

Measuring the Mass of Jupiter

EXPANDING UNIVERSE

This lab is an indoors lab that will be performed in the MCS (Math) building, room 8, which is a computer lab located in the basement. If you want to practice or repeat this later at home, you can download this free software and other supporting documentation at the web site:

<http://www.gettysburg.edu/academics/physics/clea/hublab.html>

This document is based primarily on materials supplied by the CLEA staff.

Purpose: The purpose of this lab is to give you an idea of how: 1) we know the universe is expanding, 2) we compute the age of the universe, 3) the expanding universe would look from another galaxy

Important Note: this lab has a lot of calculations. You are encouraged to work together in groups of three or less. Because there are so many calculations, you may submit one assignment per group, instead of submitting individual assignments.

Introduction

One of the most unexpected things about the universe was that virtually all the galaxies in it (with the exception of a few nearby ones) are moving away from our own, the Milky Way. This curious fact was first discovered in the early 20th century by astronomer Vesto Slipher, who noted that absorption lines in the spectra of most spiral galaxies had longer wavelengths (i.e. were redder/redshifted) compared to those lines observed from stationary objects. Assuming that the redshift was caused by the Doppler shift, Slipher concluded that the red-shifted galaxies were all moving away from us.

In the 1920's, Edwin Hubble measured the distances of the galaxies for the first time, and when he compared (i.e. graphed) these distances against the velocities for each galaxy, he noted something even stranger: The further a galaxy was from the Milky Way, the faster it was moving away. This naturally raised the question "Was there something special about our place in the universe that made us a center of cosmic repulsion?"

Astrophysicists readily interpreted Hubble's relation as evidence of a universal expansion. The distance between all galaxies in the universe is getting bigger with time, like the distance between raisins in a rising loaf of bread or two dots on an stretched rubber band. An observer on any galaxy, not just our own, would see all the other galaxies traveling away, with the furthest galaxies traveling the fastest.

This was a remarkable discovery. The expansion is believed today to be the result of a "Big Bang" which occurred 14 billion years ago, a date which we can calculate by making measurements like those of Hubble. The rate of expansion of the universe tells us how long it has been expanding. We determine the rate by plotting the velocities of galaxies against their distances, and determining the slope of the graph, a number called the Hubble's constant, H_0 . Hubble's constant tells us how fast a galaxy at a given distance is moving away from us. Hubble's discovery of the correlation between velocity and distance is fundamental in reckoning the history of the universe. Because of its importance, Hubble's experimentally determined relationship is now known as "Hubble's law."

Using modern techniques of digital astronomy, we will simulate Hubble's experiment using galaxies in clusters. Clusters of galaxies are exactly what the name would imply – a group of galaxies that all orbit around a common center of mass, much like the planets orbit the Sun and stars in the Milky Way orbit the galaxy's center. One interesting thing we now know about clusters is that they tend to have more elliptical galaxies than spiral galaxies when compared to the number of elliptical/spiral galaxies that aren't in clusters.

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The technique we will use to measure the expanding universe is very similar to one used by current cosmologists. As they expand on Hubble's experiment, we have learned some further startling discoveries. The latest research indicates that not only is the universe expanding, but it is also speeding up, due to a "dark energy" about which we know almost nothing. Perhaps this "dark energy" is related to Einstein's self-titled "worst mistake," the "cosmological constant." However, the discovery that the universe is accelerating is only a few years old. At this stage, we simply don't know why it's happening.

In this activity, you will compute the velocities of several galaxies and will estimate the distances of these galaxies from Earth. To compute the velocities, we will compute the Doppler shift of absorption lines in the galaxies. To compute the distances, we will measure the galaxies' brightness and assume we know how luminous these galaxies truly are. Then we will examine the relationship between galaxy velocity and distance, and determine a rough estimate of the age of the universe, much like what Hubble did in the 1920's.

Program use

To run the program, go to the Start menu → Programs → Natural Sciences → Astronomy → CLEA exercises → Hubble Redshift. You will need to log in (under the file menu). Use your first initial and last name as your login. (When you save data, the computer saves it as your login name.) For instance, my login would be dvakil.

Overview of the simulator

The software for the **CLEA Hubble Redshift Distance Relation** laboratory exercise puts you in control of a large optical telescope equipped with a TV camera and an electronic spectrometer, which measures how much light lands on the telescope at various wavelengths (colors).

The TV camera attached to the telescope allows you to see the galaxies, and steer the telescope so that light from a galaxy is focused onto the spectrometer. When you turn on the spectrometer, it will begin to collect photons (i.e. light) from the galaxy. The screen will show the spectrum (i.e. a plot of the intensity of light collected versus wavelength) like the one seen in figure 2. When a sufficient number of photons are collected, you will be able to see distinct spectral lines from the galaxy (the H and K lines of calcium), and you will measure their wavelength using the computer cursor. The spectrometer also determines the apparent magnitude of the galaxy by measuring how quickly it receives light from the galaxy. So for each galaxy you will have recorded the wave-lengths of the H and K lines and the apparent magnitude. From this, we will compute the velocity and distance of the galaxy.

Using the simulator – finding a galaxy

When you log in, you will see the inside of an observatory. Notice that the **dome** is closed and **tracking status** is off (i.e. the telescope is not moving to counteract the Earth's rotation). Activate the tracking and then open the dome by clicking on the **tracking** and **dome** buttons. When the dome opens, the view we see is from the finder scope. Locate the **Change View** button on the control panel and note its status, i.e. finder scope.

Next we need to find a galaxy in one of the many clusters we will examine. To do this, you must select a field of view. One galaxy cluster is already selected when you first start the program. Later, you will need to change fields to explore other galaxy clusters. To do this, select **Field...** from the menu bar at the top of the control panel. The items listed are the galaxy cluster fields that we will examine.

The view window has two magnifications (see Figure 1 below): the **Finder View** and the **Instrument View**. The latter is the view from the main telescope with red vertical lines that show the position of the spectrometer's slit. The shapes of the brighter galaxies are clearly different from the dot-like images of stars. However, faint, distant galaxies can look similar to like stars because they appear so small.

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Position your telescope near a galaxy and change to the **Instrument View**. Then steer the telescope, using the directional buttons (**N**, **S**, **E** or **W**), to slew/move the telescope until the red slit is on top of the brightest part of a galaxy. You can adjust the speed or “slew rate” of the telescope by pressing the **slew rate** button. (1 is the slowest and 16 is the fastest).

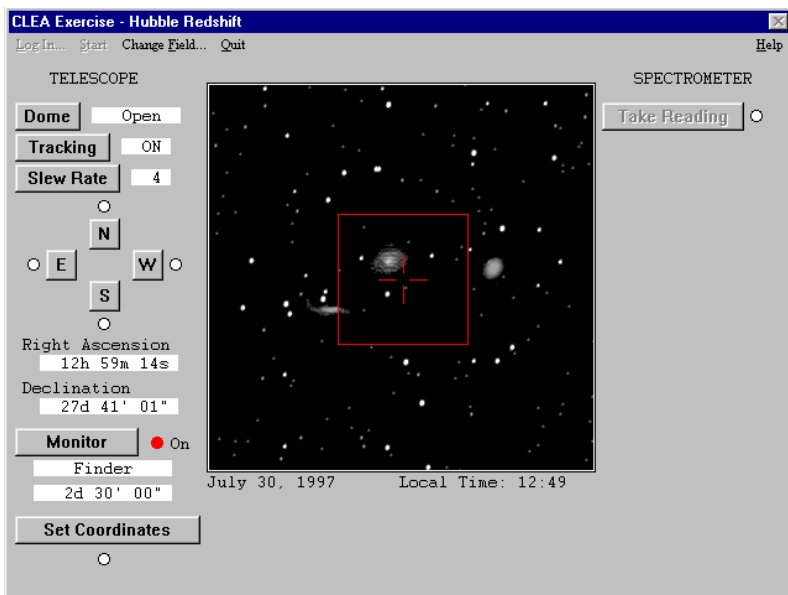


Figure 1:
Field of View from the
Finder Scope

Measuring the spectrum and apparent magnitude

When you have positioned the galaxy accurately in the slit, click on the **take reading** button to the right of the view screen. You will see a screen similar to Figure 2, below. To start collecting data, press **start/resume count**. The spectrum will build up as more light is collected – initially the data will be very bumpy/noisy. As more light collects, your spectrum should resemble what is shown in Figure 2. Continue collecting light until **Signal/Noise** is above 100. This assures that you have less than 1% noise in your data. (If Signal/Noise were 50, you’d have 2% noise.)

If the galaxy you are examining is faint, you will notice it takes a long time to collect light. To abate this problem, you may request time on the 4-meter telescope. Like a real astronomer, you will probably be turned down your first time. Wait until you are told to apply again and when you get time on the larger scope, use it to measure the faint galaxies.

When a spectrum has little noise, you should see a fairly flat galaxy spectrum with two (or, occasionally one) deep absorption lines. We need to determine the wavelength of these two absorption lines to measure the velocity of the galaxy via the Doppler effect.

To determine the wavelength of the two absorption lines, place the arrow at the bottom of the absorption line and press and hold the left mouse button. Notice the arrow changes to a cross hair and the wavelength data appears at the top of the display. **The K-line will be on the left and the H-line on the right.** Determine their wavelengths and record them in table 1 on page 9. Also record the apparent magnitude of the galaxy.

NOTE: At higher velocities, all spectral features (such as the H and K lines) are at longer wavelengths and may be redshifted out of instrument’s detection range. Measure only those lines for which you can accurately determine the line center.

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Once you have obtained these data for your galaxy, repeat this measurement for all galaxies in the field. You may share data with 2 other classmates, so I suggest you coordinate your efforts. When you have completed a field, move on to the next field. You should find 3 galaxies per field, except for the Sagittarius field, which has 7 faces, instead of 3 galaxies. (The faces represent galaxies. The faces themselves belong to the software programmers and designers.) There will be a total of 22 galaxies/faces.

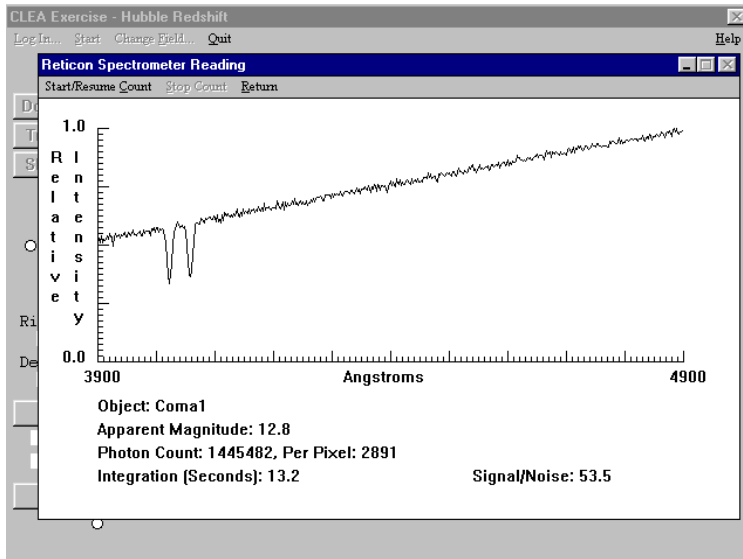


Figure 2:
Spectrometer Reading Window

Computing the distance

To compute the distance to a galaxy, we will assume all galaxies have an **absolute magnitude (M)** of -22 . Absolute magnitude means that the **apparent magnitude (m)** of the galaxy, when located at a distance of 10 parsecs (10 pc), would be -22 . Note that is almost as bright as the Sun as seen from Earth. [We have discussed apparent magnitudes several times in this class.] Galaxies, thankfully, are much further than 10 pc and therefore significantly fainter than the Sun. The relationship between the **absolute magnitude**, the **apparent magnitude**, and the distance (in units of parsecs) is given by the following 2 equivalent formulas:

$$M = m + 5 - 5 * \log D \quad \text{or} \quad \log D = \frac{m - M + 5}{5}$$

Example calculation: Assume a galaxy has an apparent magnitude of 12.30 and an absolute magnitude of -22 (as do they all, in this lab):

$$\log D = \frac{m - M + 5}{5} = \frac{12.30 - (-22) + 5}{5} = \frac{39.30}{5} = 7.86$$

This tells you that the logarithm (base 10) of the galaxy's distance, in units of parsecs, is 7.86. To compute a distance from this logarithm, raise 10 to that power. Convert your answer to Megaparsecs (Mpc, which is "millions of parsecs").

Continuing from the above example:

$$\Rightarrow D = 10^{7.86} = \underline{72,440,000} \text{ pc which is equal to } 72.44 \text{ million pc } \boxed{72.44 \text{ Mpc}}$$

This galaxy is 72.44 million parsecs from Earth. Had "log D" been 8.86 instead of 7.86, the distance would be 724,400,000 pc, or equivalently 724.4 Mpc. (10 times further.)

Compute the distances to all of the galaxies and fill in the rest of table 2.

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Computing the velocity

To compute the velocity of each galaxy, we must determine the Doppler shift of each absorption line in the galaxy. The Doppler shift is denoted by the symbol $\Delta\lambda$, where the Δ means “change” (or shift) and λ means wavelength of the absorption line. To compute the Doppler shifts, subtract the rest wavelength of the absorption line from the value you measured.

Rest wavelengths: K line of calcium is 3933.67 Å H line of calcium is 3968.5 Å.

$$\Delta\lambda = \lambda_{\text{measured}} - \lambda_{\text{Lab}}$$

Example calculation: Assume you observe a galaxy’s K line at 4030 Å.

$$\Delta\lambda_{\text{K}} = 4030 - 3933.67 = 96.33$$

To compute the speed of a galaxy from the Doppler shift, use the following formula, in which “c” represents the speed of light (300,000 km/s):

$$v = c * \frac{\Delta\lambda}{\lambda_{\text{Lab}}}$$

Continued example: $\text{velocity}_{\text{K}} = c \times \frac{\Delta\lambda}{\lambda_{\text{Lab}}} = 3 \times 10^5 \frac{\text{km}}{\text{sec}} \times \frac{96.33}{3933.67} = 7350 \frac{\text{km}}{\text{sec}}$

Complete the velocities for both the H line and K line for each galaxy, and determine the average velocity for that galaxy from the two lines. Complete table 3 on page 10.

Computing Hubble’s constant

When Edwin Hubble (and others who followed up on his work) graphed galaxies’ velocity against their distances, he noticed that as a galaxy got further, it also got faster. This can be expressed in 2 equivalent simple relationships:

$$v = H_0 \times D \quad \text{or} \quad H_0 = v \div D$$

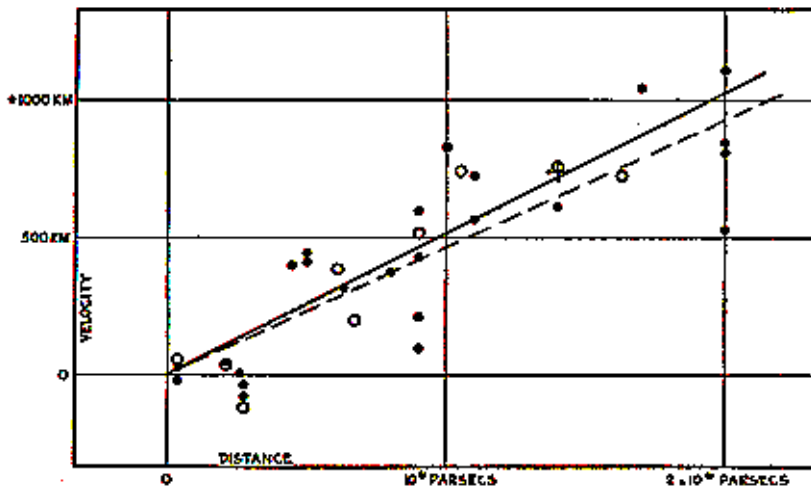
where H_0 is a constant called Hubble’s constant mentioned in the introduction.

Hubble’s constant is directly related to the age of the universe. We will measure it in two separate ways. First, we will compute it for each galaxy and compute an average H_0 . Complete this first method and fill in the rest of table 4 using data from tables 2 and 3.

Second, we will do what Hubble did and graph velocity on the vertical (y) axis and distance, in units of megaparsecs (Mpc) on the horizontal (x) axis. Draw a single line through the entire graph that best represents the trend for what you see, as seen in Hubble’s original data below (Figure 3). Compute the slope of the best-fit line; the slope is Hubble’s constant.

To compute the slope, pick two points on the line that are NOT data points and that are near opposite corners of the graph. The slope is the vertical change (i.e. the “rise”) divided by the horizontal change (the “run”) between these two data points. Draw a horizontal and vertical line to indicate the rise and run. You should get a slope (H_0 = Hubble’s constant) between 50 and 100 km/s per Mpc from your data.

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Computing the age of the universe

Hubble's relationship (also known as "Hubble's law") tells us that the velocity of a galaxy depends on its distance. Therefore, if galaxies have been moving at the same speed throughout all of the universe's history, we can figure out when any two galaxies were at the same place. This time, when all galaxies (and, in fact, everything in the known universe) were at the same location is called the "Big Bang." However long ago that occurred is the age of the universe.

We will compute this time by using a fictional galaxy that is 800 Mpc away and the data we have measured.

What to submit

- Your (group's?) answers to the following questions. Show all work.
- Tables 1-4 below. Also include table 5, if you are doing the extra credit.
- Your graph(s), with a title, both axes labeled, and a slope triangle & calculation clearly indicated.

Questions (Complete tables 1-4 and draw your graph before answering these)

- [1 pt] Which value of Hubble's constant do you think is better: the one from the slope of the graph, or the value computed from the average of each individual galaxy? Justify your choice.
- [1 pt] Based on your data, why were you asked to measure all 3 galaxies in each cluster, instead of picking one galaxy per cluster?
- [1 pt] What causes individual galaxies in a cluster to have noticeably different velocities from each other? (There are at least two important effects. Determining more than one will earn you 1/2 pt of **extra credit**.)
- [1 pt] According to your data, how fast (in km/s) would a galaxy be moving if it were 800 Mpc away? [Use Hubble's law!]
- [1/4 pt] Convert 800 Mpc into km. There are 3.09×10^{19} km in one Mpc.
- [1 pt] Knowing how many km away a galaxy is, and assuming that it has been moving at a constant speed, determine how many seconds this 800 Mpc galaxy has been moving away from the Milky Way.
- [1/4 pt] Convert this answer to years. There are 3.15×10^7 (=31,500,000) sec in one year.
- [1/4 pt] Convert this to billions of years. There are 10^9 (=1,000,000,000) in one billion.
- [1/4 pt] According to your data, what is the age of the universe?

Note that no matter what distance you start with for the fictional galaxy, you should get the same answer for question 8. In other words, that answer should not depend on if you picked a galaxy at 800 Mpc or 2 Mpc. Using algebra, you can show that the answer to #8 is $1/H_0$, after Mpc are converted into km.

- [1 pt] In the past, do you think Hubble's constant was bigger, smaller, or the same as what you measured for today? Justify your choice. Think about distance and velocity in the past and what might affect them.

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- 11) [1 pt] Approximately 4 years ago, microwave light left over from the Big Bang (called the “Cosmic Microwave Background”) and modern versions of the technique we used in this lab (with supernova explosions replacing galaxies) indicated that the universe is 13.5-13.7 billion years old. A) How close was your answer to the value scientists now believe? B) Compute the percent error between your answer and what we think the real answer is. (See page **Error! Bookmark not defined.** for percent error computations.)
- 12) [2.5 pts] In 1-2 paragraphs, explain the “big picture” of this lab – what did we do, why did we do it, and what did you learn. Notice this question asks for 1-2 paragraphs, not 1-2 sentences. As always, feedback (positive or constructive) is welcome.

The following exercise may be completed for **extra credit**.

We have computed data and the age of the universe based on observations from our own Milky Way. From the Milky Way, we observe that nearly all galaxies are moving away from us. It is natural to think that this means that we are at the center of an expanding (or repulsing) universe. However, before we trust that natural reaction, let’s examine what someone would see from another galaxy.

Assume you are in a galaxy (named galaxy A) that is moving away from the Milky Way at a speed of 10,000 km/sec (10^4 km/s). Let’s assume all galaxies are moving in one dimension, rather than 3, for simplicity sake. If we think of the Milky Way as being at the start of a number line, our galaxy A would be moving to the right at a speed of 10,000 km/sec. Galaxies closer to us would also be moving to the right, but slower. Galaxies further would be moving to the right faster.

- 13) [1/4 pt] How fast and in which direction would an observer IN galaxy A see us moving?
- 14) [1/4 pt] Pretend there is a 2nd galaxy (B) twice as far from us as galaxy A. From the perspective of galaxy A, how fast and in which direction is galaxy B moving?
- 15) [1/4 pt] Pretend there is a 3rd galaxy (C) three times as far from us as galaxy A. From the perspective of galaxy A, how fast and in which direction is galaxy C moving?
- 16) [1/4 pt] Using your value of Hubble’s constant, determine how far away galaxy A is from the Milky Way.
- 17) [1/2 pt] How far away are galaxies B and C from galaxy A?
- 18) [1 pt] Hopefully, from the above questions, you can figure out the relationship between the velocity we see in the Milky Way, compared to the velocity seen from galaxy A as well as a relationship between Milky Way distances and galaxy A distances. Apply these relationships to all of the data in table 4 and fill in table 5 from galaxy A’s perspective
- 19) [1/2 pt] Draw a velocity-distance graph from galaxy A, and compare this new slope to the slope you measured from the Milky Way graph. Comment appropriately.
- 20) [1 pt] What can you conclude about the following statement: “the Milky Way is at the center of the expanding universe, because all galaxies are moving away from us.”

Table 1 – Data from telescope [4 pt]

Galaxy	Measured K-line wavelength (λ)	Measured H-line wavelength (λ)	Apparent magnitude (m)
UMa 1-1			
UMa 1-2			
UMa 1-3			
UMa 2-1			
UMa 2-2			
UMa 2-3			
CrBr1			
CrBr2			
CrBr3			
Boot1			
Boot2			
Boot3			
Coma1			
Coma2			
Coma3			
EDW			
LAM			
PRC			
GAS			
MBH			
MKL			
RFG			

Table 2 – Distances [3 pts]

Galaxy	Abs Mag (M)	App Mag (m)	Log D	D (parsecs) [pc]	D (Mpc) (Megaparsecs)
UMa 1-1					
UMa 1-2					
UMa 1-3					
UMa 2-1					
UMa 2-2					
UMa 2-3					
CrBr1					
CrBr2					
CrBr3					
Boot1					
Boot2					
Boot3					
Coma1					
Coma2					
Coma3					
EDW					
LAM					
PRC					
GAS					
MBH					
MKL					
RFG					

Table 3 – Velocities [3.5 pts]

Galaxy	H-line λ	$\Delta\lambda_H$	velocity _H	K-line λ	$\Delta\lambda_K$	velocity _K	velocity _{avg}
UMa 1-1							
UMa 1-2							
UMa 1-3							
UMa 2-1							
UMa 2-2							
UMa 2-3							
CrBr1							
CrBr2							
CrBr3							
Boot1							
Boot2							
Boot3							
Coma1							
Coma2							
Coma3							
EDW							
LAM							
PRC							
GAS							
MBH							
MKL							
RFG							

Table 4 – Hubble data for graph [1 pt]

Galaxy	Vel _{avg}	Dist (Mpc)	H ₀ (vel/dist) – Hubble’s constant
UMa 1-1			
UMa 1-2			
UMa 1-3			
UMa 2-1			
UMa 2-2			
UMa 2-3			
CrBr1			
CrBr2			
CrBr3			
Boot1			
Boot2			
Boot3			
Coma1			
Coma2			
Coma3			
EDW			
LAM			
PRC			
GAS			
MBH			
MKL			
RFG			

Don't forget:

Compute average value of Hubble’s constant from the table above. _____ [1 pt]

Hubble’s constant from graph _____ [2 pts]

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Table 5 – Hubble plot data from galaxy A (**extra credit** – See Question 18.)

Galaxy	Vel _{avg}	Dist (Mpc)	H ₀ (vel/dist) – Hubble’s constant
UMa 1-1			
UMa 1-2			
UMa 1-3			
UMa 2-1			
UMa 2-2			
UMa 2-3			
CrBr1			
CrBr2			
CrBr3			
Boot1			
Boot2			
Boot3			
Coma1			
Coma2			
Coma3			
EDW			
LAM			
PRC			
GAS			
MBH			
MKL			
RFG			

Don’t forget:

Compute average value of Hubble’s constant from the table above. _____

Hubble’s constant from new graph _____