Hubble Law Lab Using Pre-Selected Spiral Galaxies

Learning Objectives

Using analyses of images and spectra of 18 spiral galaxies, the students will

- determine a value for Hubble's constant;
- estimate the age of the Universe from this constant and compare it to the age of the Sun and the Milky Way;
- discuss the effect that various uncertainties in measurements have on the Hubble constant ;
- explain how the "peculiar velocities" of galaxies in clusters affect their conclusions;
- summarize how our view of the Universe has changed as the value of the Hubble constant has improved.

Background and Theory

In the 1920's, Edwin P. Hubble discovered a relationship that is now known as Hubble's Law. It states that the recessional velocity of a galaxy is proportional to its distance from us:

$$v = H_o d \qquad \text{[Eqn. (1)]}$$

where v is the galaxy's velocity (in km/sec), d is the distance to the galaxy (in megaparsecs; 1 Mpc = 1 million parsecs = 3.26 million light years), and H_o is the proportionality constant, called "The Hubble Constant." Hubble's Law states that a galaxy moving away from us twice as fast as another galaxy is twice as far away. The Hubble constant remains a hotly contested quantity in astrophysics. In order to precisely determine the value of H_o, we must determine the velocities and distances to many galaxies, preferably those extremely far away, at least 326 million light years (100 Mpc).

The recessional velocity of a galaxy is measured using the Doppler effect, even though the redshifts here are due to the expansion of space and not the motion of the galaxies themselves. The radiation coming from a moving object is shifted in wavelength:

$$\frac{\lambda_{measured} - \lambda_{true}}{\lambda_{true}} = \frac{v}{c} = z \qquad \text{[Eqn. (2)]}$$

where λ_{true} is the rest or true wavelength of the radiation, $\lambda_{measured}$ is the wavelength as measured at the telescope, making the left-side of Eqn. (2) the fractional value the recessional velocity of the galaxy is of the speed of light.

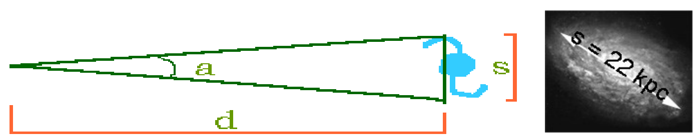
In this case, wavelengths are measured in Angstroms Å, an outdated unit equal to 1 ten-billionth of a meter. The speed of light has a constant value of ~300,000 km/sec. The quantity on the left side of Eqn. (2) above is usually called **the redshift**, and is denoted by the letter z.

We can determine the velocity of a galaxy from its spectrum by measuring the wavelength shift of an absorption or emission line whose wavelength is known and solve for v.

Example: An absorption line that is found at 5000Å in the lab is found at 5050Å when analyzing the spectrum of a particular galaxy. Therefore this galaxy is moving with a velocity ***v*** = (50/5000) * ***c*** = 3000 km/sec away from us.

A trickier task is to determine a galaxy's distance, since we must rely on more indirect methods. One may assume, for instance, that all galaxies of the same type are the same physical size, no matter where in the Universe they are. This is known as "the standard ruler" assumption. To use this assumption, however, we have to know the actual size of the "ruler" and to do that, we need the distances to the galaxies that form our standard ruler. So, since we are working with spiral galaxies, we choose nearby galaxies such as Andromeda, Triangulum, Messier 81, and others to which we have found an accurate distance measure using variable stars or other reliable distance indicator. We find that, on average, the actual size of these standard ruler galaxies is 22 kiloparsecs (22,000 parsecs or ~72,000 light years).

To determine the distance to a galaxy one would need to measure only its apparent (angular) size, and use the small angle equation: ***a* = *s* / *d***, where ***a*** is the measured angular size (**in radians**), ***s*** is the galaxy's true size (diameter, 22 kpc in our work here), and ***d*** is the distance to the galaxy.



a* = *s/d or ***d* = *s/a*** [Eqn. (3)]

Procedure

Access to http://www.astro.washington.edu/astro211/HubbleLaw/hubbles_law_preselected.html **is essential!**

Use the worksheet on the last page of this exercise if you are using the pre-formatted spread sheet to do your calculations to record your data (and to use as backup in case something goes wrong). You may choose to work alone or with a partner on this part of the exercise.

Finding the sizes of the galaxies

1. From the master on-line Galaxy List, choose a galaxy given on the list on your worksheet.
2. Find the angular size of the galaxy using its image. 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, click on opposite ends of the galaxy, at either end of the longest diameter. Be sure to measure all the way to the faint outer edges. Otherwise, you will dramatically underestimate the size of the galaxy, and introduce a systematic error.
   - The angular size of the galaxy (in milliradians, or one-millionth of a radian) will be displayed; record this number on your worksheet.
3. **Repeat step 2 for all 18 of the galaxies on the worksheet.** Use the worksheet as your data backup!

Right-click on the link (hubbles_law1.xls) given on the web page for this exercise and open it or choose to save the target on the computer you are using. Ignore the numbers and errors shown on the spread sheet as they will all disappear once you start entering your data. You may wish to enter the galaxy sizes, in megaparsecs, into the correct spread sheet cells.

Finding the redshifts of the galaxies

When you click on the galaxy's spectrum link, you will see the full optical spectrum of the galaxy at the top of the spectrum page. Below it are enlarged portions of the same spectrum, in the vicinity of some common spectral features. The small vertical bars near the lower left corners of these spectra indicate the rest wavelengths of the lines. Measure the wavelength by clicking at the middle of the spectral line (bottom of an absorption line, top of an emission line) in the galaxy's spectrum.

4. Find the red-shifted wavelength for Ca K, Ca H and H-alpha lines for each galaxy on the worksheet using its spectrum.
5. **Repeat step 4 for all 18** of the galaxies on the worksheet.

If using the pre-formatted Excel spread sheet, hubbles_law1.xls, follow these directions (these are for Excel under XP; if using Vista, they will need to be modified):

REMEMBER TO SAVE YOUR SPREAD SHEET OFTEN!

- Enter the angular size of each galaxy in the correct column on the spread sheet.
- Enter the measured wavelengths in the correct columns for Calcium K and H lines and H-alpha line.
- The spread sheet should automatically calculate the distances to the galaxies, the redshifts, and the velocities as you enter your data.
- The spread sheet should also automatically update the chart of the data as you enter your numbers.
- After you have finished entering all of your data and your chart shows all of the data points, you need to add a trendline to the data and tell the program to display the fit of that line: Activate the chart region in the spread sheet by left-clicking on an edge.
- From the top menu, choose "Chart" and "Add Trendline."
- From that menu, choose "Linear" for Trend/Regression type.
- Click on "Options" and check all three options at the bottom: Set intercept = 0, Display equation on chart, and display R-squared value on chart.
- Click "OK."

The chart now shows the slope of the line in the form: ***y = mx + b*** (but here ***b = 0***, the origin of the graph, so is not explicitly stated). Round off the slope to 2 significant digits (e.g., 75.4839485 would be 75). The ***R***-squared value is a measure of how well the fit represents the data; if the value was equal to 1, then the fit would be perfect. Anything close to 1 is good here.

Age of the Universe

If the Universe has been expanding at a constant speed since its beginning, the Universe's age would simply be $1/H_o$. (You may choose to do most of the calculations within the Excel™ spreadsheet.)

- Find the inverse of your value of H_o.
- Multiply the inverse by 3.09×10^{19} km/Mpc to cancel the distance units.
- 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

Example:

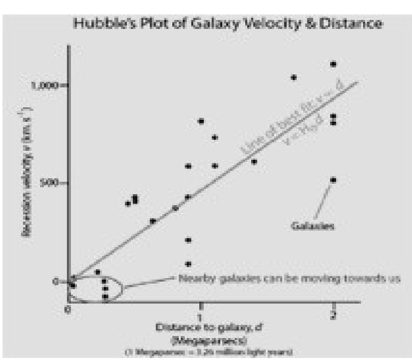
Your Hubble constant is 75 km/sec/Mpc, then:
$1/75 = 0.0133 = 1.33 \times 10^{-2}$
$(1.33 \times 10^{-2}) \times (3.09 \times 10^{19}) = 4.12 \times 10^{17}$
(4.12×10^{17}) divided by $(3.16 \times 10^{7}) = 1.3 \times 10^{10}$
This is 1.3×10^{10} years, or 13×10^{9} years, or 13 billion years.

The "expansion age" of the Universe is $t = 1/H_o$. This is a very simple model for the expansion of the Universe. A better model would account for the deceleration caused by gravity. Models like this predict the age of the Universe to be: $t = 2/3H_o$. Adjust the age of the Universe using this relation by simply multiplying your original age by 2/3.

After you have finished with this exercise, you will need to go to the "CollectIt" website that is part of Catalyst Tools here at the U of W and upload your work -- the spread sheet with all of your data and results.

After uploading your spreadsheet, you should EACH INDIVIDUALLY log onto the web page containing the questions that accompany this exercise, and answer all of them. You need not do so in one sitting; you can choose to save your work and return later to answer additional questions. Although you may confer with your classmates, your answers here must be your own. You can change any answer until you actually submit your work. Check our assignments web page for the due date. It will be counted as late if submitted after 5 pm on that date, and the web site will be unavailable 4 days after that.

Congratulations. You have now earned your first cosmology badge!



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Worksheet to backup spreadsheet calculations

Name(s) ____

Table 1: Data

Galaxy	Measured Size	Measured Wavelength of Spectral Lines		
ID	**(mrad)**	**Calcium K**	**Calcium H**	**Hydrogen**
NGC 1357				
NGC 1832				
NGC 2276				
NGC 2775				
NGC 2903				
NGC 3034				
NGC 3147				
NGC 3227				
NGC 3368				
NGC 3623				
NGC 3627				
NGC 4775				
NGC 5248				
NGC 5548				
NGC 6181				
NGC 6217				
NGC 6643				
NGC 6764				

Rest Wavelengths :
Ca-H: 396.85 nm (3968.5 Å) : Ca-K: 393.37 nm (3933.7 Å) : H-alpha: 656.28 nm (6562.8 Å)

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