy

The velocity is relatively easy for us to measure using the Doppler effect. An object in motion (in this case, being carried along by the expansion of space itself) will have its radiation (light) shifted in wavelength. For velocities much smaller than the speed of light, we can use the regular Doppler formula:

$$\frac{(\lambda - \lambda o)}{\lambda o} = \frac{v}{c}$$

λ **measured wavelength**
λ_o rest (laboratory) wavelength
v velocity
c speed of light

The quantity on the left side of this equation is usually called the **redshift**, and is denoted by the letter **z**.

The formula for redshift should remind you of the process where you calculated your percentage error: [(your value) - (true value)] / (true value). Thus, we can view the redshift as a "percentage" wavelength shift.

For this lab, all wavelengths will be measured in Angstroms (Å), and we will approximate the speed of light at 300,000 km/sec. Thus, we can determine the velocity of a galaxy from its spectrum: we simply measure the (shifted) wavelength of a known absorption line and solve the equation **v = c z**.

For Example: *A certain absorption line that is found at 5000Å in the lab (rest wavelength) is found at 5050Å when analyzing the spectrum of a particular galaxy. We first calculate z: redshift = [(measured wavelength) - (rest wavelength)] / (rest wavelength)*

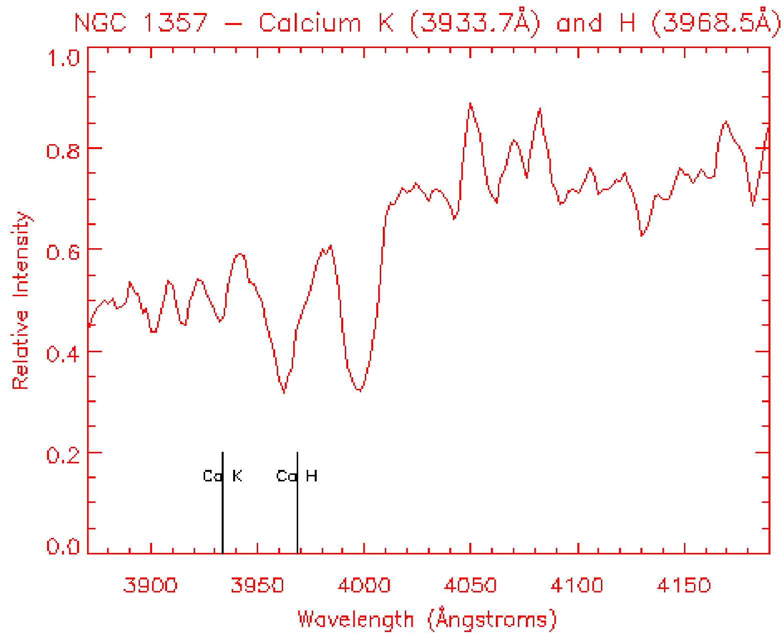
$$z = \frac{\lambda - \lambda_o}{\lambda_o}$$

We find that z = 50/5000 = 0.001 (=v/c) *and so conclude that this galaxy is receding with a velocity of 3000 km/sec* **(v = z*c).**

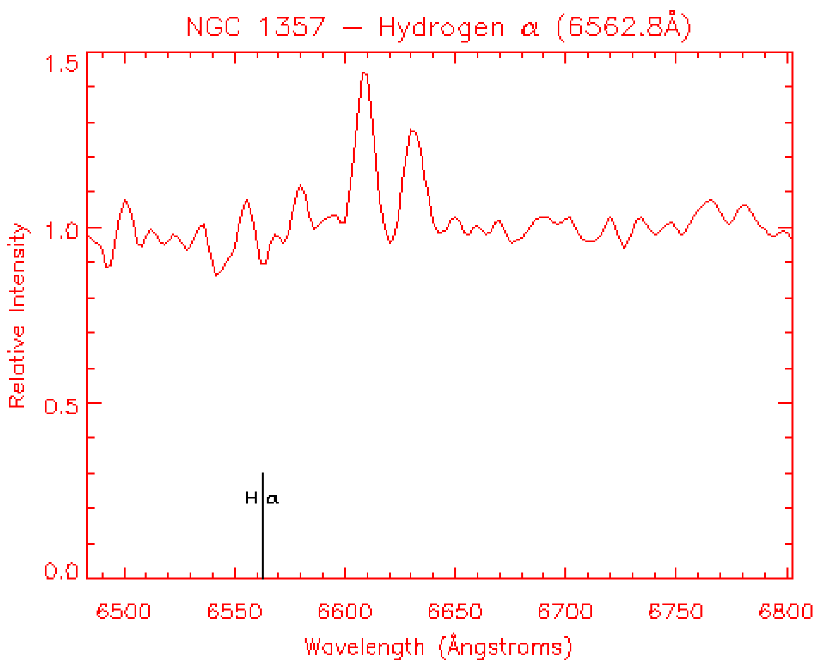
Measuring the Spectral Lines

- The **velocity** of the galaxy is determined by measuring the redshift of spectral lines in the **spectrum** of the galaxy. The full optical spectrum of the galaxy is shown at the top of the web page containing the spectrum of the galaxy being measured (see link below). Below it are enlarged portions of the same spectrum, in the vicinity of some common galaxy spectral features: the hydrogen transitions hydrogen-alpha (656.28 nm), hydrogen-beta (486.13 nm), hydrogen-delta (410.17 nm) as well as the "K and H" lines of ionized calcium (393.37 and 396.85 nm). The enlarged portions of the same spectrum are **"clickable"** and will return a wavelength value corresponding to where you "clicked." Take a brief look at the spectrum for NGC1357 and the analysis of the spectrum. You should try to use similar logic when measuring the rest of your selected galaxies.

- You are now ready to do your measurements, but before you do, take a look at a sample analysis.

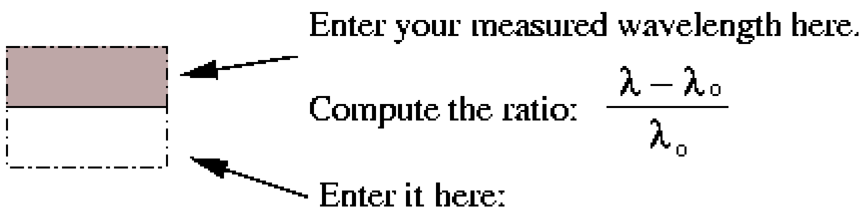


The absorption lines due to ionized calcium will be among the strongest ("deepest") of all the lines. It's a good initial step with any of the spectra to find these two lines. The black lines at the bottom of the figure (Ca K and Ca H) show the location of the **rest** wavelengths. These rest wavelengths are also spelled out at the top of the figure. As you can easily see, the measured wavelengths are going to show a sizeable shift toward redder wavelengths. On the working spectra, you will be clicking at the **bottom** of each of these strong wavelengths. For this galaxy, the measured wavelength of the Ca K line was 3962.0 Angstroms (carry at least 5 significant digits); and for the Ca H, 3997.2 Angstroms. The differences between measured and rest wavelengths are (3962.0 - 3933.7) 28.3 Angstroms and (3997.2 - 3968.5) 28.7 Angstroms. The redshifts are 28.3/3933.7 = 0.0071, and 28.7/3968.5 = 0.0072.



As you can see in this figure, there are two strong emission lines that are greater than 30 Angstroms away from the rest wavelength of hydrogen-alpha, shown by the black vertical line at the bottom. Pick the strong emission line that is to the left (blue-ward) of the other strong emission line, even if the other one has more intensity. (The strong emission line on the right is usually due to oxygen.) We expect the wavelength shift for this hydrogen line to be slightly greater than that of the calcium lines (for reasons that you need not worry about). The measured wavelength was 6608.6 Angstroms, giving a shift of (6608.6 - 6562.8) 45.8 Angstroms. The redshift is 45.8/6562.8 = 0.0070. You should recognize immediately that although the wavelength shift was greater, the redshift (z) is nearly exactly the same. (As it should be if we are measuring the correct line; after all, it's the same galaxy!)

1. Make sure you have a copy of the Data Table, either from downloading or from the course pak.
2. Note that for each galaxy there are two lines of data under each "spectral lines" column. The first line contains the measured wavelength. The second line contains the calculated redshift.

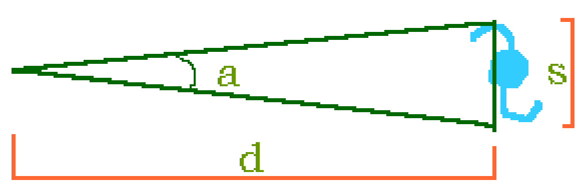


3. Start with NGC 1357 to see if you can duplicate or come close to the values discussed under the analysis. Note how the data table has been filled in for NGC 1357, and make sure you understand what numbers go where and what calculations are being done.
4. Move on to the next galaxy, NGC 1832. Note that this galaxy, too, has been measured for you. Again, see if your measurements mimic these.
5. Use the velocities of these galaxies as part of what is needed to calculate the Hubble constant. At this stage you should try to weed out all but about 12-15 galaxies (including those already done).
6. Now move on to the next galaxy that you have selected. Starting with the calcium lines, measure the wavelength of the **same but shifted** line by clicking at the middle of the spectral line (i.e. at the "greatest depth" of absorption or the "peak" of emission) in the spectrum of the galaxy. Write this wavelength in the box below the appropriate line designation in your data table. (Note: It is due to the peculiarities of each galaxy that some spectral lines are absent, or show up in **emission** instead of **absorption**.)
7. Do this for the rest of your selected galaxies, trying to measure the shifts of the 3 lines discussed in the analysis for NGC 1357. For each of your galaxies, you will measure, calculate redshifts, average redshifts, derive a velocity (remember: $v = z * c$). These are the **"y"** values for your graph. Then you will be ready to find the **"x"** values -- the corresponding distances.
8. For the galaxies **not used** simply cross out the row next to the galaxy number.

Here is the "intercept" page (reached on-line, of course) that will link you to the real data for the 27 galaxies.

Step 4: Finding the 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 we are measuring galaxies of similar Hubble type**. We then assume that they are all the same physical size, no matter where they are. This is known as "the standard ruler" assumption. We must first calibrate the actual size by using a galaxy to which we know the true distance. We are looking for galaxies in the sample that are Sb galaxies, as we would use the nearby Sb galaxy, M31 the Andromeda galaxy, to calibrate the distances. We **know** the distance to the Andromeda galaxy through observations of the Cepheid variables in it. Then, to determine the distance to more distant, similar galaxies, one would only need to measure their **apparent** (angular) sizes, and use the small angle formula.



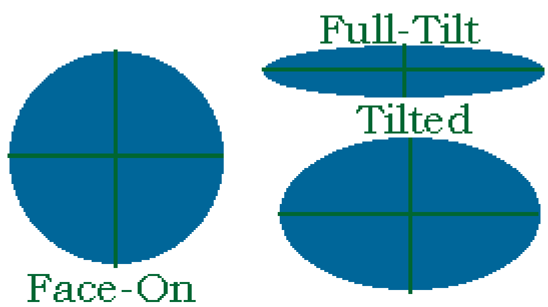
$$\mathbf{a} = \mathbf{s} / \mathbf{d} \quad \text{or:} \quad \mathbf{d} = \mathbf{s} / \mathbf{a}$$

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.

Measuring the Galaxies

- **It is up to you to decide the criteria you will use in measuring these galaxies. It is suggested that you try to measure as far out as you can see any fuzzy disk.**
- The **angular size** of the galaxy is measured by using its **image**. Note that the images used in this lab are **negatives**, so that bright objects -- such as stars and galaxies -- appear dark. Note also that 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.)

Take a look at this schematic of a galaxy viewed from three different angles. Thought question: We assume that the spirals are all round, and that their different shapes are simply because we are viewing them from different angles. When measuring the angular sizes of the galaxies, why should you measure along the ***longest*** *axis only?*



The angular size of the galaxy (in *milliradians*; 1 mrad = 0.057 degrees = 206 arcseconds) will be displayed; write this number down on your table, under "Galaxy Size."

If, at any point, you make an error while you're measuring (e.g. a miss-click), simply click on the "back" button of your web browser and take the measurement again.

Here is the "intercept" page (found on-line) that will link you to the real data for the 27 galaxies.

Checking Your Data

It would be a good idea to have your instructor look at your data now, before you do a ton of calculations. You wouldn't want to spend hours of your time only to discover that you made mistakes in steps 3 and 4.

Initial Calculations

If you feel confident of your data, then you are ready for the preliminary calculations:

Velocity Determination

For **each measured line** calculate the (redshift **z**), and enter this value in the box under the measured wavelength. Then take the average redshift of the measured lines for each galaxy, and enter it on the appropriate column. Finally, use this average redshift to calculate the velocity of the galaxy using the modified Doppler-shift formula:

$$\mathbf{v} = \mathbf{c}\,\mathbf{z}$$

Distance Determination

Determine the distance (in Mpc) to each galaxy using the following, revised version of the small angle formula. Recall, we have had to make an important assumption: all of these galaxies are about the same actual size. Once you have the angular diameter in *mrad* (and with some adjusting of units), just take the **actual size** of each galaxy -- 22 kpc -- and divide it by the measured angular diameter. For example, if one of the galaxies had a measured angular diameter of 0.50 *mrad*, 22 / 0.50 = 44 Mpc.

Details for the manipulation of the units to come out with the correct distances
From calibrations, we know that galaxies of the type used in this lab are about **22 kpc** (1 kiloparsec = 1000 pc) across. We may then find the distance to the galaxies: **distance (kpc) = size (kpc) / a (rad)** or equivalently, upon multiplying the left side by 1000 and dividing the right side by 0.001 (which is exactly the same thing): **distance (Mpc) = size (kpc) / a (mrad)**
Note that we now have the equation in a form where we can simply substitute the size in kpc (22) and divide it by the angle returned by our measurements (already in *mrad*).

THE HUBBLE LAW

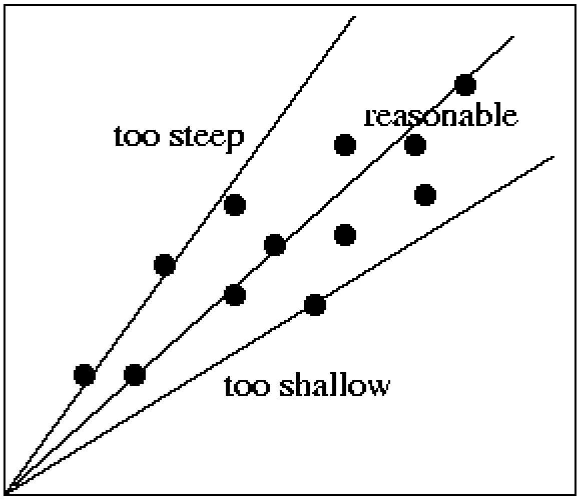
Data Analysis

Step 5: Data Analysis

Determining the Hubble constant

1. Graph 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 best fits the points on the graph; remember that this line **must pass through the origin** (the 0,0 point). Measure the slope of this line (rise/run), this is your value of the Hubble constant, in the units of *km/sec/Mpc*. Please show all calculations and record the slope (the Hubble constant) in the Table of Results (under Step 6).

Determining the uncertainty in the Hubble constant



2. Hubble's Law predicts that galaxies should lie on a straight line when plotted on a graph of distance vs. velocity. Your data probably do not make a perfectly straight line, and you most likely had to make a guess as to where to draw your line. One simple way to estimate the uncertainty in the value of H_o is to draw the steepest *reasonable* line *and* the shallowest *reasonable* line on the graph, and calculate their slopes. **Half of the difference** between these two slopes would be your uncertainty. Record in the table.

Determining the Age of the Universe:

3. Maximum age of the Universe: If the universe has been expanding since its beginning at a constant speed, the universe's age would simply be $1/H_o$.
   a. Find the inverse of your value of H_o.
   b. Multiply the inverse by 3.09×10^{19} km/Mpc to cancel the distance units.
   c. Since you now have the age of the Universe in seconds, divide this number by the number of seconds in a year: 3.16×10^7 sec/yr. This age represents a very simple model for the expansion of the universe, and is the maximum age the universe can be. Record this number in the Table of Results.

EXAMPLE: **Your Hubble constant is 75 km/sec/Mpc, then 1/75 = 0.0133 = 1.33×10^{-2}** **$(1.33 \times 10^{-2}) \times (3.09 \times 10^{19}) = 4.12 \times 10^{17}$**	**(4.12×10^{17}) divided by $(3.16 \times 10^7) = 1.3 \times 10^{10}$** **This is 1.3×10^{10} years,** **or 13×10^9 years,** **or 13 billion years.**

4. The age of the Universe with gravity: A better model would account for the deceleration caused by gravity. Models like this predict the age of the universe to be: $t = (2/3)*(1/H_o)$, or **2/3 of the maximum age** of the Universe. Re-calculate the age using this relation, and record in the Table. Remember to show all calculations.

Once you have the age of the Universe under both models, and the uncertainties attached to each model, you are ready to go onto Step 6: Questions.

The Hubble Law: Credits

Luis Mendoza and Bruce Margon designed the Hubble Law lab originally, with lots of technical support from Toby Smith, Eric Deutsch, and Brooke Skelton, present and past members of the University of Washington Astronomy Department.

The galaxy spectra were obtained by Robert C. Kennicutt Jr. of the University of Arizona. The spectra are published in The Astrophysical Journal Supplement Series, Volume 79, Pages 255-284, 1992, and are also available on the WWW. The digital images of the galaxies have been extracted from the CD-ROM version of the Palomar Observatory Sky Survey, produced under NASA contract by the Space Telescope Science Institute, operated by AURA, Inc. We gratefully acknowledge the various copyrights for that work.