Lab #15: Hubble's Law

This lab is to be completed in groups of 2-3 and you should all participate actively. You should answer all of the questions on this sheet of paper and hand in ***just one copy per group*** *with all your names on it. However, it is to your advantage if you all keep a record of your answers so you will have something to study from.*

Purpose: To use simple observational evidence to recreate the most profound discovery in cosmology. By calculating the distance to other galaxies and finding the velocity they are moving relative to us, you will be able to show that the universe is expanding.

Materials:
The galaxy images and corresponding spectra are at
http://www.astro.washington.edu/users/solontoi/HubbleLaw/galaxies.html

Outline: Here's a brief outline of the lab procedure, the steps will be walked through later on.

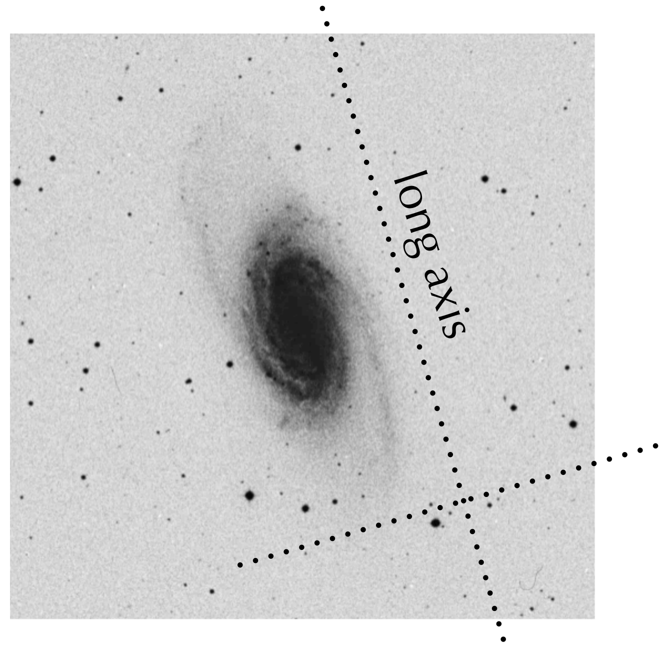
✦ Find the distance to each galaxy
- -Find the angular width of each galaxy
- -Assuming spiral galaxies are all the same size, use the standard rod method to calculate the distance to each galaxy

✦ Find the velocity of each galaxy
- -Find the wavelength of 2-3 emission/absorption lines in the spectra of each galaxy
- -Calculate the redshift of each galaxy, using the observed wavelength and the emitted wavelength
- -Calculate the velocity each galaxy is moving relative to us based on the redshift

✦Find the rate of expansion of the Universe
- - Graph the velocity of each galaxy against the distance
- - Determine a best fit line for your data
- - Calculate the slope of the best fit line and know this to be *H*, the rate of expansion and the Hubble constant.

NOTE on procedure - for this lab you will measure distances and redshifts for many galaxies. The data presented in the lab cover a broad range in image and spectral quality. It is important to use as many galaxies as possible but if you feel a galaxy's image or spectrum is bad or strange enough that it will severely skew your results you can opt not to use that galaxy's data in your final calculations. If you opt to throw out any galaxy you must indicate what your justification was for throwing it out.

Part 1. Find Distances



For each galaxy in your sample you will need to measure its angular size. Use the image link to bring up a centered image of the galaxy, like the one shown here. Identify the long axis of the galaxy and then measure the angular size by clicking on each side of the galaxy along this axis. After each click the web-page will report the x,y pixel coordinate that you clicked on. After you click the second point it will report the angular size of the galaxy in milliradians. If you make an error, make sure to click the try again link to reset the page.

It is up to you to determine criteria for what defines the edge of a galaxy. Just try to be consistent from galaxy to galaxy.

A) Measure and record the angular size, D_A, of each galaxy in your data table (5pts)

To get the distance to these galaxies, we will assume that every galaxy is the same physical size, D= 22 kilo-parsecs (kpc). Then, by measuring how small they appear on the sky, we can estimate how far away each galaxy is. This is called the **standard rod approximation**. For small angular sizes, the angular and physical sizes are related to the distance in the following way:

$$\text{angular size} = \frac{\text{physical size}}{\text{distance}}$$

B) Solve the above equation for distance and write the new equation down below (1pt).

C) Then complete the following sentences (1pt):

At fixed physical size, as the angular size increases, the distance ____________

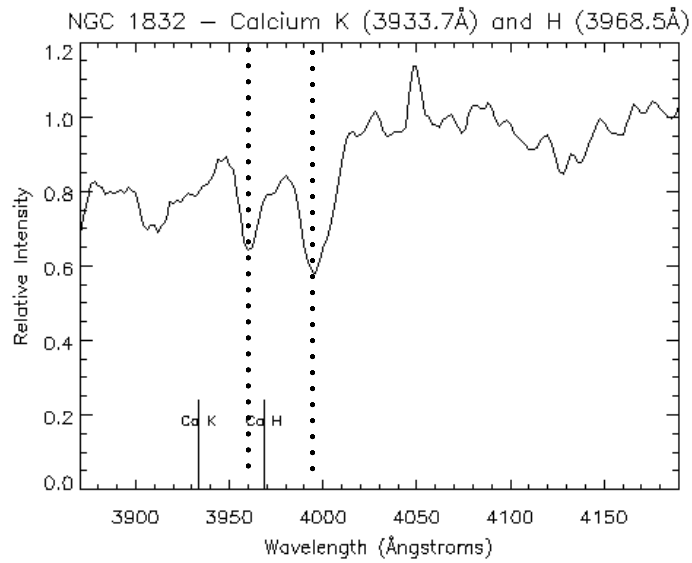
At fixed angular size, as the physical size increases, the distance ____________

NOTE - if you keep the angle in units of milliradians (the unit provided by the webpage) and the physical size in units of kpc, then your distance will come out in units of mega-parsecs (Mpc). These are the units that you want for this lab, since Mpc is a much bigger unit than light years and therefore more appropriate for extragalactic distances.
For reference, 1 Mpc = 1,000,000 parsecs = 3,260,000 light years.

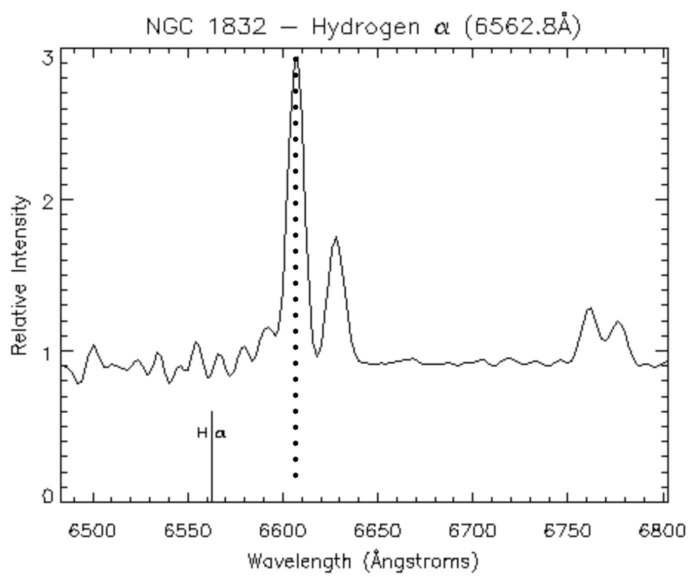
D) Calculate and record the distance to each galaxy in your data table. Show your work for just one of the galaxies below. (5pts)

Part 2. Find Velocities

To measure velocities, you'll need to measure the shift in wavelength for three different lines for each galaxy. You should use the Calcium H and K lines as well as the H-alpha line. The spectra link will take you to a page containing zoomed in sections of the galaxy's spectra, like the one shown here. On the left hand side you will find the Calcium K and H lines. The absorption lines due to calcium will be some of the strongest (deepest) of the spectral lines. At the bottom of the image are two black lines that show the rest wavelengths of the calcium lines. The rest values are listed at the top of the image. You will need to click on each of the absorption lines in order to measure the wavelength at which these lines are observed in the galaxy.



You will also do the same thing on the right hand size to measure the Hydrogen α emission line. Generally there are two strong emission lines to the right of the H α rest wavelength. H α will be the one with the smaller (bluer) wavelength. Sometimes it has a small "hump" on the blue side of the emission feature.



For the galaxy shown here, the shifted Ca H and K and H α features are indicated with dashed lines.

A) Record your three observed wavelengths of the lines in each galaxy in your data table (5 pts)

To get the velocity, you will use your shifted wavelengths and the Doppler formula:

$$\frac{\lambda_{shifted} - \lambda_{rest}}{\lambda_{rest}} = z\,, \quad \text{where } z = v/c$$

where $\lambda_{shifted}$ is your measured wavelength, λ_{rest} is the wavelength of the line if the galaxy were at rest and z is the redshift. The redshift is equal to the velocity of the galaxy, v, divided by the speed of light, c.

B) First, find the redshift for ALL of the lines you measured (this means doing this calculation three times for every galaxy) and record your three redshifts for each galaxy in your data table. Show your work for one of the lines below. (5 pts)

C) Now solve the above equation for velocity in terms of redshift and the speed of light and record it below (1pt).

D) Average the redshifts for each galaxy and use the average redshift to find your best estimate for the velocity of each galaxy. Record these numbers in your data table and show your work for one of the galaxies below. (5 pts)

Part 3. Data Analysis

A. Make a plot of distance on the x-axis, velocity on the y-axis for all your galaxies. NOTE: you should also include a point at (x=0, y=0). Please use graph paper and attach it to this lab (I have some available if you need it). Remember to include title, and axis labels, careful units, etc.

B. The Hubble constant, H is equal to the slope of this line. Draw a best fit line through your data to estimate the Hubble constant. Your line should go through (0,0). The slope of this line is your estimated value of the Hubble Constant. Record the value below, and be sure to include units.

H = ________________

C. Now estimate the uncertainty in your measurement of the Hubble constant by drawing in the steepest and the shallowest lines that still fit your data. Measure the slopes of the steepest and shallowest lines and average the difference between H and those two slopes:

$$\frac{(H_{high} - H) + (H - H_{low})}{2} = \text{uncertainty in H}$$

Calculate your uncertainty in H and record it below. Be sure to include units.

Uncertainty in H =_______________

D. If you take 1/H and multiply that by 10^{12} you will get an estimate of the age of the universe in years. Use your value of H to estimate the age of the universe and your uncertainty in H to estimate the uncertainty in the age, and record your answer below.

Age of the universe = ______________+- ____________

Note about your value of H: Until recently the uncertainties measured for the hubble constant were VERY large (researchers would disagree by as much as 50 km/s/Mpc!) so don't fret if yours are too.

Part 4. Interpretation

A. What does the point at (0,0) represent? (1pt)

B. The long-standing view of the Universe before Edwin Hubble was that everything was standing still, i.e. the Universe was static. Does your analysis support or refute this claim? Why? (2pts)

C. Look up the current best estimate for the age of the Universe, and calculate the difference between that value and your estimate and record it below.

Error = ____________________

Is this error consistent with the uncertainty in your measurement? Why/why not? (3pts)

D. In your analysis, you assumed that all galaxies are the same physical size = 22kpc. If one of the galaxies was in fact smaller than 22kpc, would your estimate of the distance to that galaxy be an under- or overestimate? What if a galaxy was in fact larger than 22kpc? Show your work. (3pts)

E. In reality, galaxies aren't all the same size: the average galaxy size is 22 kpc, and their sizes vary by some amount about this average value. In what way does the **standard rod assumption** (assuming that all galaxies are the same size) affect your measurement of the Hubble constant? (2 pts)

F. What if, in reality, the average size of galaxies were smaller than 22 kpc? How would this affect your measurement? Would your estimate of the Hubble constant assuming D=22kpc be an underestimate or an overestimate? Justify your answer with a few sentences, and a careful sketch. (3pts)

Galaxy	Angular Size	Distance	λ_1	λ_2	λ_3	z_1	z_2	z_3	$\langle z \rangle$	v

Galaxy	Angular Size	Distance	λ_1	λ_2	λ_3	z_1	z_2	z_3	$\langle z \rangle$	v