

THE EXPANSION RATE AND AGE OF THE UNIVERSE

I. Introduction:

The visible Universe contains about 100 billion galaxies of several different types. The oldest galaxies 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-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 explosion 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 expansion of the Universe, seen in the recession of galaxies away from each other. We will measure the *Expansion Rate* of these galaxies and from that derive the current *Age of the Universe*.

Distances: One of the fundamental problems in cosmology is how to determine accurate distances for 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. Indirect methods must be *calibrated* using nearby galaxies which are close enough for us to resolve individual stars whose distances we can determine by direct methods. Basically, there are two methods to determine distances to very distant galaxies.

1) *Giant ellipticals* all 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.

2) The second method assumes that a certain types of galaxies all have the same *absolute magnitude*, M (intrinsic brightness). From the observed *apparent magnitude*, m, the distance can be derived using the *Inverse Square Law*. Because most galaxies were more actively forming stars in the past, this method has the disadvantage that the *absolute magnitudes* of galaxies at large distances may be brighter. Therefore, this *standard candle* method is not as reliable as the *standard rod* method described above.

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 a.u. = 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. The horizontal *angular size* of each image = 3.93 *arc minutes* ($3.93'$) = 235.8 arc seconds ($235.8''$).

Average horizontal *linear size* of each photograph is: _____ mm

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

2) Measure the *diameter*, d (in millimeters), 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.

Estimate the size of your *measurement error* for the diameters: _____ mm

3) Convert the *measured diameter*, d(mm), to *angular diameter*, A("), using the *scale* of the photograph from Question 1. Remember that:

$$A(") = d(\text{mm}) \times \text{scale}("/\text{mm})$$

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:

$$R(\text{Mpc}) = [206.265 \times L(\text{kpc})] / A" = (206.265 \times 32) / A$$

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.

5) Name the nearest of your five galaxies: _____

Name the galaxy with the largest angular diameter: _____

Should these answers be the same or different? Explain why.

III. Determining the Recession Velocities of Galaxies:

The Big Bang explosion gave birth to our Universe and all the galaxies within it. This explosion generated a universal expansion, with every galaxy moving away from every other one with a recession velocity that increases with distance. No single galaxy is located in the center of this cosmic explosion, 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.

A spectrum is an image of a galaxy spread out into colors (or wavelengths) of visible light. The blue/violet spectral region (on the left side) has the shortest wavelengths, ~ 3000 Angstroms (1 Angstrom, \AA , = 0.000,000,000,1 meter = 10^{-10} meter). The red region (on the right side of the spectrum) has the longest wavelengths, ~ 5000 \AA .

6) 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 \AA and 5014.9 \AA , and correspond to the lines labeled *a* and *g* at the bottom of Fig. 1.

The difference in wavelength (\AA) between the helium lines is _____ \AA

The measured distance between these lines is _____ mm

Therefore, the *spectral scale* = [difference in wavelength (\AA)] / [measured distance] = _____ $\text{\AA}/\text{mm}$

7) 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.

8) Use the spectral *scale* derived in Question 6 to compute the *wavelength shift* of each galaxy spectrum (in Angstroms). Record the results in the sixth column of Table 1.

$$\text{wavelength shift}(\text{\AA}) = \Delta\lambda(\text{\AA}) = \text{measured spectral shift}(\text{mm}) \times \text{spectral scale} (\text{\AA}/\text{mm})$$

9) The *wavelength shifts* (in Angstroms) are meaningless, unless you compare them to the wavelength that spectral line would have if the galaxy were 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 \AA and 3933.7 \AA , respectively. Compute their average rest-frame wavelength:

$$\lambda_0 = [\text{_____}(\text{\AA}) + \text{_____}(\text{\AA})] / 2 = \text{_____}(\text{\AA})$$

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 .

$$\text{redshift} = Z = [\text{wavelength shift}(\text{\AA})] / [\text{rest-frame wavelength}] = \Delta\lambda / \lambda_0$$

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

$$V = c \times \Delta\lambda(\text{\AA}) / \lambda_0(\text{\AA}) = c \times Z$$

where: Z is the redshift that you calculated (column 7 of Table 1),

and c is the speed of light ($c = 300,000 = 3 \times 10^5$ 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 in two ways using (a) a graph of recession velocity *versus* distance, and (b) by straightforward calculation using individual values of V and R in Table 1.

11) On an 8 x 11 inch sheet of graph paper plot the measured *recession velocities*, V (km/sec), on the vertical scale versus the measured *distances*, R (in Mpc), on the horizontal scale, for all five galaxies plus our Milky Way Galaxy (given in Table 1). For the vertical scale use 5,000 km/sec = 1 cm on your graph paper; for the horizontal scale use 50 Mpc = 1 cm. Mark both scales on the graph paper and label the axes.

What relationship do you observe between the recession velocity and the galaxy distances?

This was exactly the discovery that Hubble made – 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).

12) Draw a *best fit line* through the points on your graph, with the line going exactly through the origin. The line you draw should have equal numbers of galaxies above and below it. The *slope* of this line is equal to the *Hubble constant*. Determine your value of the *Hubble Constant* by reading the velocity that corresponds to $R = 1000$ Mpc from the best-fit line on your graph.

$$H = V/R = \underline{\hspace{2cm}} \text{ km/sec/1000 Mpc} = \underline{\hspace{2cm}} \text{ km/sec/Mpc}$$

13) You can also make a crude 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:

$$H = \text{_____} \text{ (include units !)}$$

How does this average value of the Hubble constant compare to the best fit value that you obtained in Question 12?

V. Determining the Age of the Universe:

When Hubble first determined the expansion rate of the Universe he obtained $H = 550 \text{ km/sec/Mpc}$. However, when the 200 inch telescope at Mount Palomar came into use in 1948, several errors in the distance scale were discovered. It turned out that the real Universe was several times larger than previously thought. Currently, it is believed that the most likely value of the Hubble Constant is between 70 and 75 km/sec/Mpc. If the real Hubble Constant is indeed about 73 km/sec/Mpc, this is 7–8 times smaller than Hubble's value. Thus our Universe is ~ 7 –8 times bigger and older than Hubble thought. This illustrates how difficult extragalactic astronomy is.

14) If the true value of the Hubble constant is 73 km/sec/Mpc, what is the percentage error in your determination from the graph? SHOW WORK

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

- a)
- b)
- c)
- d)

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?

15) 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:

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

Hubble's law tells us that $V = H \times R$, 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 best-fit 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:

$$H = \underline{\hspace{2cm}} \text{ km/sec/Mpc} / (3 \times 10^{19} \text{ km/Mpc}) = \underline{\hspace{2cm}} \text{ km/sec/km}$$

Finally, the *total* Age of the Universe in seconds:

$$T = 1 / H \text{ (km/sec/km)} = \underline{\hspace{2cm}} \text{ seconds}$$

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 = 3.156×10^7 sec.

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

$$1 \text{ Gyr} = \underline{\hspace{2cm}} \text{ sec}$$

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

$$T = \underline{\hspace{2cm}} \text{ Gyr}$$

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

16) 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 Angstrom	Spectral Shift / lambda0	Recession Velocity v (km/sec)	Hubble's constant H=v/R
0 Our own	--	--	0	0	0	0	0	--
1
2
3
4
5

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, $A(") = d(\text{mm}) \times \text{scale}("/\text{mm})$

Photographic scale, from Question 1 = -----

Col. 4: Distance, $R(\text{Mpc}) = 206.265 \times L(\text{kpc}) / A(")$

From Question 4, $L = \text{-----}$

Col. 5: Spectral shift, measured distance (mm) that Ca II lines shifted in spectrum

Col. 6: Wavelength shift, $\Delta\lambda(A) = [\text{spectral shift}(\text{mm})] \times [\text{spectral scale}(A/\text{mm})]$

Spectral scale, from Question 6 = -----

Col. 7: Redshift, $Z = [\text{wavelength shift}(A)] / [\text{rest-frame wavelength}(A)] = \Delta\lambda/\lambda_0$

Average rest-frame wavelength of CAI lines, from Question 9, $\lambda_0 = \text{-----}$

Col. 8: Recession velocity, $V(\text{km/sec}) = [\text{speed of light}] \times [\text{redshift}] = c Z$

Speed of light, $c = 3 \times 10^5 \text{ km/sec}$

Col. 9: Hubble Constant (km/sec/Mpc), $H = [\text{recession velocity}] / [\text{distance}] = V / R$

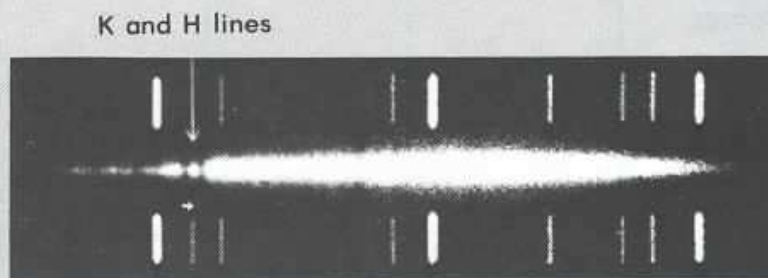
Fig. 1 [shown on next page]. Images [LEFT PANELS] and spectra [RIGHT PANELS] of five distant giant elliptical galaxies. The galaxy spectrum is the cigar-shaped horizontal light streak sandwiched between two helium comparison spectra. The vertical dashes labeled a and g at the bottom point to the strong 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.

Galaxy in

Redshift



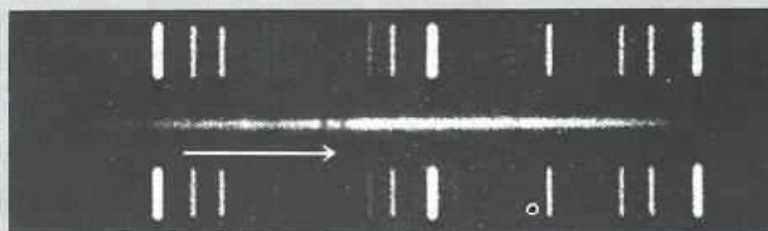
Virgo



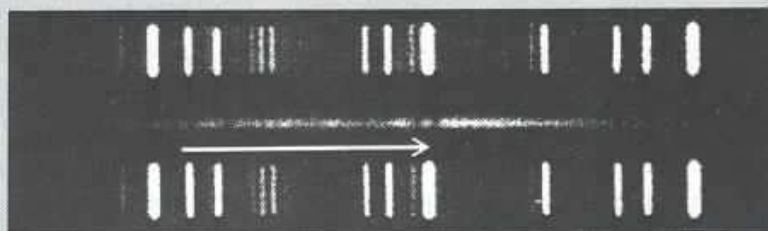
Ursa Major



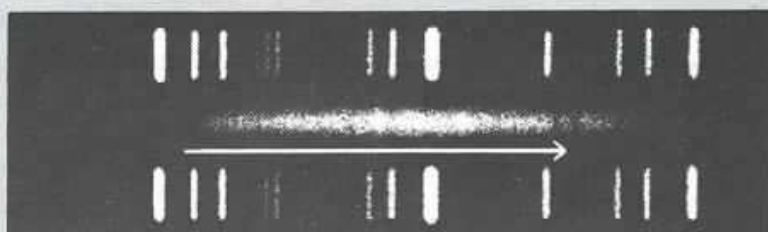
Corona Borealis



Bootes



Hydra



a b c d e f g

150"

Arrows indicate shift for calcium lines K and H.