The Hubble Project: A Lab Project

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October 2025

1 Introduction

When we think of the universe, it is easy to imagine it as a vast and unchanging space filled with distant galaxies. Yet, the idea that the universe is constantly expanding challenges this view and shows that the cosmos itself is dynamic. This experiment explores that expansion through Hubble's Law, which connects how fast a galaxy is moving away from us to how far away it is. By studying the light from galaxies and measuring how its wavelength stretches, we can uncover the relationship between distance and velocity that defines the universe's growth.

In this lab, we created a Hubble diagram using data from six galaxies at one point in the sky to understand how their redshifts relate to their distances. Each redshift value shows how the galaxy's emitted light has shifted toward longer wavelengths as space expands, while the distance was determined using Hubble's constant, which represents the rate of this expansion. Once we formed a linear fit from our data, the slope revealed an experimental value of the Hubble constant that could then be used to estimate the age of the universe.

We think of this experiment as a way to connect our understanding of cosmic motion with the same spirit of discovery seen in our earlier labs. Just as the Spherical Harmonics Lab explored mathematical patterns that describe energy distributions and wave behavior, this lab shows a universal pattern that describes the expansion of everything we know. Through these calculations, we begin to see how physics links the smallest observations of light to the largest scales of space and time, giving us a glimpse into how the universe has evolved since its beginning.

2 Setting up the Formation of Hubble Diagram

To find the age of the universe, a Hubble diagram is needed to have an idea of the current distances that each galaxy has. Therefore, to properly form the Hubble diagram, six different galaxies will be sampled, where only the u component for their magnitudes will be looked at:

Galaxy	RA	Declination	Magnitude
301 (587722984423686301)	178.261	1.041	22.37
445 (587722984423686445)	178.270	1.028	26.18
298 (587722984423686298)	178.247	1.022	23.18
395 (587722984423686395)	178.250	1.020	21.66
312 (587722984423686312)	178.298	1.014	21.61
688 (587722984423620688)	178.182	0.975	18.24

Table 1: Galaxies (represented with their last three digits) with their right ascension (RA), declination, and magnitude)

3 Calculating The Redshifts of Galaxies

To find the redshifts that each of the six galaxies posses, the following formula will be used:

$$1 + z = \frac{\lambda_{observed}}{\lambda_{rest}} \tag{1}$$

Therefore, this equation can be rewritten to look for the redshift, z:

$$z = \frac{\lambda_{observed}}{\lambda_{rest}} - 1 \tag{2}$$

Where $\lambda_{observed}$ represents a wavelength that comes from each galaxy, in this case only the galaxies γ wavelength will be represented to calculate the redshifts of each galaxy. Therefore, each galaxy's $\lambda_{observed}$ represents the peak of γ wavelength in a galaxy's frequency v. wavelength graph, while λ_{rest} is at a constant for γ at 4340.5 Å. When using those values for equation (2) results in the following estimated values for each galaxy's redshift:

Galaxy	$\lambda_{observed}$(Å)	Redshift
301	6091	0.403
445	6469	0.490
298	6074	0.399
395	6074	0.399
312	6074	0.399
688	4449.2	0.025

Table 2: $\lambda_{observed}$ is only looked at for the γ wavelength

By looking at the table defined above, there are three galaxy clusters to be defined by looking at a galaxy's redshift, with galaxies 298, 395, and 312 belonging to one cluster all with a red shift of 0.399, galaxy 301 belonging to a cluster with a redshift of 0.403, galaxy 445 belonging to a cluster with a redshift of 0.490, and galaxy 688 belonging to a cluster with a redshift of 0.025. Furthermore, when looking at the relationship between the magnitude and the redshift, they have a linear fit of 76% (comes by multiplying the value of R^2 by 100) in the graph below:

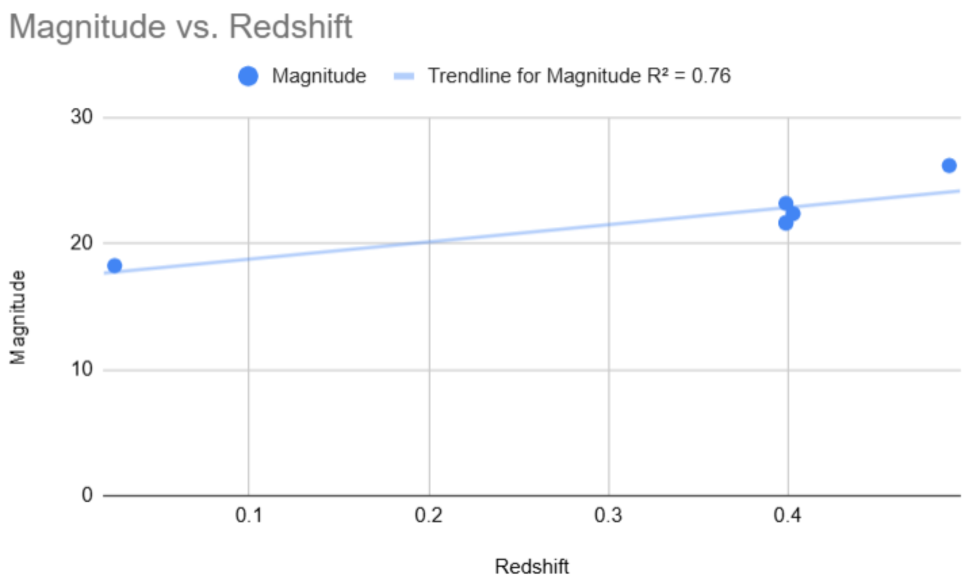

Figure 1: Magnitude vs. Redshift showing linear relationship.

4 Formulating Distances of Galaxies

One of the key factors to form a Hubble Diagram is to find each galaxy's distance along with it's relative distance. Therefore, to find the galaxy's distance Hubble's Law will be established:

$$v = H_0 d \tag{3}$$

Then, the relationship of $v = cz$ will be established since each galaxy has a redshift less than 1, and be subbed into Hubble's Law:

$$cz = H_0 d \tag{4}$$

From there, the distance for each galaxy can be found by rewriting equation (4) as the following:

$$d = \frac{cz}{H_0} \tag{5}$$

From here, each of the galaxy's redshift, z, will be plugged into equation (5), and Hubble's constant will be estimated: $H_0 \approx 70$ km/sMpc and speed of light will be estimated: $c \approx 3X10^5$ km/s. Therefore, plugging these values in equation (5) results in distance in Mpc since the km/s of c and H_0 cancel each other out resulting in:

Galaxy	Redshift	Distance (Mpc)
301	0.403	1727
445	0.490	2100
298	0.399	1710
395	0.399	1710
312	0.399	1710
688	0.025	107.1

Then, to find the relative distance of each galaxy the formula to find the radiant flux, F is used:

$$F = 2.51^{-m} \tag{6}$$

Where the $-m$ represents the magnitude of a galaxy. Afterwards, equation (6) can be rewritten by taking the square root of F and then taking the inverse of the square root, giving the following equation:

$$d_{Relative} = (\sqrt{F})^{-1} = (\sqrt{2.51^{-m}})^{-1} \tag{7}$$

From here, each galaxy's magnitude, m, will be plugged into equation (7) resulting in the galaxy's relative distances resulting in the following.

Galaxy	Magnitude	Relative Distance
301	22.37	29536
445	26.18	170502
298	23.18	42876
395	21.66	21304
312	21.61	20820
688	18.24	4416

To clarify how far the galaxies are apart from each other, the galaxies will become on a "normalized" scale by assuming that the galaxy with the smallest relative distance, 688, has a relative distance of 1. Therefore, taking all the relative distances and dividing them by 688's relative distance of 4416 results in the following:

Galaxy	Relative Distance	Normalized Relative Distance
301	29536	6.69
445	170502	38.61
298	42876	9.71
395	21304	4.82
312	20820	4.71
688	4416	1

5 Forming the Hubble Diagram

By having the galaxy's redshifts, the galaxy's velocity can be calculated by the following relationship (since the redshift is less than 1):

$$v = cz \tag{8}$$

And if $c \approx 3X10^5$ km/sec, then the galaxy's velocities can be calculated giving an idea on how fast they are moving away from the point of view of Earth:

Galaxy	Redshift	Velocity
301	0.403	120900
445	0.490	147000
298	0.399	119700
395	0.399	119700
312	0.399	119700
688	0.025	7500

Table 3: Velocity is in km/sec

Then, when graphing a Redshift vs. Distance graph (graph below), it shows a linear relationship between the redshift and distance: the greater the redshift, the greater the distance, and the lesser the redshift, the lesser the distance.

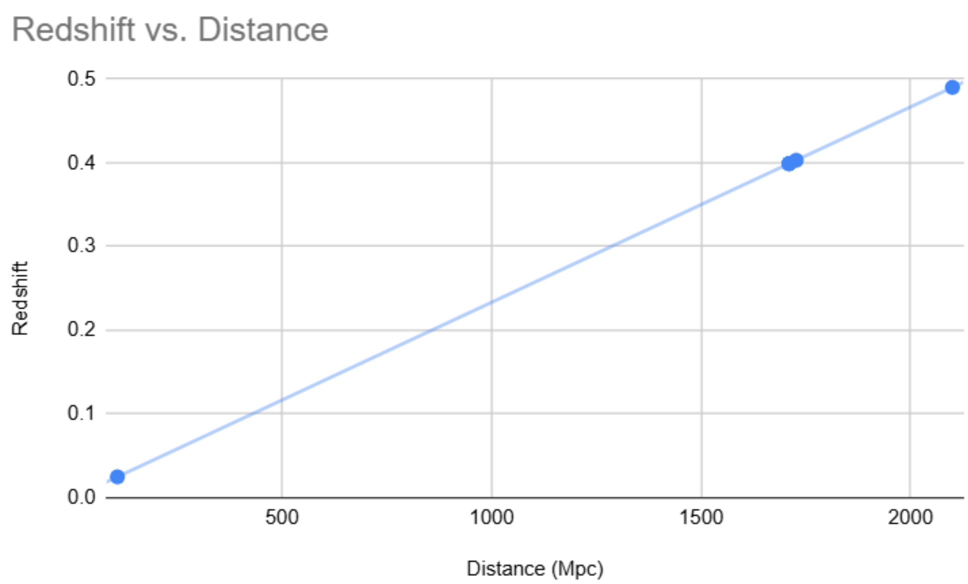

Figure 2: Redshift vs. Distance (Mpc) showing linear relationship.

From this graph the Hubble's constant, H_0, can be calculated by recalling the previously defined equation:

$$cz = H_0 d \tag{9}$$

Then, if the distance, d, is divided by both sides, then $\frac{z}{d}$ is the slope, m of this graph. Therefore, the equation can be rewritten as follows:

$$H_0 = cm \tag{10}$$

Then, to find the slope, the standard slope formula will be used:

$$\frac{z_2 - z_1}{d_2 - d_1} \tag{11}$$

Here, the first value is the galaxy 688's distance and redshift of $(d_1, z_1) = (107.1, .025)$ and the last value is the galaxy 445's distance and redshift of $(d_2, z_2) = (2100, 0.49)$. Using the standard slope formula results in a slope of $m = 2.33X10{-}4$ 1/Mpc. Then multiplying by the speed of light of $3X10^5$ km/s results in the Hubble's constant of $H_0 = 69.9$ km/sMpc.

Calculating the Age of the Universe

To get the age of the universe, recall Hubble's law:

$$v = H_0\, d, \tag{12}$$

where v is a galaxy's recessional velocity, d its distance, and H_0 the Hubble constant. From here, another equation will be defined to find t_0, which is referred to as the now time:

$$d = vt_0 \tag{13}$$

Then, if d is replaced with $\frac{v}{H_0}$ from equation (12) then the present age of the universe is approximated by the Hubble time,

$$t_0 \approx \frac{1}{H_0}. \tag{14}$$

Then, recalling that from the Redshift vs. Distance graph, a Hubble's constant of 69.9 km/sMpc was calculated, to get t_0 for equation (14) H_0 needs to be in units of s^{-1}. Therefore, by establishing the relationship of $1Mpc = 3.06X10^{19}$ km, H_0 can be converted to units of s^{-1}:

$$H_0 = \frac{69.9\text{kms}^{-1}}{3.06X10^{19}\text{km}} = 2.28X10^{-18}\text{s}^{-1} \tag{15}$$

From here, using equation (14), it will result in a time now, t_0 value of $4.39X10^{17}$ seconds. Then, establishing that $1yr = 3.156X10^7$ s will result in the age of the universe to be the following:

$$t_0 \approx 4.39X10^{17}\text{s} * \frac{1\text{yr}}{3.156X10^7\text{s}} \approx 1.39X10^{10}\text{yr} \tag{16}$$

Thus our Hubble-time estimate for the present age of the universe is $t_0 \approx 13.9$ billion years old. This agrees with a percent error of 0.72% of the determined age of the universe to be around 13.8 billion years old, noting that the $t_0 \approx 1/H_0$ relation assumes constant (coasting) expansion and neglects the effects of matter and dark energy on the expansion history.

6 Conclusion

When we think about the universe, it is difficult to imagine that everything we see is constantly moving apart. Through this lab, we were able to see that motion directly by forming a Hubble diagram and observing the linear relationship between a galaxy's redshift and its distance. This connection revealed that galaxies farther away from Earth are receding faster, confirming that the universe is expanding. From our calculated slope, we determined the Hubble constant and used it to estimate that the universe is approximately 13.9 billion years old, showing how much time has passed since its beginning.

This experiment gave us more than a number; it offered a way to visualize the story of the universe itself. Each point on the graph represents a galaxy moving through space, and together they form a pattern that explains how the cosmos has grown over billions of years. It was remarkable to see how a few simple measurements of light could be connected to such a grand concept.

In the end, this lab showed how observation and calculation can work together to reveal one of the most fundamental truths in physics: that the universe is not fixed, but expanding, carrying every galaxy, star, and planet along with it. What began as a study of redshifts and distances became a glimpse into the origin and evolution of everything we know.

References

[1] Ferreira, G. "Hubble Diagram Project." *Sloan Digital Sky Survey (SDSS) Science Portal.* `https://cas.sdss.org/dr5/en/proj/advanced/hubble/`

[2] Kiley, D. "General Relativity Lecture – Hubble Expansion." *Los Angeles City College, Physics 103 Lecture (Canvas and YouTube).* `https://youtube.com/watch?time_continue=1442&v=6HBTANw0jSk&embeds_referring_euri=https%3A%2F%2Filearn.laccd.edu%2Fcourses%2F323932%2Fpages%2Fgeneral-relativity-lectures%3Fmodule_item_id%3D22241864&source_ve_path=MjM4NTE`

[3] Sloan Digital Sky Survey (SDSS). "Galaxy 301 Object Explorer." *SDSS Science Portal.* `https://cas.sdss.org/dr5/en/tools/explore/obj.asp?id=587722984423686301`

[4] Sloan Digital Sky Survey (SDSS). "Galaxy 445 Object Explorer." *SDSS Science Portal.* `https://cas.sdss.org/dr5/en/tools/explore/obj.asp?id=587722984423686445`

[5] Sloan Digital Sky Survey (SDSS). "Galaxy 298 Object Explorer." *SDSS Science Portal.* `https://cas.sdss.org/dr5/en/tools/explore/obj.asp?id=587722984423686298`

[6] Sloan Digital Sky Survey (SDSS). "Galaxy 395 Object Explorer." *SDSS Science Portal.* `https://cas.sdss.org/dr5/en/tools/explore/obj.asp?id=587722984423686395`

[7] Sloan Digital Sky Survey (SDSS). "Galaxy 312 Object Explorer." *SDSS Science Portal.* `https://cas.sdss.org/dr5/en/tools/explore/obj.asp?id=587722984423686312`

[8] Sloan Digital Sky Survey (SDSS). "Galaxy 688 Object Explorer." *SDSS Science Portal.* `https://cas.sdss.org/dr5/en/tools/explore/obj.asp?id=587722984423620688`

7 Everything past this point is the old lab, it's redone on the top to reflect it more accurately on creating a hubble diagram

8 Setting up the Formation of Hubble Diagram

To find the age of the universe, we need to construct a Hubble diagram to have an idea about the current distances and redshifts that the galaxies currently have. Therefore, to properly form the Hubble Diagram, six different galaxies will be sampled where their redshifts and magnitudes will be looked:

Galaxy	Magnitude (u)	Redshift
786 (587731186738331786)	18.32	0.009
049 (588015509267153049)	17.74	0.06
477 (587722983367901477)	18.94	0.105
795 (587725575888961795)	19.74	0.152
099 (587725589849506099)	21.24	0.238
283 (587728948510720283)	21.98	0.314

Table 4: Galaxies with their magnitude and redshifts

Furthermore, in terms of the magnitudes each galaxy comes with six different magnitudes: u, g, r, i, and z, with this formation of the Hubble Diagram only looking at the magnitude of u for each galaxy. In addition, when looking at the relationship between the magnitude and the redshift, they have a linear fit of 93.14% (comes by multiplying the value of R^2 by 100) in the graph below:

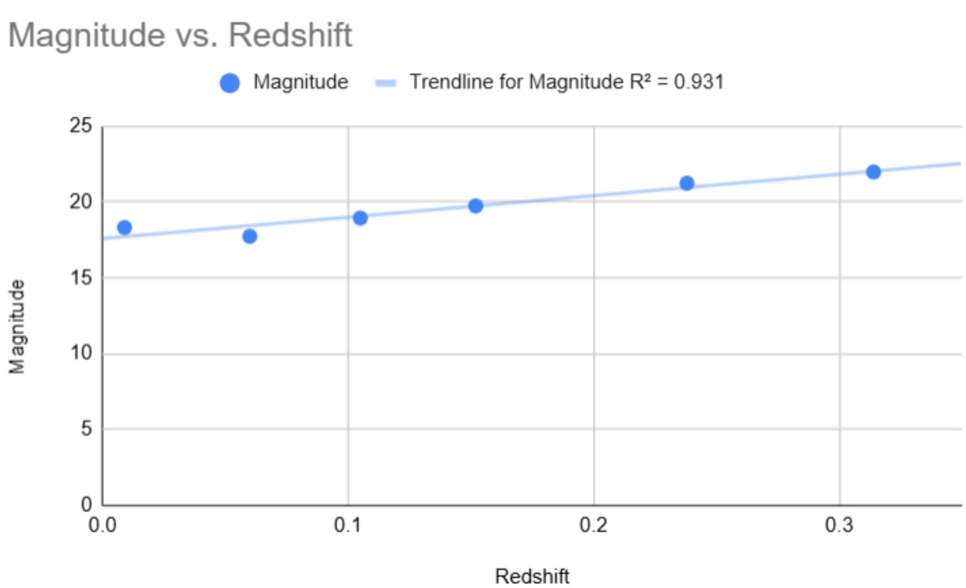

Figure 3: Magnitude vs. Redshift showing linear relationship.

9 Formulating Distances of Galaxies

One of the key factors to form a Hubble Diagram is to find each galaxy's distance along with it's relative distance. Therefore, to find the galaxy's distance Hubble's Law will be established:

$$v = H_0 d \tag{17}$$

Then, we will use the relationship of $v = cz$ where z represents a galaxy's redshift and sub it into Hubble's Law

$$cz = H_0 d \tag{18}$$

From there, we can find the distance for each galaxy be rewriting equation (2) as the following:

$$d = \frac{cz}{H_0} \tag{19}$$

From here, we will plug in each galaxy's redshift, z, into equation (3) and will estimate that the Hubble's constant: $H_0 \approx 70km/sMpc$ and we will estimate that the speed of light: $c \approx 3X10^8 m/sec$. Therefore, this will result in each galaxy's distance in meters to be the following:

Galaxy	Redshift	Distance (m)
786	0.009	38571
049	0.06	257143
477	0.105	450000
795	0.152	651429
099	0.238	1020000
283	0.314	1345714

Table 5: Galaxies with their redshifts and distances

Then, to find the relative distance of each galaxy we can use the formula to find the radiant flux, F:

$$F = 2.51^{-m} \tag{20}$$

Where the $-m$ represents the magnitude of a galaxy. Afterwards, we can rewrite the equation by taking the square root of F and then taking the inverse of the square root, giving the following equation:

$$d_{Relative} = (\sqrt{F})^{-1} = (\sqrt{2.51^{-m}})^{-1} \tag{21}$$

From here, we will plug in each galaxy's magnitude, m, into equation (5) resulting in the galaxy's relative distances resulting in the following.

Galaxy	Magnitude	Relative Distance
786	18.32	4582
049	17.74	3508
477	18.94	6094
795	19.74	8806
099	21.24	17560
283	21.98	24683

Table 6: Galaxies with their magnitudes and relative distances

To clarify how far the galaxies are apart from each other, the galaxies will become on a "normalized" scale by assuming that the galaxy with the smallest relative distance, 049, has a relative distance of 1. Therefore, taking all the relative distances and dividing them by 049's relative distance of 3508 results in the following:

Galaxy	Relative Distance	Normalized Relative Distance
786	4582	1.306
049	3508	1
477	6094	1.737
795	8806	2.510
099	17560	5.006
283	24683	7.036

Table 7: Galaxies with their relative distances normalized

10 Exercises 8-9, 15-17