DAY LABORATORY EXERCISE #7:
HUBBLE LAW

Goals:
- To determine the relationship of a galaxy’s distance with its spectral shift.
- To gain an understanding of the large scale nature of the Universe.

Equipment: Galaxy photographs, Galaxy and calibration spectra, rulers, calculators.
Methods:
- Compile a database of information concerning a sample of galaxies.
- Graph the information to identify any possible relationships between measured quantities.

Introduction - In the first quarter of this century, astronomy was truly beginning to take off as new technologies and new scientific theories were developed. Due to advances in engineering, astronomers could now build large telescopes, capable of detecting extremely faint objects. Photography allowed recording their images for analysis. With the invention of quantum mechanics in the 1920’s, the spectra of stars and galaxies were for the first time beginning to be understood. Armed with new knowledge and the tools to expand that knowledge further, the astronomers Edwin Hubble and Milton Humason began observing galaxies.

Galaxies were a very interesting class of objects to study, and at this time it was unknown whether galaxies were indeed outside the Milky Way or merely nebulae within our own galaxy. The evidence gathered by Humason and Hubble would assist in settling this debate, and also would provide the first step towards revealing the nature of the Universe as a whole.

Humason and Hubble photographed a large number of distant galaxies and recorded their spectra. In addition to providing information regarding the composition of the galaxies, these spectra also provided information concerning the galaxies’ spectral shifts. Once Humason and Hubble collected their data, they analyzed the distances and spectral shifts they determined for the galaxies, and found a relationship between them.

DAY LABORATORY EXERCISE #7:
THE HUBBLE LAW

Name/ID\#_____________________________ TA's Initials:________

Class/Section: AS102/ ______ Date due:___________

Procedures:

In this lab you will determine what kind of relationship exists (if any) between the distance to a galaxy and its spectral shift. An astronomer's work has two parts; making the observations, and analyzing the data to produce useful information. In this case, the observations have already been made. You must analyze the data as an astronomer would and see what you can learn from them.

A. Galaxy distances

Determining distances to galaxies is not easy. No galaxy is close enough to have a measurable parallax. So, other methods need to be used to determine a galaxy's distance. There are many ways to measure the distance to a galaxy, yet no method currently available is perfect. Each method depends on other measurements or assumptions, each of which may be suspect. The method we will use in this lab contains a critical assumption, but the method should suffice to give us fairly reasonable estimates of the distances to galaxies.

If all galaxies were same size, one could estimate their *relative* distances by comparing their apparent sizes - the ones that look smaller would be more distant. In fact, there is a large range in the physical sizes of galaxies. However, on average, the largest galaxies found in clusters of galaxies are about the same size. Consequently, it is possible to estimate the distances to galaxy clusters by studying their largest members. The galaxies you will measure have all been chosen to be representative of the largest galaxies in clusters of galaxies.

1. Measure the apparent diameter (in millimeters) of the giant elliptical galaxies on the photographs provided. Since the galaxies do not have sharp boundaries, it is essential that you be consistent in the way you measure different galaxies. Write your measurements in Table 1. **Note:** The last four lines in Table 1 give the distances and apparent radial velocities for four objects. These will be used in Procedure step C, #1.
2. The apparent diameter of a galaxy is related to its distance by the relation:

$$D = \frac{S}{d}$$

where D is its measured diameter on the photograph (in mm) and d is the distance to the galaxy in Mpc (millions of parsecs). The quantity S is a scale factor that relates these two rather different sets of distance units. In order to find S, you need at least one object whose distance is known by some other method. In this case, let us assume that we know that the distance to the Virgo cluster of galaxies is 22 Mpc. The galaxy NGC 4478 is a member of the Virgo cluster. Using this information, calculate S and record it in Table 1.

3. Now using the value of S you have just found, calculate the distances of the galaxies whose diameters you have measured. For each galaxy, take S and divide it by the diameter of the galaxy, D. Put your answers in Table 1.

B. Galaxy apparent radial velocities - Also shown on the photographs are spectra of the galaxies. Like the direct photographs, these spectra are photographic negatives (so that the brightest parts are darkest). The top spectrum in each picture is a calibration spectrum produced in the lab, so it is motionless. We can compare this spectrum to the spectrum of a galaxy to determine if the galaxy shows any radial motion. On the spectra, red is always to the right and blue is to the left.

1. Measure the shift (in mm) of a spectral line from its normal position on each of the spectra and enter your measurement in Table 1.
2. This shift you measure, however, needs to be converted into nanometers of wavelength to represent the actual spectral shift. We need to determine the conversion factor between the shift you measured in millimeters on the photographic spectra and the wavelength shift in nanometers. Measure the distance in millimeters between any two spectral lines on the calibration spectrum. Then find the difference in nanometers of wavelength between the same two spectral lines (the lines in the calibration spectrum of NGC 4478 are labeled with their wavelengths). Now divide the difference in wavelengths by the distance between the lines in millimeters. This will give you a conversion factor in units of nm/mm, which you should enter in Table 1.

3. To convert your measured redshifts from millimeters of distance to nanometers of wavelength multiply the spectral shift in millimeters by the conversion factor determined in the previous step. Enter your result in column 5 of Table 1.
4. To find the apparent radial velocity of each galaxy in km/sec, use the Doppler shift formula:

$$v = \frac{\Delta\lambda}{\lambda} c \ , \ v << c$$

where $c = 3 \times 10^5 \, km/s$ = the speed of light, λ = the wavelength of the spectral line as it is measured in the laboratory, and $\Delta\lambda$ is the wavelength amount of spectral shift. This Doppler shift formula applies only for the special case where velocities are much less than the speed of light. Enter your results in Table 1.

Table 1
Galaxy Distances and Spectral Shifts

Object	Diameter(D) (mm)	Distance (d) (Mpc)	Spectral Shift (mm)	Spectral Shift ($\Delta\lambda$) (nm)	Radial Velocity(km/s)
NGC 4478					
NGC 4570					
NGC 1273					
NGC 1278					
NGC 4853					
NGC 4881					
NGC 7501					
NGC 7503					
IC 1183					
NGC 7499					
NGC 6044					
NGC 6047					
Pegasus I	-	60	-	-	3700
Perseus	-	100	-	-	5400
Coma	-	110	-	-	6700
Hercules	-	200	-	-	10300

Scale Factor *S* = ____________ (divide this value by the diameter of your Galaxy, D, to get its distance, d)

Conversion factor = ____________ (multiply this value by the Doppler shift in mm to get the Doppler shift ($\Delta\lambda$) in nm)

C. The Hubble Diagram - When Hubble had collected very similar data to yours, he did what any good scientist would do, he graphed them! He found that when the observed distances of galaxies were plotted versus their apparent radial velocities, there was a simple relationship between the two.

1. Graph your results, together with the extra four objects given in Table 1, on a piece of graph paper. Plot the vertical axis as radial velocity with respect to the Earth (in km/sec) and the horizontal axis as the distance from the Earth to the clusters of galaxies (in Mpc). Draw a best fit line through the center of the spread of the data points and the origin. (Note that the line will not exactly pass through each data point, but it must pass through the origin.)
2. The slope of this line is called the Hubble constant. The relationship can be expressed by the equation:

$$V = H_0 d$$

where V is the apparent radial velocity of the galaxy, d is the distance to the galaxy, and H_0 is the Hubble constant, in units of km/sec/Mpc. The equation itself is called Hubble's law. Calculate the slope of your best fit line and record the slope you calculated in the space below.

Hubble constant H_0 = ______________________.

1. The Hubble constant has strange units: km/sec/Mpc. As km and Mpc are both units of distance, the units can be canceled to units of just 1/sec. This is an expression for one way to estimate the age of the Universe:

$$\text{Age of Universe} = 1 / H_0$$

Calculate the approximate age of the universe based on your value for H_0 and record this answer in the space below. (Once you have the answer in seconds you should convert it to billions of years)

Age of the Universe = __________________________.

D. The Expansion of the Universe

An implication of the Hubble Law is that the more distant a galaxy is from us, the faster it appears to recede. Also, we have not detected any distant galaxies with *blue*shifts, so *all* the galaxies seem to be receding from us. Many astronomers in the early part of this century concluded from this lack of blueshifts that we were at the center of an expanding universe.

However, there is a way to maintain the concept of the Universe's expansion, yet not require that we be located at its center.

1. Figures 1 and 2 show a section of the universe seen at two different times, Time = 0 years and Time = 1 billion years. At Time = 0 years, we see the Milky Way and a relatively nearby galaxy (Galaxy A) and a more distant galaxy (Galaxy B). At a later time (Time = 1 billion years) we see all three galaxies again in different positions because of their respective motions. Using the Milky Way as your reference point, measure the distances to the galaxies at both times and determine the apparent radial velocities of galaxies A and B (in units of Mpc/billion years).

Which galaxy is receding from the Milky Way faster?

Does this agree with the Hubble Law?

2. Now imagine that we do not live in the Milky Way, but in Galaxy B. How would the Universe appear to us then? Using Galaxy B as your reference point, measure the distances to the Milky Way and Galaxy A at both times and determine their radial velocities.

Which galaxy is receding from Galaxy B faster?

Does this agree with the Hubble Law (from your perspective on Galaxy B) ?

Based on these measurements, can you tell where the center of the Universe is? If so, how? If not, why not?

Summary Questions

1. List at least three ways that an astronomer can measure the distance to a galaxy. Which method is probably the most reliable and why?

2. In this lab you measured two separate quantities (a galaxy's distance and its spectral shift). Which of these two quantities is the most uncertain? Why?

3. The Gemini cluster of galaxies has a radial velocity of 23,000 km/sec. Use your graph to determine its distance. (Alternatively you may use your value of the Hubble constant and the Hubble Law)

4. Since light travels at a finite speed, we are seeing the distant galaxies as they appeared in the past. How long ago did the light from the galaxies in the Gemini cluster leave that cluster? (Hint: 1 pc = 3.26 light years and 1 Mpc = 10^6 pc, so 1 Mpc = 3.26 x 10^6 light years)

5. Suppose the velocity of expansion of the universe is slowing down with time; how would this affect the Hubble Law? Explain. For example, will the straight line you drew on your data plot curve up or down at larger distances? (Hint: Remember the further away you look, the further back in time you are observing).