PHYS 15 - Introduction to Cosmology
Fall 2021
Prof. Jeremy Tinker
Class Project

DUE DATE: December 15, 2021

In this project, you will construct your own distance ladder using parallax, variable stars, and supernovae to determine how the universe has expanded over the past 8 billion years. Your goal: Determine if your universe is experiencing decelerated expansion, accelerated expansion, or is behaving as though it were an empty universe (even though we know that can't be true that the universe is empty).

NOTE: Every student gets their own dataset. Every student has a different universe. All three possibilities above are valid answers. You can download your person dataset from the following URL: https://cosmo.nyu.edu/~tinker/COSMO_2019_PROJECT_TARBALLS/

Notation for this project:

θ = parallax angle [arcsec]
d = distance to stars or galaxies [units will be pc for stars and Mpc for galaxies]
DM = distance modulus [units of magnitudes]
m = apparent magnitude
M = absolute magnitude
P = period [days]
z = redshift

Step 1: Calibrate the Period-Magnitude relation for variable stars.

You have been given 10 variable stars that are close enough such that they can have good parallax measurements. You need to first determine how far away these stars are, and then determine what the period is for each star as well as its mean apparent magnitude. These are found in the figures "paralla_N.pdf". The key in each figure, shown the lower left of the panel, is that the separation between each dot is 10 milliarcsecs. The black stars are background objects, far away. The close star is shown at it's positions in June and January (red and blue).

To convert parallax angle to distance, use the equation:

$$d\,[\mathrm{pc}] = \frac{1}{\theta\,[\mathrm{arcsec}]}$$

You have 10 stars, listed "Star 0" to "Star 9", files "parallax_N.pdf". Measure the distance for all 10. Then go to the files listed "p_variable_N.pdf" and measure the period and the mean apparent magnitude of each. These data have "noise" in them— i.e., no measurements are perfect. There are gaps in time, and there are errors in the magnitudes. To be helpful, I have given you the true underlying light curve of the variable start in "Star 0".

NOTE: the angle "theta" here is HALF the <u>total</u> angle between the two positions of the star.

For each star, you need to determine the "distance modulus". This is the difference between the apparent magnitude (what we see in the sky) and the absolute magnitude (what we would see if the star were at 10 pc). In other words,

$$m - M = DM$$

To convert the distance you have measured for each star to a distance modulus, use the following equation:

$$DM = 5\log(d/10)$$

It is important to remember that distance *d* in this equation is <u>always in parsecs</u>. Use the value of DM to convert m to M and make a plot showing <u>log</u> Period P vs absolute magnitude M for the 10 variable stars.

Once you have that plot, draw a straight line through the points that you think best described the data. This is your calibration of the P-M relation for variable stars, and you will use it in the next step to calibrate the supernovae as standard candles.

Step 2: Calibrating SN.

In reality, not all SN are the same. They vary in luminosity and timescale. In this project, we will assume that all SN are identical. Thus, all you have to do it determine what the intrinsic luminosity (the absolute magnitude) of ALL SN are by averaging the results you get for 10 calibration SN that went off in galaxies close enough such that the distances to the galaxies could be obtained from variable stars.

First, look at the files 'SN_variable_N.pdf. ' They show the light curves for the variable stars within the same galaxies as the SN. These results will be noisier than before, because these stars are <u>much</u> further away. Once again measure the period and the average apparent magnitude for each variable star. From this, you will get the absolute magnitude from Step 1— use your best fit line relating logP vs M, and your new measurements of logP to infer the new M. Then determine the distance modulus for each star (and thus the galaxy that star lives in).

Next, look at the light curves for each Supernova in the files 'calibration_SN_N.pdf'. You will measure the peak value— the brightest it is. <u>Note that I have made the y-axis get smaller (brighter) as you go upward.</u> Once you measure the peak apparent magnitude, convert that to a peak absolute magnitude using the DM values from the variable stars. You will then have 10 measurements of the intrinsic luminosity of SN. Average those values together. They will not all be the same, due to errors in the measurements.

Step 3: Creating your Distance-Redshift relation.

Now comes to final step. There are 20 SN lightcurves in the files “faint_SN_N.pdf”. They are faint because they are very far away. The errors on these measurements are will be larger than before. In each figure, the redshift z of the supernova is also listed.

From the light curve, you will determine the peak apparent magnitude, and calculate the DM from the now-known peak absolute magnitude of all SN from the previous step. You have been given a blank plot with redshift z on x-axis and distance, on log (d/Mpc) on the y-axis. Note that the y-axis is logarithmic and assume distance is in Mpc. This file is called “hubble_diagram.pdf”.

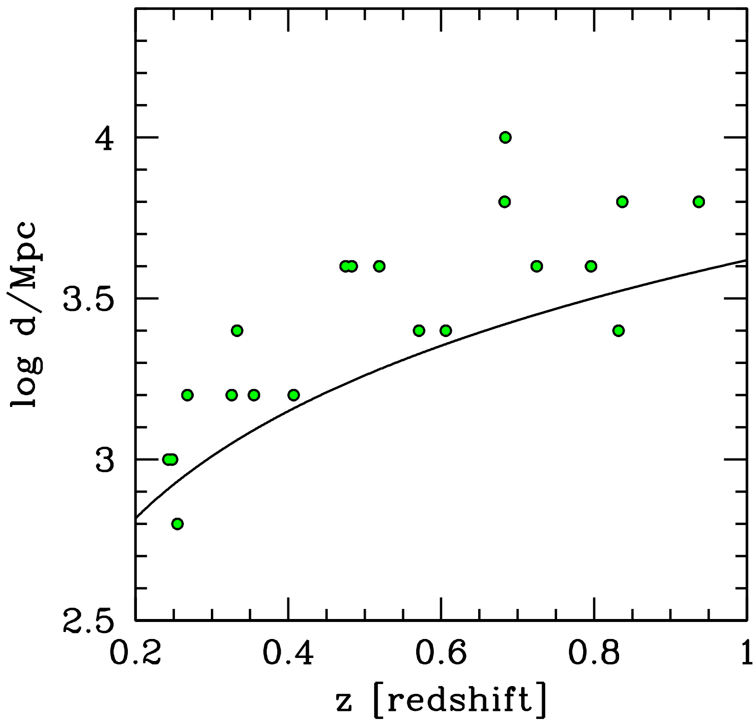
The solid black curve is what the distance-redshift relation should look like for a “coasting universe” (empty universe). Above this line is a universe that is experiencing accelerated expansion. Below this line is a universe that is experiencing decelerated expansion. Where do your data lie? What is the likeliest source of error in your process (outside of the errors on the magnitudes— I mean error in the things that you physically did to make this plot).

What you will hand in:

0) Your tarball project number “project_NNN.tar” (the number in place of NNN)
1) The P-M relationship for variable stars.
2) Your calibration of the SN peak luminosity. (In a table of numbers)
3) Your Hubble Diagram plot.
4) A short answer section explaining your interpretation of the data— ie, “Which Universe do you live in?” and “What is the most likely source of error?” This should be 1-2 paragraphs in length.

For each of these items, <u>you need to have a written description</u> of what you have done to make it clear what each item is. It does not have to be long, but enough to clearly follow your process throughout your report.

Attached below is a version of the final plot. This observer lives in an accelerating universe, but you can see that the result is very noisy.


log d/Mpc
z [redshift]
2.5
3
3.5
4
0.2
0.4
0.6
0.8
1