Lab #8:
Hubble's Law by Project CLEA

April 2, 2012
Due April 6, 2012

1 Introduction

The late biologist J.B.S. Haldane once wrote: "The universe is not only queerer than we suppose, but queerer than we can suppose." One of the queerest things about the universe is that virtually all the galaxies in it (with the exception of a few nearby ones) are moving away from 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 (were "redder") than those 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 1920s, Edwin Hubble measured the distances of the galaxies for the first time, and when he plotted these distances against the velocities for each galaxy he noted something even queerer: The further a galaxy was from the Milky Way, the faster it was moving away. Was there something special about our place in the universe that made us a center of cosmic repulsion?

Astrophysicists readily interpreted Hubbles relation as evidence of a universal expansion. The distance between all galaxies in the universe was getting bigger with time, like the distance between raisins in a rising loaf of bread. 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 a result of a "Big Bang" which occurred between 10 and 20 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 Parameter, H_0, which tells us how fast a galaxy at a given distance is receding from us. So Hubbles discovery of the correlation between velocity and distance is fundamental in reckoning the history of the universe.

2 Theory

The redshift of a galaxy can be determined by comparing the measured wavelength of a specific line or set of lines to the known wavelength of the line(s) when the emitter/absorber is at rest. For this lab, we use the K and H lines of Ca II (i.e. singly ionized Ca), with rest wavelengths of 3933.7 Åand 3968.5 Å, respectively. The recessional velocity v of the galaxy is then given by:

$$v = \frac{c * (\lambda_{obs} - \lambda_{rest})}{\lambda_{rest}}$$

where λ_{rest} is the rest wavelength of the line given above, λ_{obs} is the measured wavelength of the line from the galaxy's spectrum, and $c = 2.99792 \times 10^5$ km/s.

To find the Hubble constant, we also need to determine the distance to the galaxies. To do this, we assume that all of the galaxies in this sample have an absolute magnitude of $M = -22$. (Note that this can be a dangerous assumption in general, as galaxies come in all sizes, and thus quite a range of luminosities. The galaxies in this lab's sample have been selected based on characteristics that suggest that the $M = -22$ assumption is fairly reasonable. In the real world, one would use something like the Tully-Fisher relation to estimate the luminosity of the galaxy, and then translate that to an absolute magnitude.) When you observe the galaxies in this lab, you will get not only the spectrum of the galaxy, but also its apparent magnitude. You can then determine the distance using the distance modulus equation:

$$m - M = 5 * log_{10}(d/10 \text{ pc})$$

or, solved for d:

$$d = 10^{0.2*(m-M+5)}$$

where distance is in pc.

Once you have the recessional velocities of the galaxies and their distances, you can find the Hubble constant. Hubble's law says:

$$v = H_0 * d$$

which looks like the equation of a line, with the slope of H_0 and a y-intercept $= 0$. Once you have the Hubble constant calibrated by fitting a line to your measured velocities and distances for a sample of galaxies, you can use the relation directly to find the distance to other galaxies (since you don't always have some luminosity standard candle for every galaxy to find the distance instead). Assuming the Hubble constant has been constant throughout the lifetime of the universe (which is not strictly true, but gets you close enough for the purposes of this lab), you can also determine the age of the universe. Hubble's constant is a velocity (in km/s, for this lab) divided by a distance (in Mpc, for this lab). From $d = vt$, we know that $t = d/v$, which means that:

$$t = d/v = 1/H_0$$

assuming that you do a unit conversion to get H_0 into units of s^{-1}.

3 Procedure

1. Open the Hubble Redshift program by double clicking on the CLEA_hub icon in the Astro121 folder. Select **Log In** from the menu bar, and enter student names and the lab table number. Click **OK** when ready. The title screen appears.

2. Select **Start** from the menu bar to begin the exercise. The screen shows the control panel and view window as found in the "warm room" at the observatory.

Notice that the dome is closed and tracking status is off.

3. First, open the dome by clicking on the **Dome** button.

The dome opens and the view we see is from the finder scope. The finder scope is mounted on the side of the main telescope and points in the same direction. Because the field of view of the finder scope is much larger than the field of view of the main instrument, it is used to locate the objects we want to measure. The field of view is displayed on-screen by a CCD camera attached on the finder scope. Locate the **Monitor** button on the control panel and note its status, i.e. finder scope.

4. Turn on the tracking by clicking the **Tracking** button. The telescope will now track in sync with the stars.

5. Before we can collect data we need to do the following:
(a) Select a field of view (one is currently selected).
(b) Select an object to study (two from each field of view).

To review the fields of study for todays lab, select **Change Field** from the menu bar at the top of the control panel. The items you see listed are the fields that contain the objects we have selected to study.

This list contains 5 fields for study tonight; Ignore the Sagittarius field, as it's just a gag field with pictures of the software writers. You will need to select 2 galaxies from each field and collect data with the spectrometer (a total of 10 galaxies).

To see how the telescope works, change the field of view to Coma Berenices at RA 12 hr 59 min and Dec. 27 deg 41 min. Press OK to move the telescope to the correct position.

Notice the telescope slews (moves rapidly) to the RA and DEC coordinates we have selected. The view window will show a portion of the sky that was electronically captured by the charge coupled device (CCD) camera attached to the telescope.

The view window has two magnifications:
(a) Finder View is the view through the finder scope that gives a wide field of view and has a red square which outlines the instrument field of view.
(b) Spectrometer View is the view from the main telescope with red vertical lines that show the position of the slit of the spectrometer.

6. Find a galaxy and slew the telescope using the N, S, E, W buttons so that the galaxy is inside the red finder window (the red box in the Finder View). You can make the telescope move faster or slower by changing the slew rate, where 1 is very slow, and 16 is fastest. Note that N is up, and E is left (rather than right, like on a map, because we're looking up at the sky instead of down at the ground).

Click on the **Monitor** button to change the view from the Finder Scope to the Spectrometer. The field of view is now smaller so that you can accurately position the galaxy in the slit of the spectrometer. Use the directional buttons (N, S, E or W), to slew the telescope **to carefully**

position, in the slit, the object you intend to use to collect data; Any of the galaxies are suitable. To move continuously, press and hold down the left mouse button. Notice the red light comes on to indicate the telescope is slewing in that direction.

The more light you get into your spectrometer, the stronger the signal it will detect, and the shorter the time required to get a usable spectrum. **Try to position the spectrometer slit on the brightest portion of the galaxy**. If you position it on the fainter parts of the galaxy, you are still able to obtain a good spectrum but the time required will be much longer. If you position the slit completely off the galaxy, you will just get a spectrum of the sky, which will be mostly random noise.

7. When you have positioned the galaxy accurately in the slit, click on the **Take Reading** button to the right of the view screen.

Photons are collected one by one. We must collect a sufficient number of photons to allow identification of the wavelength. Since an incoming photon could be of any wavelength, we need to integrate for some time before we can accurately measure the spectrum and draw conclusions. The more photons collected, the less the noise in the spectrum, making the absorption lines easier to pick out.

To initiate the data collection, press **Start/Resume Count**. Make sure an object name appears in the spectrum window, and not just "Reading Sky".

8. When the Signal/Noise (in the lower right of the spectrum window) reaches **15** or more, click the **Stop Count** button. The computer will plot the spectrum with the available data. Clicking the **Stop Count** button also places the cursor in the measurement mode. Using the mouse, place the arrow anywhere on the spectrum, 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. As you hold the left mouse button, move the mouse along the spectrum. You are able to measure the wavelength and intensity at the position of the mouse pointer.

Find the H and K lines of calcium. These lines are approximately 40 Å apart; the K line is first (i.e. left, or lower wavelength), followed by the H line. They should stand out from the noise. If not, continue to count photons.

9. Record the object name, apparent magnitude, signal/noise, and the measured wavelength of the H and K lines of calcium on the data sheet located at the end of this exercise. Accuracy for wavelength is only necessary to the nearest Å.

When you have finished recording the line measurements for your first galaxy, you should choose a second galaxy in the same galaxy field and repeat steps 6 through 9. Then you should go to **Change Field** on the menu and record data for two galaxies in each of the 5 galaxy fields (ignoring Sagittarius). **Note that to change fields, you must be in the Finder View!** Also note that the galaxies in some of the fields will not be obvious in the Finder View. You will have to switch to the Spectrometer View to see them. These galaxies are very far away. It may take 2 minutes or more to record the spectrum for each galaxy. You do not need to save any data within the CLEA program. Just the values that you write in your table.

11. Now open MATLAB. Create a folder in the A121 folder on the desktop with the usual naming conventions, and save your work there. Be sure to navigate to that folder within MATLAB.

12. Create three arrays: one of the apparent magnitudes you recorded, one of the H line measured wavelength, and one of the K line measured wavelength. Remember, you can create an array by giving it a name, such as appm, and setting the name equal to the values you recorded, separated by commas and enclosed in []. For example, if I recorded apparent magnitudes of 8, 5, 3, 9, 10, 6 for 6 galaxies (you will have more), I would create the apparent magnitudes array by:
>> appm = [8,5,3,9,10,6] (your values will be different!)
Suggested names for the other two arrays are hlines and klines.

13. Create an array for the distances to the galaxies using the apparent magnitude and assuming M = -22 for all of the galaxies. Make another array that converts the distances from pc to Mpc.

14. Create two arrays which calculate the redshift z for the H lines and the K lines. Remember that K is the shorter wavelength line of the H and K pair.

15. Create an array which calculates the recessional velocities for the H lines and for the K lines. The redshifts of these galaxies are small enough that we need not worry about the relativistic version of the Doppler shift formula.

16. Create an array which takes the average of the H line and K line velocity for each galaxy. Record the average velocity for each galaxy in the table on the last page of this lab.

17. Now let's take a look at our results visually by plotting average velocity **in km/s** (y-axis) vs distance **in Mpc** (x-axis). Plot the data using points rather than lines, because the plot will look funny with lines, given that your distances are not sorted. You should hopefully see a linear trend in the data, but there may be quite a lot of scatter in the points. Rather than estimating the best linear fit to get the slope of the line, let's have MATLAB find the line for us. To do this, we'll use the **polyfit** command:
>> p = polyfit(distmpc,avgv,1)
which tells polyfit to fit a line (1) for x-values distmpc and y-values avgv. Polyfit then gives the parameters of the line (remember, a line is $y = ax + b$, where a is the slope and b is the y-intercept), where p(1) is the slope a, and p(2) is the y-intercept b. What we're interested in is just the slope a, or p(1). This value is your value of H_0, in km/s/Mpc, which you should **record on your data sheet**.

18. Now, let's overplot your linear fit onto the data. To do this, create a new array of linearly-spaced distances that will go in order from your lowest value of distance on the x-axis of your plot to the highest value on the x-axis. Since it's a straight line, it doesn't really matter how many points you use; It will look smooth even with just 2 points. To get the y-values for your fit, you can use the **polyval** command:
>> fit1 = polyval(p,newdist)
assuming you named your polyfit parameter array "p" and your orderly array of distances "newdist". You can then plot the fit using "newdist" as the x values and "fit1" as the y-values. Plot the fit as a line, rather than as points.

18. Unfortunately, **polyfit** does not make it easy to force the y-intercept value to be zero, but this is what we'd really like to do. Instead, we can use the magic of MATLAB's matrix math to do this. Try the command:

$>>$ a = avgv/distmpc

Note that this time, there should be no period before the slash. The value "a" is the slope of the best fit line for your data, assuming that the y-intercept is zero. To see what difference this makes, **overplot this fit to the data**, calculating the fit using the "newdist" array you created in the previous step. Be sure to use a different linestyle than the one used in the previous step!

19. Give your plot a title, axes labels, and a legend. Note that to do an apostrophe in the title, you need to use two single quotes (not a double quote) instead of just one.

Either print it directly, or save it as a jpeg using the command:

$>>$ print -djpeg filename.jpg

where filename is the same name that you gave your folder for this lab. Print 2 copies, one for each lab partner.

20. Calculate the age of the Universe, using first the value of H_0 from polyfit, and then the value of H_0 from the matrix math solution. Give your final answer in Gyrs, and write them on the indicated spaces on the Data Table sheet.

4   What should you turn in?

You should turn in the data table, remembering to include H_0 from your slope and the calculation for the age of the universe (for both methods of determining the slope), the plot of your data with the linear fits overplotted, and your code (pared down to only the relevant commands needed to create your arrays, do all your calculations, and make the plots). You can skip handing in the data table, if you publish your m-file and make all of the values it asks for (including the units AND the list of object names AND the signal/noise) clear in the published file.

Data Table: Pick 2 Galaxies in Each Field						
Object	apparent magnitude	signal/ noise	K line (rest: 3933.7 Å)	H line (rest: 3968.5 Å)	distance Mpc	avg. vel. (km/s)

The Hubble constant, from polyfit, has a value of: _____
(Don't forget the units!)

The Hubble constant, from a = avgv/distmpc, has a value of: _____
(Don't forget the units!)

The age of the universe, assuming a constant H_0 (from the polyfit parameters), is: (**Show or explain how you get your answer in the space below, or as a calculation in MATLAB! And don't forget the units!**)

The age of the universe, assuming a constant H_0 (from the matrix math solution), is: (**Show or explain how you get your answer in the space below, or as a calculation in MATLAB! And don't forget the units!**)