Lab-2: Measuring the Hubble Diagram using Standard Rulers

1 Introduction

In 1929, Edwin Hubble measured that distant galaxies were systematically redshifted relative to galaxies that were closer (see Figure 1). From this data, Hubble inferred that the universe was expanding, an idea initially worked out by Georges Lemaitre using EinsteinÕs theory of gravity. In this lab, you will conduct a measurement similar to Hubble's and will produce your own version of his famous Hubble diagram shown below.

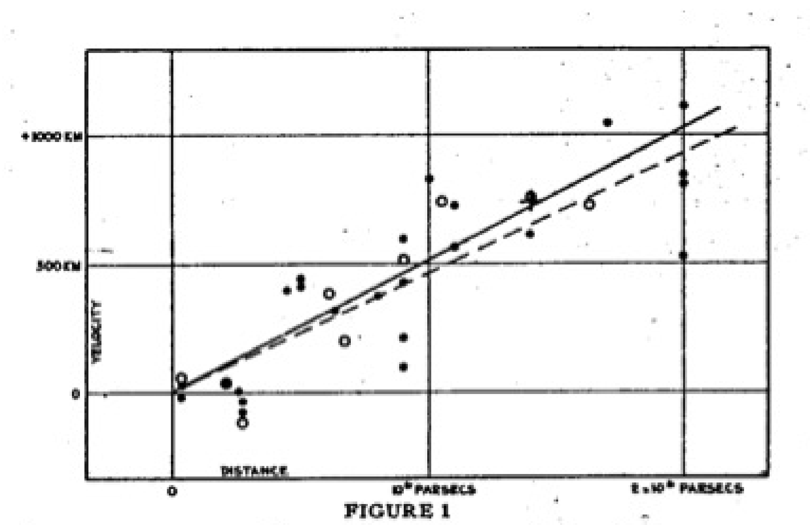

Figure 1: Velocity-Distance Relation among Extra-Galactic Nebulae (Hubble et al. 1929).

2 Method

In Figure 2, we illustrate the impact of an expanding universe of photons emitted from distant objects. Because the speed of light is constant, photons that we measure today were emitted in the past, with photons originating from objects that are further away being emitted earlier in time. This means that photons from objects that are further away are older, and thus, those photons have experienced more expansion by the universe. This plot below illustrates the relationship between the expansion experienced by a photon and the distance of its emitter.

From this relationship, we can determine whether the universe is expanding, contracting, or static by looking at a number of galaxies and measuring their distance (corresponding to the x-axis) and the expansion experienced by their photons (corresponding to the y-axis).

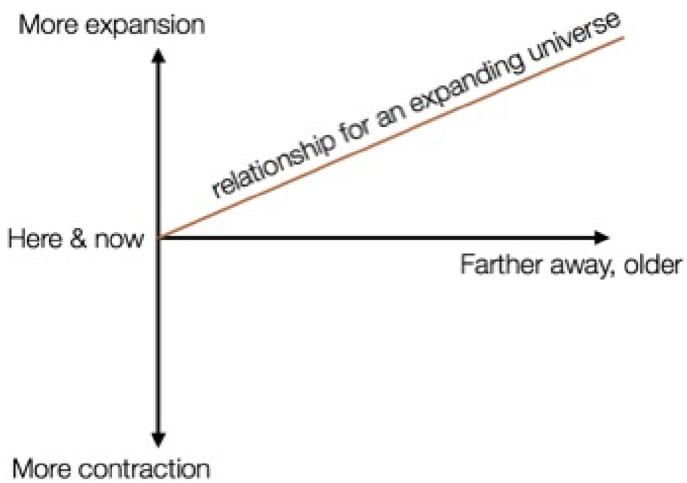

Figure 2:

2.1 Measuring Distances

We will use geometry to measure the distance of our galaxies, by assuming that they can be used as *standard rulers*, objects with the same physical size. Galaxies that are closer will look bigger and subtend a larger angle. Whereas galaxies that are further away will look smaller and subtend a smaller angle. This relationship between the angular size of the galaxy and its distance is illustrated in Figure 3.

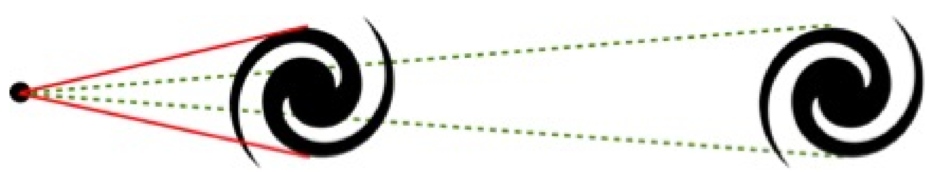

Figure 3:

Typical galaxies are about 22 kpc across. Using the geometry shown in the Figure 3, we can arrive at the following relationship:

$$Angular\ Size = \frac{22\,\mathrm{kpc}}{Distance} \tag{1}$$

So, by measuring the angular size of our galaxy images, we can use the above equation to determine the distance to the galaxy.

3 Data and Observations

3.1 Stone Edge Observatory

The Stone Edge observatory (SEO) is a 24 inch reflecting telescope, located in Sonoma, California. Stone Edge has a charge coupled device (CCD) camera and is equipped with a full set of filters, including the same *ugriz* bands as used by the Sloan Digital Sky Survey (SDSS) (see Figure 4).

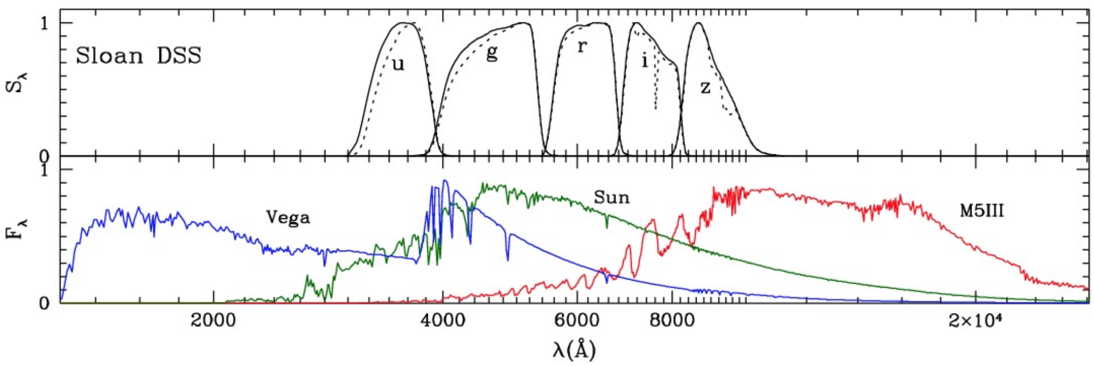

Figure 4: Filter transmission functions for SDSS, plotted above spectra for three different stars of different surface temperatures: Vega (A-type, ∼10,000 K), our Sun (G-type, ∼6,000 K), and an M5III star (M-type, < 3500 K). Its clear from this image that these three objects will look much different in our image depending on what filter bands we use. Image source: http://www.aanda.org/articles/aa/full/2004/28/aa0250-04/img19.gif

3.2 Observations

For this lab, we will use a combination of real-time and remote queue observing. From Table 3.2, randomly select at least **five galaxies** to be observed. For each galaxy, you will likely have to look up information like: Right Ascension (RA), Declination (Dec), and redshift (z), and make sure that it is observable by SEO during the next couple of weeks. Feel free to add additional galaxies, but be mindful of its night time visibility from SEO, and also its magnitude and distance. In practice, to have reasonably modest observations, in terms of exposure time and angular extent, I would guess that a reasonable magnitude (M) and redshift range to be something like $15 < M < 6$ and $0.003 < z < 0.15$, respectively.

Galaxy Name	z	R.A. (J2000)	Decl. (J2000)	Notes
NGC 1357	0.006651	03:33:17.05	-13:39:50.97	
NGC 1395				
NGC 1832				
NGC 2403				
NGC 2775				
NGC 2903				
NGC 3034				
NGC 3147				
NGC 3227				
NGC 3368				
NGC 3516				
NGC 3627				
NGC 3941				
NGC 4486	0.00420	12:30:49.42	12:23:28.04	
NGC 4631				
NGC 4775				
NGC 5248				
NGC 5548				
NGC 6181				
NGC 6217				
NGC 6643				
NGC 6764				
NGC 7469				

Table 1: A list of potential galaxies that should be reasonable to observe for this lab, with space given for the redshift, Rght Ascension (R.A.), and Declination (Decl.) for each object.

Figure 5: Two galaxies that you might observe for this lab. (Left) NGC 1357 is an isolated spiral galaxy situated in the constellation of Eridanus. Optical image taken with the 32-inch Schulman Telescope, image source: http://www.caelumobservatory.com/gallery/n1357.shtml. (Right) NGC 4486, also known as M87, is a nearby elliptical galaxy in the constellation Virgo. It is known for having a large population (∼10,000) of globular clusters, about 100 times more than the Milky Way galaxy, and made even more famous through observations of its supermassive black hole by the Event Horizon Telescope (EHT). For scale, the above image is 97 arcminutes across. Image source: http://www.eso.org/public/images/eso1525a/

3.3 Instructions for Scheduling Observations

Your lab group will want to have the ability to do both real-time observations, and queue observations.

For scheduling queue observations:

1. Queue observations are scheduled through this link [1]
2. If you didnt do this for the last lab, have one person from your lab group email Amanda Pagul (apagul@uchicago.edu), and have her create an account for you lab group.
3. Submit object observations in the queue. Note, that you will have to choose reasonable observing / exposure times for your object. So it would be a good idea to do

[1] https://queue.stoneedgeobservatory.com

some basic calculations for what would be appropriate given the magnitude of your object, compared to other objects you've looked at.

For scheduling real-time observing time for SEO:

1. **Queue observations are scheduled through this link** [2]
2. **Have one person from your lab group email Amanda Pagul (apagul@uchicago.edu), and have her create an account for you lab group.**
3. **Make sure to check out the SEO calendar** [3]**. Pick a date and time that would be convenient for your group to observe your targets and reserve time on the calendar.**

4 Data Analysis

4.1 Making RGB Images

In this section, you will make red-green-blue (RGB) color images of each galaxy that you observed last week. Download your data from stars.uchicago.edu[4]. To make a RGB image, we are going to make a composite image from your *gri* filter measurements. Using these filters, i is your reddest color and g is your bluest color. To make an RGB image, you can use whatever software you prefer, but either ds9[5] or python[6] are good options, with tutorials linked to the footnotes.

When you take your images, you should assess how they look, i.e., do you clearly see each galaxy? If you are disappointed they could have been affected by bad weather, and might also be improved with longer exposures. Feel free to take additional observations, either repeating the same observations (i.e., hoping for better weather, or to coadd more observations for better signal-to-noise), or increase your exposure time. Last week, if you took 30-sec exposures and it looks too faint, maybe try 120-sec or 240-sec exposures this time. If you really need new data now, feel free to download data from a different directory in the archive starting from the list of galaxies in Table 3.2 or an appropriate substitute.

[2] https://queue.stoneedgeobservatory.com
[3] https://github.com/bradfordbenson/ASTR21200_2023/wiki/Stone-Edge-Observatory
[4] See instructions at: https://github.com/bradfordbenson/ASTR21200_2023/wiki/Stone-Edge-Observatory
[5] https://astrobites.org/2011/03/09/how-to-use-sao-ds9-to-examine-astronomical-images/
[6] https://docs.astropy.org/en/stable/visualization/rgb.html

4.2 Measuring the Angular Size of Galaxies

In this section, we will measure each galaxy's angular size. You can use whatever program you want, but this should be possible in ds9 or python. It shouldn't matter significantly which filter band you use, but you might want to check and comment on any differences.

For your lab report, you will want to include the following information:

1. Which galaxies did you observe? You will want to include a Table with key properties of your galaxies, e.g., R.A., Decl., redshift, and measured angular size.
2. From your observations, can you tell what kind of galaxy is it (e.g., spiral, elliptical, unclear)?
3. What is the angular size of your galaxy? How did you define the angular extent of the galaxies? Did you use a uniform threshold across your images? What was it?
4. What systematics could affect your measurement? Are there any differences between the *gri* images? What are sources of potential systematic uncertainty in the way you did your measurement?

4.3 Measuring the Expansion Rate of the Universe, or the Hubble Constant

The wavelength of light changes as the universe expands, an effect known as cosmological redshift. If the universe expands, the wavelength is stretched, becoming longer and redder. For a contracting universe, the wavelength will be compressed becoming bluer. We define the redshift, z, as:

$$z = \frac{(measured\,wavelength - original\,wavelength)}{original\,wavelength} \tag{2}$$

The redshift is a measure of how much the wavelength of the light has been stretched or compressed. Typically redshift is measured using spectroscopy, where the location of well-known emission and absorption lines of particular atoms or molecules are measured, then compared to their known laboratory-measured values, and then giving a measurement of the effectively recessional velocity of your galaxy, or redshift. Using Simbad or NED, find the redshift for each galaxy that you observed.

For your lab report, you will want to include the following information:

1. Using your measurements, make a plot of distance versus redshift for your galaxies, and include it in your lab report.

2. Compare your plot with the sketches on page 1. Does your data indicate that the universe is expanding? Contracting? Static? Why?

3. By using the relationship between redshift and velocity as $v = c\,z$, where c is the speed of light, make a plot of distance versus velocity and fit a line. The *Hubble* constant is the slope of the line and measured in units of (km / sec / Mpc). What do you get for your measurement of the *Hubble* constant? How does it compare to the accepted value of 70 (km / sec / Mpc)?

4. Discuss differences between the statistical and systematic uncertainties that effect this measurement. For example, if we measured 100 more galaxies this way, the statistical uncertainty should decrease like $\sqrt{N_{galaxies}}$, so could we get an arbitrarily tight constraint on the Hubble constant this way? If not, what systematics limit this measurement? And how do the systematics described in Section 4.2, affect your measurement here?

5 Lab Report

Prepare a *jupyter* notebook that documents your entire analysis for the lab. Make sure to explain your steps and conclusions; imagine writing a tutorial for another astronomy student, who is not taking the class. Use *markdown* boxes (which can also parse LaTeX). Note that you can also include figures (i.e., in png, jpg, etc. form) that are produced outside of the notebook (e.g. with ds9).

The explanations in the *jupyter* notebook will be what we read, but we might look at your code if we think you did something wrong. Make sure that the report is logical; each section should have a short introduction, then code with results and plots, then a conclusion. Make sure the section numbering follows this manual (e.g., Introduction, Data, Data Analysis, Conclusions). Once your notebook is finished, make sure to restart it and re-run all cells. Then save the notebook in pdf format, e.g., through the print menu.

A Using ds9 to measure angular extent

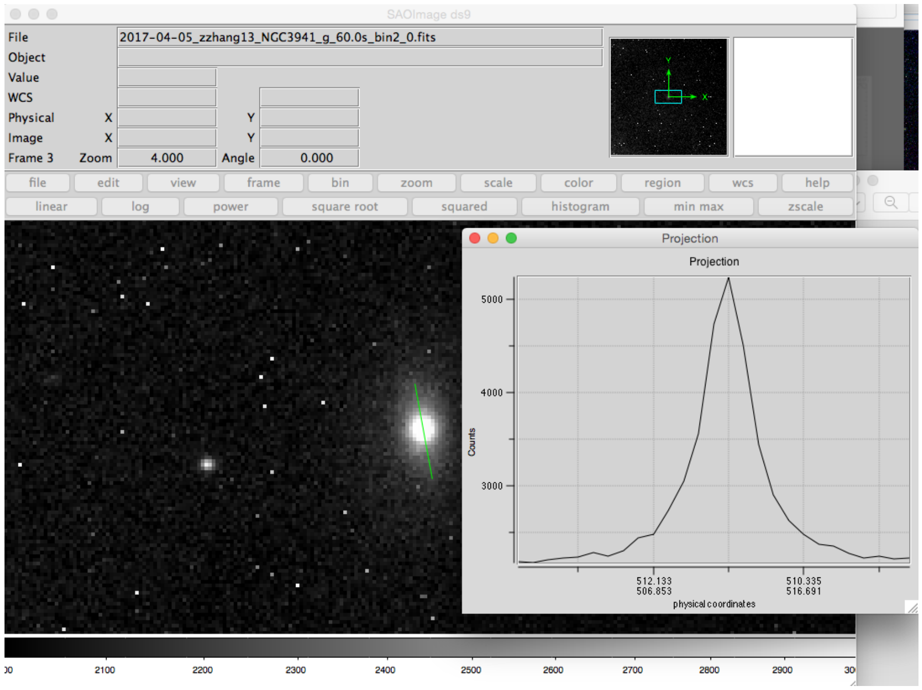

Figure 6: Using ds9 to measure the angular size of a galaxy. In this image, the green line shows the approximate extent of the galaxy, and the projection plot shows the photon counts measured in this cut through the galaxy.

Under the *Scale* tab, click on *Log*. Also under the *Scale* tab, go to *Scale Parameters* which will open a plot of the *Pixel Distribution*, a histogram of the number of counts per pixel in your image. Feel free to play around, but I would recommend choosing *Low* and *High* values above the minimum and significantly below the maximum. For my images, *Low* and *High* values of ∼2000 and 3000, respectively, worked well. For this step, you might want to *zoom* into your galaxy to better see how the values affect how your galaxy looks.

Next, *zoom* in on your galaxy to measure its angular extent. From the *Region* tab, click on *Region > Shape > Projection*. Click and drag your cursor across the source (see Figure 6). A new window will open displaying the brightness profile of the image along the line you drew. Measure how many pixels across your galaxy is using the end-points of the line that you drew. The Stone Edge Observatory pixel scale is 1.52 arc seconds per pixel if you used a setting of bin=2. Convert your measurement to arc seconds.

For more information about using ds9, you can use this helpful tutorial:

https://astrobites.org/2011/03/09/how-to-use-sao-ds9-to-examine-astronomical-images/