NAME:___________________________

Prelab Questions for Hubble Expansion Lab.

1. What is the standard rod method? What is the main source of error in this method?

2. Define the Doppler Effect. What does it mean for a galaxy’s spectrum to be redshifted?

3. In 1929 Edwin Hubble calculated the age of the universe to be 1.73 Gyr. How far away was this calculation from what astronomers now believe is the age of the universe?

THE EXPANSION RATE AND AGE OF THE UNIVERSE

What will you learn in this Lab?

Learn how to estimate distance to galaxies. Learn how to determine the redshift of galaxies using spectra. Learn how the redshift of galaxies changes with distance to show how our universe is expanding. Finally you will learn how to calculate the age of the universe.

What do I need to bring to the Class with me to do this Lab?

For this lab you will need:

- A copy of this lab script
- A pencil
- Scientific calculator

Introduction:

The visible Universe contains about 100 billion galaxies of several different types. The galaxies with the oldest stellar populations are the elliptical galaxies, which show almost no evidence of new stars being born. Most of their stars were formed long ago, and these galaxies have not changed very much since. The spiral galaxies are of intermediate stellar age. Each of them shows a slightly different spiral pattern where star formation occurred and is still going on. Finally, there are dwarf and irregular galaxies which only recently started to form most of their stars and are presumably the youngest in the family of galaxies.

Thus, it is not surprising that the Universe has not always looked the same. Galaxies change with time because stars form and die. When did this start? Astronomers think that the Universe had its beginning through a big expansion that created the seeds out of which all galaxies (and the stars within them) formed. This event is known as The Big Bang. It can still be observed through the current expansion of the Universe, seen in the recession of galaxies away from each other. The recession velocity of galaxies increases with distance. No single galaxy is located in the center of this cosmic expansion, because the expansion occurs at the same rate everywhere. Even though it appears to us that our Milky Way Galaxy is in the center of the cosmic expansion, observers at any other galaxies would see the same universal expansion and think they were at the apparent center. This is because the Universe expands without an apparent center in space, but only a center in time: the moment zero, when the Big Bang started.

The consequence of the universal expansion is that all galaxies recede at high velocities from each other. This results in an apparent shift of their light towards longer (redder) wavelengths. This effect is called the Doppler redshift. The amount of redshift is directly proportional to the recession velocity. This redshift can be found by measuring how far a line in the galaxy's spectrum is shifted to longer wavelengths (red-wards). To measure this we use the spectrum next to each galaxy's photograph in Figure 1. We will measure the Expansion Rate of these galaxies and from that derive the current Age of the Universe.

I. Distances: One of the fundamental problems in cosmology is how to determine accurate distances to galaxies. The majority of galaxies are too far away to use parallaxes or other standard candles, such as Cepheid variable stars or luminous supergiants, to measure their distances. In general, these galaxies are too distant for us to see individual stars. Thus, we must use an indirect method such as the apparent size of the entire galaxy to determine its distance

1) The galaxies you'll work with today have approximately the same linear diameter, L, (expressed in kilo-parsecs). Thus, one can measure the galaxy's angular diameter, A (in arcseconds), and derive its distance, R (in kilo-parsecs), as follows:

$$L(\text{kpc}) / R(\text{kpc}) = A('')/206265''$$

$$\text{Therefore: distance} = R(\text{kpc}) = [206265'' \times L(\text{kpc})] / A('')$$

This distance determination technique is referred to as the standard rod method. It is not perfect, because not all galaxies have the same linear diameter. However, we will use this approximation to find distances for the galaxies in our sample.

Units: Because a variety of different kinds of units are needed in this Lab Exercise, some conversions are listed below:

1 Mega-parsec = 1 Mpc = 10^3 kilo-parsecs = 10^6 parsecs
1 kiloparsec = 1 kpc = 1000 parsecs = 10^3 pc = 3×10^{19} km
1 parsec = 1 pc = 3×10^{13} km = 206265 astronomical units
1 astronomical unit = 1 AU = average Earth to Sun distance = 1.5×10^8 km

II. Determining the Distances of Galaxies

We will use the standard rod method to determine the distances to five galaxies whose images and spectra are shown in the photograph (Figure 1). All five galaxies are reproduced at the same scale, so that more distant galaxies appear smaller.

1) Determine the scale of the photographs.

Average horizontal linear size of each photograph is: ______________________mm

The angular size of each image = 3.93 arcminutes (3.93′) = **235.8 arcseconds (235.8")**.

Thus, the scale of each photograph is: angular size/linear size = ________________"/mm

2) Measure the diameter, d in millimeters (mm), of all 5 galaxies in Figure 1. The measurements must be as accurate as possible, preferably within 0.2 mm. Repeat each measurement a few times. For galaxies that are not circular in shape, determine the diameter along the major and minor axes (i.e. the longest and shortest dimensions) and average the two values. The fifth photograph is of a double galaxy; measure only the left-most galaxy. Record the names of the galaxies in the first column of Table 1 and your measurements in the second column.

3) Convert the measured diameter, d(mm), to angular diameter, A("), using the scale of the photograph from Question 1 and the following equation.

$$A('') = d(mm) \times scale(''/mm)$$

Record your values of the angular diameter, A(“), in the third column of Table 1.

4) Compute the distance, R, to each of the galaxies using your angular diameters, A("). Because the distances are very large we will use mega-parsec (Mpc) rather than kilo-parsecs (kpc). We are observing giant elliptical galaxies which are assumed to have intrinsic linear diameters, **L = 32 kpc**. Hence their distances, R(Mpc) are:

$$R(Mpc) = [206.265 \times L(kpc)] / A'' = (206.265 \times 32)/A$$

This version of the formula takes into account the fact that L is in kpc, and R is in Mpc, the common units of measure for both quantities. Compute the distances to all five galaxies, and record the values in the fourth column of Table 1.

III. Determining the Recession Velocities of Galaxies:

A spectrum is an image of a galaxy spread out into colors (or wavelengths) of visible light. Go to Figure 1 and look at the spectrum of the galaxies in our sample. The blue/violet spectral region (on the left side) has the shortest wavelengths, ~3000 Angstroms (1 Angstrom, Å, = 0.000,000,000,1 meter = 10^{-10} meter). The red region (on the right side of the spectrum) has the longest wavelengths, ~5000 Å.

5) First, calibrate the spectral scale (i.e. how many Angstroms are in one millimeter on the spectrum photograph). We use a calibration spectrum from the chemical element helium. The helium spectrum is shown above and below each galaxy spectrum. The helium calibration lines are marked with the arrows in the upper spectrum. They have wavelengths of **3888.7 Å** and **5014.9 Å**, and correspond to the lines labeled a and g at the bottom of Fig. 1.

The difference in wavelength (Å) between the helium lines is ____________________ Å

The measured distance between these lines is ________________________mm

Therefore, the spectral scale = [difference in wavelength (Å)] / [measured distance] =

____________________ Å /mm

6) Now determine the redshift for every galaxy. We use the two strong absorption lines caused by the element calcium (the so-called H and K lines) to measure the galaxies' redshifts. These lines show up as the two black dips in the cigar shaped galaxy spectrum. The amount of the spectral shift of these lines is indicated by the horizontal arrow below each galaxy spectrum. Measure the length of this arrow to within 0.5 mm, and record the results in the fifth column of Table 1. The amount of spectral shift is directly related to the redshift or recession velocity of the galaxy.

7) Use the spectral scale derived in Question 5 to compute the wavelength shift of each galaxy spectrum (in Angstroms). Record the results in the sixth column of Table 1.

wavelength shift (Å) = $\Delta\lambda$(Å) = measured spectral shift(mm) x spectral scale (Å /mm)

8) The wavelength shifts (in Angstroms) are meaningless, unless you compare them to the wavelength that spectral line would have if the galaxy was not moving away from us. The position of the un-shifted line is referred to as the laboratory or rest-frame wavelength, λ_0 . The laboratory wavelengths of the calcium H and K lines are 3968.5 Å and 3933.7 Å, respectively. Compute their average rest-frame wavelength:

λ_0 = [______________(Å) + _________________(Å)] / 2 = __________________(Å)

The tail of the arrow in each spectrum indicates the rest-frame wavelength position of the average of the calcium lines. The head of the arrow indicates their redshifted position. Divide the wavelength shift, $\Delta\lambda$, by the average rest-frame wavelength of the calcium lines, λ_0 . Record the results in the seventh column of Table 1. This ratio is a dimensionless number, which is referred to as the redshift, z.

redshift = z = [wavelength shift(Å)] / [rest-frame wavelength] = $\Delta\lambda / \lambda_0$

9) Using the Doppler relation, the recession velocity, V, for each galaxy is:

$$V = c \times z$$

where: z is the redshift that you calculated (column 7 of Table 1),
and c is the speed of light (c = 300,000 km/s = 3×10^5 km/sec)

Record the recession velocities, V, in the eighth column of Table 1.

IV. Determining the Expansion Rate of the Universe:

In 1929, Edwin Hubble discovered that the Universe is expanding. He used photographs similar to those in this lab. From the distances and recession velocities measured for the galaxies above, we can determine the expansion rate of the Universe. This was exactly the discovery that Hubble did. He discovered that the greater the distance to a galaxy, the faster it moves away from us. That's what we call expansion! Hubble expressed that relationship by the following expression:

$$V\ (\text{km/sec}) = H \times R\ (\text{Mpc})$$

Where H is now called the Hubble Constant. It indicates how many km/sec faster a galaxy will recede away from us for every Mpc of distance it is away from us. The units of the Hubble constant are kilometers per second per mega-parsec (or km/sec/Mpc).

10) Make an estimate of the Hubble constant from the measured recession velocity, V, and distance, R, for each galaxy individually. Simply determine H = V /R for each galaxy, and write the results in the ninth column of Table 1.

The average value of the Hubble constant determined this way is:

H = ________________________ km/sec/Mpc

How does this average value of the Hubble constant compare to the value Hubble obtained in 1929 (550 km/sec/Mpc).

V. Determining the Age of the Universe:

11) The true value of the Hubble constant is 73 km/sec/Mpc, what is the percentage error in your determination from Question 10? SHOW WORK

$$\%error = \left|\frac{73 - H}{73}\right| x100\% = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

Name at least two uncertainties resulting from your measurements on the photographs (two of them have to do with scales of the photograph):

a)

b)

The major source of uncertainty in the determination of the Hubble Constant has nothing to do with your measurements, but is the consequence of one of our assumptions. Which assumption do you think that is?

12) We can now calculate the current Age of the Universe. If all galaxies were packed closely together at the initial moment of the Big Bang, and if the expansion of the Universe has not slowed down since then, a galaxy we observe today (at a distance, R, and with a recession velocity, V) would have traveled exactly the distance R during the total Age of the Universe, T. Since distance = rate times time, we can write:

$$R = V \times T \qquad \text{or:} \qquad V = R / T$$

Hubble's law tells us that V = H x R, so we can substitute:

$$R / T = H \times R$$

Thus, the Age of the Universe, T, is equal to:

$$T = 1 / H$$

Compute the current Age of the Universe, using your value of the Hubble Constant. However, our galaxy distances were measured in mega-parsecs. Therefore, in order to determine the age (in seconds), we must change our value of H from units of km/sec/Mpc into units of km/sec/km. Using your value:

H = ________________km/sec/Mpc / (3 x 10^{19} km/Mpc) = _________________sec^{-1}

Finally, the total Age of the Universe in seconds:

T = 1 / H (sec^{-1}) = ___________________seconds

Since a second is a very small unit, change this age from seconds to Giga-years (Gyr) (units of a billion years). Number of seconds in a year = 365.2425 days x 24 hours x 60 minutes x 60 seconds = 3.156 x 10^7 sec.

Since, 1 Giga-year (Gyr) = 1 billion years = 1,000,000,000 year = 10^9 yr

$$1 \text{ Gyr} = 3.156 \times 10^{16} \text{ sec}$$

Thus, from your best-fit value of H, the Age of the Universe is:

T (Gyr) = T (sec) / 3.156 x 10^{16} sec = ______________________Gyr

The currently adopted best value for the Age of the Universe is 13.7 Gyr. How large is your percentage error in T?

$$\%error = \left|\frac{13.7 - T}{13.7}\right| x100\% = \underline{\qquad\qquad\qquad}$$

13) The current age of our solar system is about 4.65 Gyr.
The oldest stars in the Milky Way Galaxy are about 12 - 13 Gyr.
The oldest known galaxies, the giant ellipticals, have ages about 13 Gyr.

If your determination of the Age of the Universe is the true value, is it consistent with these galaxy ages? Explain.

If you had measured a Hubble constant twice as large as you did, what would your Age of the Universe have been?

Would that value have been consistent with the above galaxy ages? Explain why or why not.

Table 1. Galaxy distances and redshifts (as measured from Figure 1).

Galaxy name	Diameter d(mm)	Angular size A(“)	Distance R(Mpc)	Spectral shift (mm)	Spectral shift in Å	Spectral shift / λ_0	Recession velocity v(km/sec)	Hubble’s constant H=v/R
0	Milky way	--	--	0	0	0	0	--

Notes to recall the expressions above (be sure to include units!):
Col. 2: Diameter, d, measured size (mm) from galaxy photograph
Col. 3: Angular size, A(") = d(mm) x scale("/mm)
Photographic scale, from Question 1 =
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Col. 4: Distance, R(Mpc) = 206.265 x L(kpc) / A(")
From Question 4, L =
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Col. 5: Spectral shift, measured distance (mm) that Ca II lines shifted in spectrum
Col. 6: Wavelength shift, $\Delta\lambda$(Å) = [spectral shift(mm)] x [spectral scale(Å /mm)]
Spectral scale, from Question 5 =
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Col. 7: Redshift, z = [wavelength shift(Å)] / [rest-frame wavelength (Å)] = $\Delta\lambda/\lambda_0$
Average rest-frame wavelength of CAI lines, from Question 8, λ_0 =
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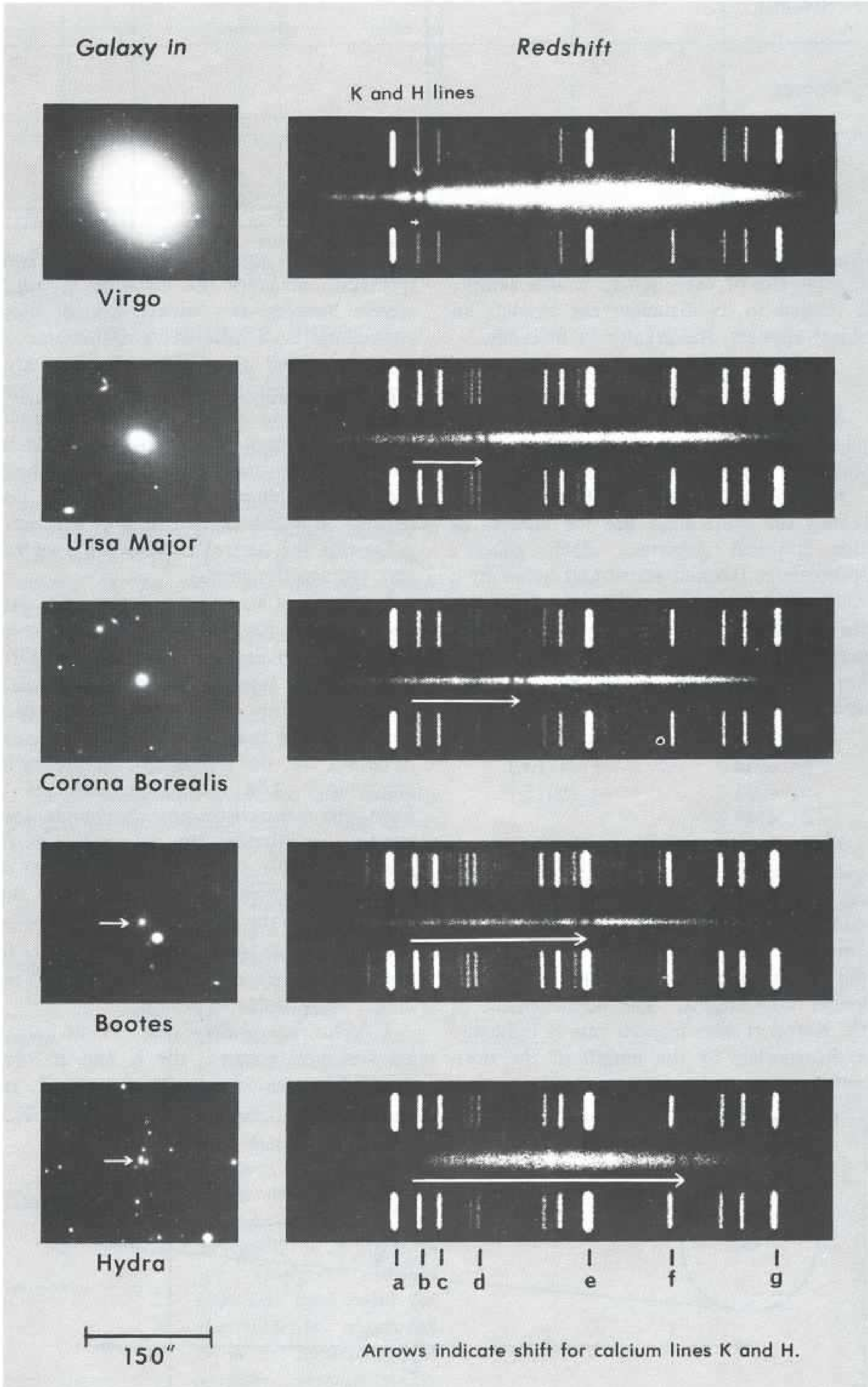
Col. 8: Recession velocity, V(km/sec) = [speed of light] x [redshift] = c z
Speed of light, c = 3 x 10^5 km/sec
Col. 9: Hubble Constant (km/sec/Mpc), H = [recession velocity] / [distance] = V / R
Fig. 1 [shown on next page]. Images [LEFT PANELS] and spectra [RIGHT PANELS] of five distant giant elliptical galaxies. The galaxy spectrum is the cigar-shaped horizontal light streak sandwiched between two helium comparison spectra. The vertical dashes labeled a and g at the bottom point to the strong helium comparison lines at 3888 Å and 5015 Å, respectively. The horizontal arrows show the amount of redshift of the calcium K and H absorption lines in each galaxy’s spectrum. The left panels will be used to measure the galaxy apparent diameters and — given their known linear diameters — their approximate distances. The right panels will be used to measure their spectral redshifts resulting from the universal expansion. The two together will estimate the expansion rate of the universe (in Table 1), and thereby the age of the universe. Photographs are from Hale Observatories.



Arrows indicate shift for calcium lines K and H.