Astronomy 101U Homework #4 – Is the Universe Really Expanding?

(Original conception by Bruce Balick. Modified by Doug Ingram with help from Woody Sullivan. Modified again and updated by Doug Ingram It is originally modelled on a lab using the Voyager software for the Mac. In that version, the students took the data themselves using the program to guide them.)

I. Introduction

Is the tranquil universe that you observe at night really a universe at rest? You have heard (or will hear) that it is not; other people and the text claim that it is expanding. Any rational, observant person should be puzzled by this assertion. After all, you have no direct sensory evidence of your own to support such an outlandish notion.

The goal of this exercise is to make you challenge any claim about the overall state of motion of the universe. Let us pose the hypothesis "The universe expands," and ask you, on the basis of data you will collect, to be very skeptical of its validity. To what extent can you find the weak points underlying this assertion? Can you synthesize an equally tenable but quite different hypothesis or model consistent with the same set of data? Incidentally, Hubble and others first uncovered a pattern of apparent expansion in the 1920's. Hubble's "law" of expansion was originally just his interpretation of a pattern of data; later work with far more data has continued to give us confidence in Hubble's Law.

II. Before Your Begin

There are some concepts that you must master before tackling this exercise. You might need to review some of the relevant material. The items below are important for this assignment and for the course as a whole, so be sure you understand them!

1. Luminosity (L): A measure of the total power, or amount of luminous energy (light) emitted per second by an object. For example, common light bulbs produce 100 watts of power. Compare luminosity to apparent brightness (B), which is a measure of the amount of light an observer receives per second per unit area at some distance from an object.

2. Inverse Square Law: The apparent brightness (B) of an object of luminosity (L) changes as the inverse square of the distance to the object (r): B is proportional to L/r^2.

3. Magnitude (m): The magnitude of an object is a way of describing the apparent brightness of an object. (It's a lousy way, but astronomers can't break the habit.) A star is five magnitudes brighter than another if that star is 100 times brighter than the other. Bright stars are of 1st or 2nd magnitude. At a dark site, the eye can detect stars as faint as 6th magnitude. A small telescope can reach 10th magnitude. A large telescope with a very sensitive detector and ideal observing conditions can reach 28th magnitude.

4. Standard Candle: Objects of nearly the same luminosity (such as auto headlights) are "standard candles." You can gauge the distance of a standard candle by its apparent brightness (i.e., magnitude). That is, headlights that appear faint are inferred to be far away. **For standard candles, the apparent magnitude of an object is a measure of its distance. Be sure that you understand why!**

5. Doppler shift: The spectrum of light from a moving object appears to undergo a wavelength (or frequency, or photon energy) shift. Receding objects have spectra shifted to longer wavelengths (lower photon energies), and approaching objects have spectra shifted to shorter wavelengths. The amount of shift in the spectrum as measured by an observer is related to the velocity of the emitter. By convention, the velocity is positive (negative) when the emitting object is receding (approaching). Velocities of galaxies in your data table have been measured from the observed shifts of spectral lines.

III. What to Do With the Table

On the back of the last page of this exercise, you'll find a large table of data for 100 galaxies. This data is collected from a general sky survey that had a limiting magnitude for object detection of around 16. Anything fainter than 16th magnitude just wasn't bright enough to be picked up, and many objects close to 16th magnitude were probably "lost in the noise" since they are so faint.

You'll be extracting velocity, magnitude and positional information from the large data table for a random set of galaxies that you choose. Select 20 galaxies at random and copy down the data for these galaxies into a table of your own (keep this table on a separate page). Using the small table at the end of this write-up, convert the magnitude to a distance and add this information as an extra column to your table. If you have a fractional magnitude (e.g. 14.7) then interpolate as best you can to get the estimated distance. Keep in mind any errors that may be involved in your estimation for later.

Bear in mind that you're looking for some sort of trend of galaxy velocity with distance as far out as you can see. Once you're done with your table, plot velocity vs distance for your 20 galaxies. This is a Hubble diagram. Put velocity on the y-axis and extend the y-axis from 0 to 10,000 km/sec. Put distance on the x-axis and extend the x-axis from 0 to 500 million light years.

Below your graph, answer the following questions:

(1) Is there a trend in your graph that shows galaxy velocity increasing or decreasing with distance? Be honest!

(2) Draw your best fit straight line (try to get the line to match the slope of the points as best you can) through your 20 data points and measure the slope. Recall that slope can be found by calculating rise over run, so to get the slope, just use the starting and ending point of your line. Figure out what the change in y is for the line and divide that by the change in x. That's the slope, and that is Hubble's constant (more on Hubble's constant, H, later). If you took out the three points furthest to the top left, would this change the slope by much? What about the three points furthest to the bottom right?

Add another 20 galaxies to your own data table, paying careful attention to the Magnitudes. Try to arrange your data taking so that you get roughly an equal number of galaxies in each magnitude interval. In the end, you'll want at least 5 in each interval, so after you've collected data for 40 galaxies, if you have fewer than five in an interval, add more galaxies to the table until each interval has at least 5.

Now draw a new Hubble diagram with your 40 selected galaxies, and then answer the following questions:

(3) Draw your best fit straight line through the 40 data points and measure the slope. Does this differ significantly from the slope you measured in question (5)? If so, why? If not, why not?

(4) Again, take out the three furthest points to the top left and then to the bottom right. Will this change the slope much in either case? Explain whether (and why) it is good or bad to have the slope of your graph depend so much on these points at either end of your distribution.

(5) In your final graph, we took care to arrange things so that you would get an equal number of galaxies in each magnitude interval. It might have crossed your mind that we are manipulating the results of this exercise by giving you "artificial" instructions so that you get the results we want and prove our standard models correct. Are we introducing an unfair bias into your analysis by giving you these instruc- tions? Explain (don't skip this one, it's important!).

(6) Using your velocity vs. distance graph from (3) above, you have drawn your best fit line through the points. Write this slope down as part (a). Next, draw another line which represents to you the lowest possible slope of line that is still plausible in light of the data you have (the best way to do this is to take out the 3-5 highest points and then treat the data set as you would normally). Write down this slope as part (b). Finally, draw a line which represents that highest possible slope for the line to still represent the data and write down this slope as part (c).

(7) What you've just measured is the Hubble constant, H! It's a measure of how long the Universe has been expanding. Thus, as we have seen (or will see) in lecture, H is just a measure of how old the Universe is. Convert your three values for H into ages for the Universe (in years). You will need some familiarity with scientific notation as well as the following numbers:

1 million light years = 9.46 x 10^{18} km 1 billion years = 3.16 x 10^{16} sec

Converting your slope (in units of km/sec over Million light years) is a simple process, provided we take it one step at a time. First, substitude the number of kilometers in a million light years for the Million light years unit in the denominator. Now, assuming you got a slope of 20 from your graph, you should have something like this:

$$\mathrm{H} = \frac{20 \text{ km/sec}}{9.46x10^{18} \text{ km}}.$$

At this point, the kilometer units cancel out, so you're left with some number in units of (1/sec). Now invert your value for H to get an age for the Universe, like this:

$$\text{Age} = \frac{9.46x10^{18} \text{ sec}}{20}$$

Now you want to convert your answer into billions of years, so just divide by the number of seconds in a billion years, and you've got an age for the Universe in the units we want!

(8) You will probably notice that your values for the age of the Universe have a large potential for error. Take a look at your upper and lower values for the age and compare them to what is typically quoted (12-18 billion years) in textbooks. List all possible sources of error in this homework assignment that you can think of (at least 4, but the more the better) that could explain the difference between the accuracy of our measurement and the accuracy one normally sees quoted.

(9) Why do you suppose the 11th-12th magnitude galaxies are more numerous than the (fainter) 13th-14th magnitude galaxies in the large data table even though galaxies grow more numerous as they grow fainter (further away)?

(10) If brightest galaxies are the easiest ones to find (hence, they wouldn't be missed in data collection for our table), why are there so few (brighter) 8th-9th magnitude galaxies relative to 11th-12th magnitude galaxies in the table?

(11) Your final graph should show with some confidence that the Universe is expanding based on the pattern of motion you were able to measure. What do you suppose the graph would have looked like if the Universe were contracting instead of expanding? Draw a graph as part of your answer.

(12) What if the Universe had no large-scale motion? Again, draw a graph as part of your answer.

Appendix: Converting Magnitudes to Distances

If you assume that galaxies are standard candles then you can convert magnitudes into distances. If your galaxy has a magnitude between two of the numbers on this table, estimate the distance to the galaxy by using interpolation (its ok to be off by +/- 5 Mly on such large scales in this experiment since there are other, much larger errors involved).

Magnitude	8	9	10	11	12	13	14	15
Distance in Mly	21	33	52	82	130	210	330	520

We use distances measured in millions of light years (Mly). Textbooks occasionally use Mpc (or million parsecs); 1 Mpc = 3.26 Mly if you ever want to convert units.

Data on 100 Galaxies

Galaxy name	Radial velocity (km/sec)	Magnitude	Galaxy name	Radial velocity (km/sec)	Magnitude
NGC 4047	3426	13.1	NGC 5452	2272	13.3
NGC 3938	838	10.9	NGC 5144	3187	13.2
NGC 5055	587	9.3	M 51	565	9.0
NGC 2880	1620	12.5	NGC 5308	2132	12.2
NGC 3512	1352	13.0	NGC 5473	2156	12.3
NGC 4395	307	10.7	UGC 8658	2155	13.3
NGC 2903	467	9.5	M 60	1128	9.8
UGC 3973	6650	13.5	NGC 5256	8371	14.1
UGC 3691	2102	13.2	NGC 5660	2483	12.3
NGC 1270	5048	14.0	NGC 5633	2451	12.9
NGC 7457	790	11.7	NGC 5772	5033	13.9
NGC 428	1266	11.9	NGC 5529	2971	12.6
NGC 622	5483	14.1	NGC 5544	3292	13.2
NGC 584	1868	11.3	NGC 5380	3037	12.8
NGC 5236	337	8.2	NGC 5383	2354	12.1
NGC 1042	1360	11.5	NGC 5297	2507	12.2
NGC 720	1820	11.1	NGC 5377	1950	12.0
NGC 1199	2528	12.5	NGC 4736	329	8.9

Galaxy name	Radial velocity (km/sec)	Magnitude	Galaxy name	Radial velocity (km/sec)	Magnitude
NGC 1179	1716	11.8	NGC 5033	961	10.6
NGC 1350	1649	11.4	NGC 4357	4332	13.5
NGC 7626	3638	12.2	NGC 3982	1208	11.7
NGC 7785	4019	12.6	NGC 3780	2865	11.8
NGC 169	4682	13.3	NGC 3945	1340	11.5
UGC 1551	2817	13.3	NGC 3725	3303	13.6
NGC 7332	1451	11.9	UGC 6162	2268	13.7
NGC 7742	1818	12.3	NGC 3415	3279	12.8
NGC 1449	4131	14.4	NGC 5128	323	8.0
NGC 1395	1583	11.3	NGC 2445	3936	13.6
NGC 3115	476	10.1	NGC 3694	2250	13.5
NGC 3078	2231	12.1	NGC 3801	3174	13.0
NGC 2924	4362	13.3	NGC 2403	259	8.9
NGC 2855	1660	12.4	IC 529	2417	12.7
NGC 5128	323	8.0	UGC 5707	2816	13.7
NGC 3885	1706	12.8	NGC 2693	5006	12.7
NGC 4936	3065	12.4	NGC 2776	2643	12.2
NGC 5328	4610	12.6	NGC 253	259	8.0
NGC 5017	2384	13.1	NGC 2782	2529	12.1
NGC 4786	4509	12.8	NGC 2719	3185	13.7
NGC 4636	869	10.5	NGC 2415	3779	12.8
NGC 5812	2028	12.2	NGC 2424	3307	13.6
NGC 5921	1503	11.5	UGC 3730	2868	14.2
NGC 4486	1180	9.6	NGC 5457	388	8.2
NGC 6758	3237	12.6	UGC 3975	2639	13.9
NGC 7144	2062	11.6	IC 2656	2743	14.0
NGC 5820	3443	12.9	NGC 2655	1623	10.9
NGC 5866	874	10.9	NGC 2276	2579	11.9
NGC 6703	2590	12.5	NGC 2268	2466	12.2
NGC 6824	3675	12.7	NGC 6217	1586	11.9
NGC 6643	1736	11.8	NGC 6643	1736	11.8
NGC 6217	1586	11.9	NGC 4472	817	9.3