Due: Mon Dec 1 2014 12:00 PM EST

Question 1 2

Instructions
Lab 8: Hubble's Law: The Galaxy's Place in the Universe II

Read the lab before attending lab. You might find it easier to navigate if you expand only one or two sections at a time.

The following summary video is available to you in case you miss lab or want to review it when completing the lab:

Hubble's Law (20:26)

You are permitted 100 submissions per question. Use some of these to save your work.

If you do not save your work periodically, you risk losing it when WebAssign times you out. WebAssign does this after a few hours for security reasons.

Do not open multiple copies of this assignment, or multiple WebAssign assignments, or you risk losing your answers upon saving or submitting.

Enter all calculated values to at least two significant digits.

Do not add units when entering numerical responses. WebAssign will not accept your response.

Do not use special characters when naming files. WebAssign will not accept your file.

I hope that you enjoyed "Astronomy 101 Laboratory: Our Place In Space" and hope to see you in one of our other introductory astronomy courses.

Follow Skynet on Facebook and Twitter!

---

1. Question Details UNCAstro101L1 8.IL.001. [1921559]

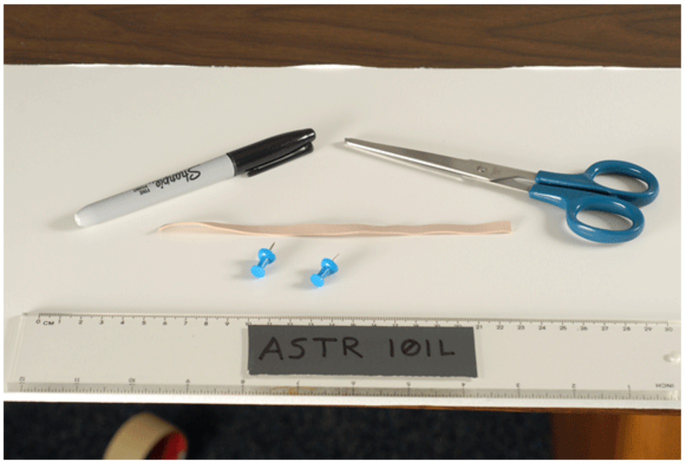
LAB 8 — HUBBLE'S LAW: THE GALAXY'S PLACE IN THE UNIVERSE II

GOALS

In Lab 8, we:
- Learn that the Big Bang was not an explosion *in* space but an explosion *of* space.
- Determine that our galaxy is not at the center of the universe and that the universe in fact has no measurable center.
- Determine whether the universe is expanding at a decelerating, constant, or accelerating rate.

EQUIPMENT

Rubber band (at least ≈18 cm long once cut)
Scissors
Ruler
Marker
Foam board
Tacks



BACKGROUND: A. HUBBLE'S LAW

As we learned in Lab 5, distances can be measured to nearby galaxies using Cepheid variable stars and to faraway galaxies using Type Ia supernovae.

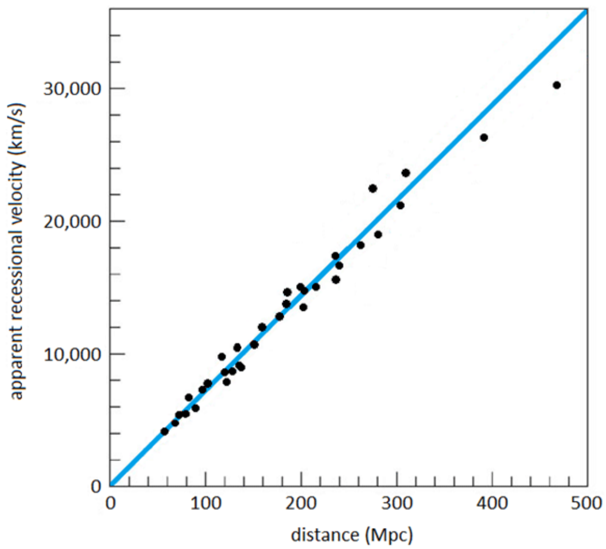
As we learned in Lab 7, the speed at which an object appears to be moving toward or away from us can be measured by how blue- or red-shifted the object's spectrum is

$v = c \times z$

where c is the speed of light and z is the redshift, which is given by

$$z = \frac{\Delta\lambda}{\lambda_{emitted}} = \frac{(\lambda_{observed} - \lambda_{emitted})}{\lambda_{emitted}}.$$

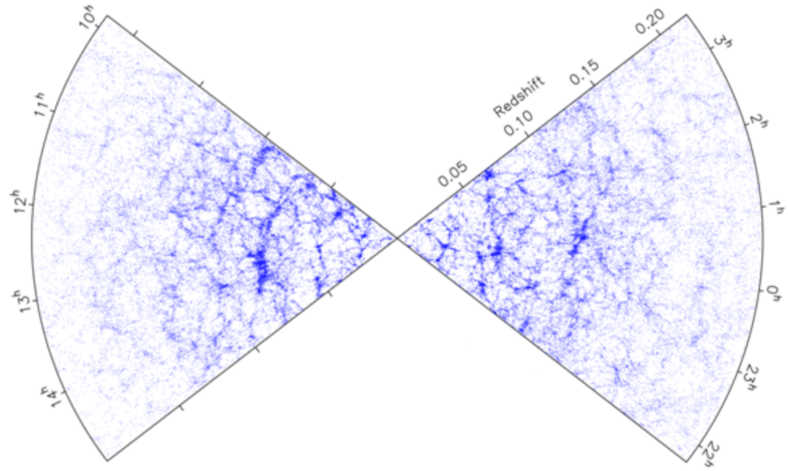
Hubble found that except for very nearby galaxies, which are gravitationally bound to us, all galaxies appear to be moving away from us. Furthermore, the farther away a galaxy is from us, the faster it appears to be moving from us.



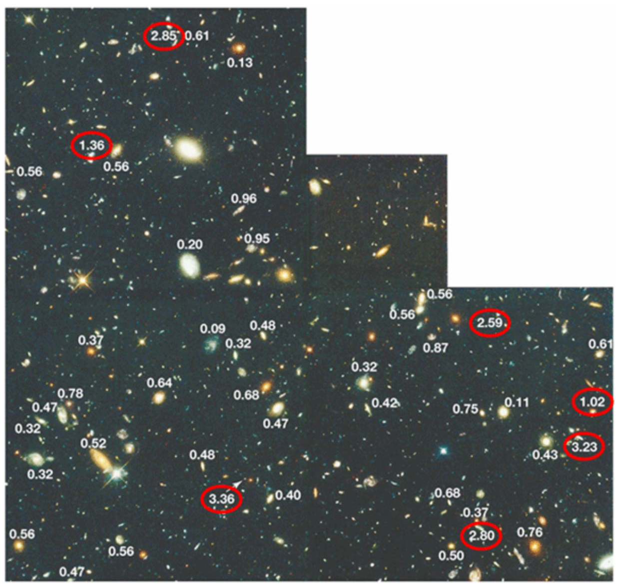
If we run time backwards, all objects in this figure would be on top of each other approximately 13.7 billion years ago. Running time forward again gives the impression that the Big Bang was an explosion of matter and energy from a fixed point in space.

However, there are a number of problems with this interpretation. For example, if the Big Bang was an explosion in space, one might expect to find the universe's matter and energy distributed in one or more giant, expanding shells about this point. However, when we look out, galaxies appear to be distributed homogeneously (same numbers at all locations) and isotropically (same numbers in all directions), at least on very large scales. (On smaller scales, they clump together due to gravity.)

For example, here are two slices of a galaxy survey of the sky. Each point is a galaxy. There are fewer galaxies far away only because galaxies are increasingly difficult to detect far away. But clearly, galaxies are not distributed in one or more giant, expanding shells about a single point in space.



Another problem with thinking about the Big Bang as an explosion in space is that we often measure redshifts $z > 1$. For example, here are redshifts that have been measured for galaxies in the Hubble Deep Field.



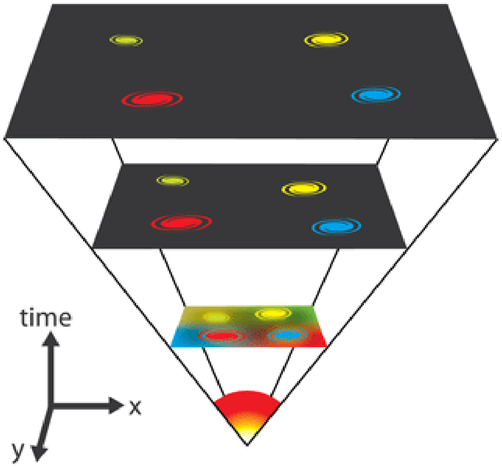
If these redshifts are due to each galaxy's motion through space, they would be Doppler redshifts, in which case:
$v = c \times z$.
But $z > 1$ would imply $v > c$! Einstein showed that nothing can move through space faster than the speed of light.

(The gamma-ray burst that was mentioned in Lab 1, that UNC undergraduate Josh Haislip and Dr. Reichart used PROMPT to discover, had a measured redshift of $z = 6.295$. This would correspond to a velocity of 629.5% of the speed of light!)

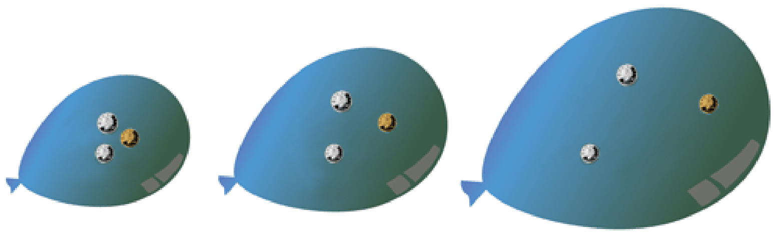
Technically, Einstein showed that this relationship breaks down when $z > 1$ and that $z > 1$ merely implies that v is less than but very close to c. However, Einstein also showed that a number of crazy things happen when an object approaches the speed of light: (1) it moves significantly more slowly through time; (2) its length contracts significantly in its direction of motion; and (3) its mass increases significantly, among other effects. Although crazy, these effects have been demonstrated to be true in laboratories — but they are not observed to be true for $z > 1$ galaxies.

So how can Hubble's Law be explained if not due to motion of the galaxies through space?

Einstein also showed that space itself can move. For example, it can expand. And if it does, it tries to carry everything in it away from everything else in it.



Like coins attached to the surface of an expanding balloon, distant galaxies appear to move away from one another, but really they are not moving through space at all. Rather, space is moving and they are being carried along for the ride.



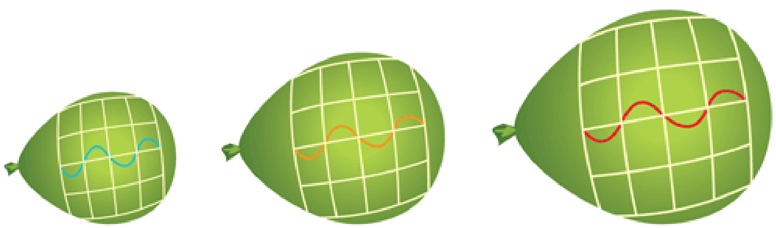
And while objects cannot move through space faster than the speed of light, space is not so restricted. Space can expand at speeds such that distant objects are carried away from one another at faster than light speeds.

Consequently, the Big Bang is better described not as an explosion *in* space, but as an explosion *of* space.

BACKGROUND: B. COSMOLOGICAL REDSHIFT

But if these are not Doppler redshifts that we are measuring, what are they? What is redshifting the light?

The answer is that light waves have no internal cohesion. They expand as the universe expands. And longer wavelengths correspond to redder, or redshifted, light.



You do not expand with the universe because intermolecular forces hold your molecules together against the expansion.

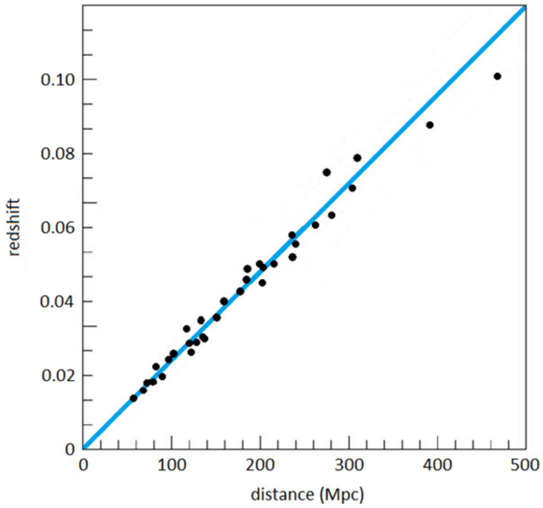
Earth does not expand with the universe because gravity holds it together against the expansion. The same is true for the solar system, the Milky Way galaxy, and our local group of galaxies, which includes Andromeda.

But more distant galaxies are too far apart and the force of gravity between them too weak to hold them together against the expansion of the universe.

Since light has no internal cohesion, light is stretched, or redshifted, as it travels across the expanding universe.

The farther away a source of light, such as a galaxy, the longer the light that it is emitting has to travel through the expanding universe, the more redshifted it is when it finally reaches us.

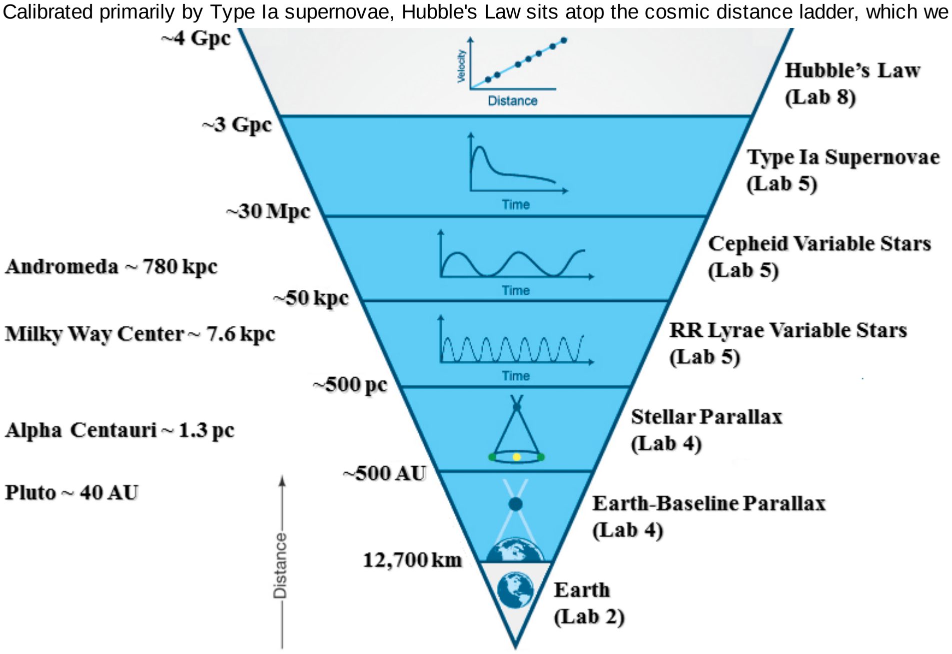
In short, the greater the distance, the greater the redshift, which is Hubble's Law.



We call this cosmological redshift, to distinguish it from Doppler redshift, which was the topic of Lab 7.

By measuring an object's cosmological redshift, Hubble's Law can be used to estimate its distance. In this way, distances can be measured to the most distant objects in the universe.

Calibrated primarily by Type Ia supernovae, Hubble's Law sits atop the cosmic distance ladder, which we first introduced in Lab 4.



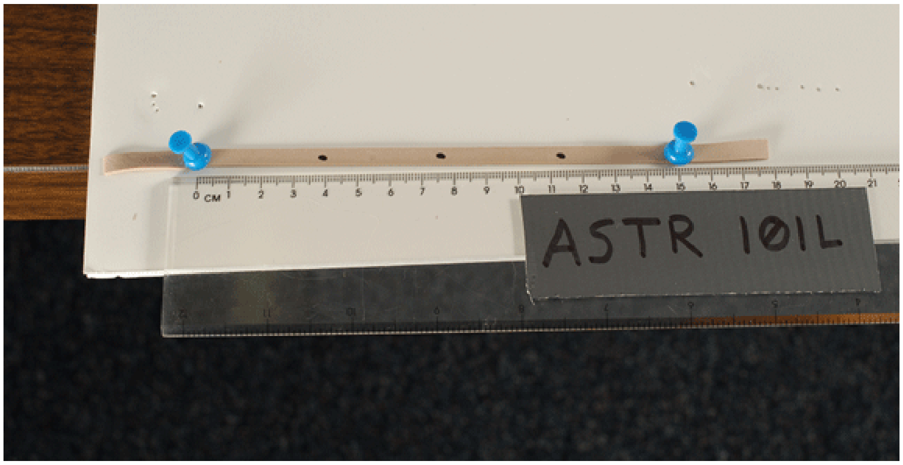
⊞ PROCEDURE: A. RUBBER BAND UNIVERSE

In this lab, we will simulate the expansion of a part of the universe simply by stretching a part of a rubber band.

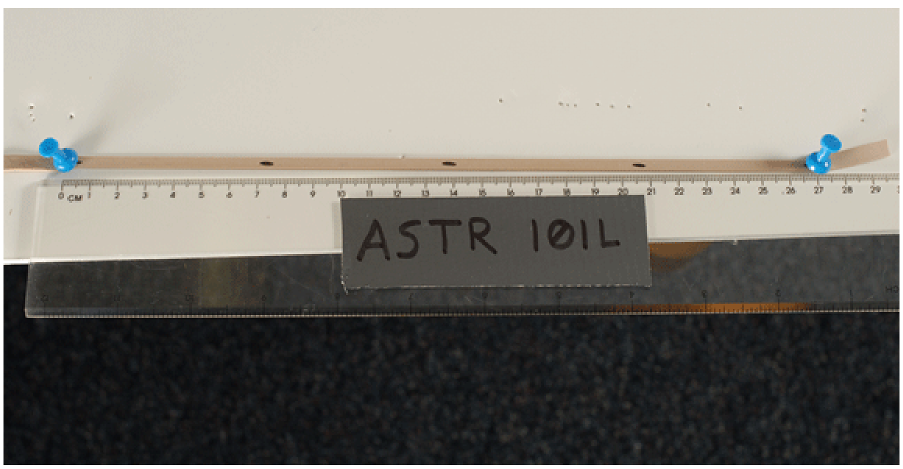
Cut your rubber band and lay it flat beside your ruler. It should be approximately 18 cm long.

Using a marker, place dots approximately 3, 6, 9, 12, and 15 cm from either edge of the rubber band. These dots will represent Galaxies 1 - 5, respectively.

Push the provided tacks through Galaxy 1 and Galaxy 5 and attach them to the provided foam board. If the tacks do not go all the way through, pull the foam board toward you until it overhangs your working surface. Then push the tacks all the way through.



In this lab, you will un-tack Galaxy 5, stretch the rubber band, and re-tack Galaxy 5.



Warning: To prevent the rubber band from pulling the tack loose and flinging it across the room (1) push the tack in at an opposing angle; and (2) push the tack all the way in.

PROCEDURE: B. HUBBLE'S LAW

In this section, we will show that Hubble's Law is a natural consequence of the expansion of space.

Consider a universe that is expanding at a constant rate. You can simulate this by stretching your rubber band at a constant rate. For example, if you increase the distance between Galaxy 1 and Galaxy 5 at a rate of 3 cm/minute, your rubber band would take 4 minutes to expand from zero size to its resting size.

Continue to stretch the rubber band from here. Imagine stopping time once every minute to take measurements. For each time listed in the first column of Data Table 1, set the distance between Galaxy 1 and Galaxy 5 to be as listed in the second column and measure the distance between Galaxy 1 and each of the other galaxies to the nearest 0.1 cm. (The dots that represent the galaxies will stretch with the rubber band; use their centers for your measurements.) Record these measurements in the remaining columns of Data Table 1.

Data Table 1: Universe Expanding at Constant Rate (Viewed from Galaxy 1) (4.5 points)

Time (min)	Distance Between Galaxy 1 and Galaxy 5 (cm)	Distance Between Galaxy 1 and Galaxy # (cm)				
		Galaxy 1	Galaxy 2	Galaxy 3	Galaxy 4	Galaxy 5
0	0	0				0
1	3	0				3
2	6	0				6
3	9	0				9
4	12	0				12
5	15	0				15
6	18	0				18
7	21	0				21
8	24	0				24
9 (now)	27	0				27

Go to this website.

Figure 1: Beginning with time = 0 min, plot distance between Galaxy 1 and Galaxy 5 (on the *Y* axis) vs. time (on the *X* axis) and verify that this universe is expanding at a constant rate. Save it as a png file.

Note: Take care when stretching the rubber band and make measurements to be precise. Careful measurements are more likely to receive credit than sloppy ones!

Question: Upload your png graph. (Submit a file with a maximum size of 1 MB. 5 points)

Choose File No file chosen

Question: Is this universe expanding at a constant rate? (1 point)

- Yes
- No

Since light travels at a finite speed, the farther away a galaxy is from Galaxy 1, the longer light takes to travel from it to Galaxy 1. Consequently, observers in Galaxy 1 see each of the other galaxies as they were when they emitted their light, not as they are now. The farther away a galaxy is from Galaxy 1, the farther back in time observers in Galaxy 1 see it.

The yellow cells in Data Table 1 mark when each galaxy emitted the light that Galaxy 1 is just now receiving. For example, Galaxy 5 emitted the light that Galaxy 1 is just now receiving at t = 5 minutes. Since now corresponds to t = 9 minutes, Galaxy 5 emitted the light that Galaxy 1 is just now receiving 4 minutes ago.

For any Galaxy #:

Let $\boldsymbol{d_{then}}$ be the distance between Galaxy # and Galaxy 1 when Galaxy # emitted the light that Galaxy 1 is just now receiving. For example, for Galaxy 5, d_{then} = 15 cm.

Let $\boldsymbol{d_{now}}$ be the distance between Galaxy # and Galaxy 1 now. For example, for Galaxy 5, d_{now} = 27 cm.

Record these values in the first two columns of Data Table 2 for each Galaxy #. Note: enter the exact values from Table 1 in the first two columns of Table 2.

Data Table 2: Universe Expanding at Constant Rate (Viewed from Galaxy 1) (4 points)

Galaxy #	Distance Between Galaxy 1 and Galaxy # (cm)			Cosmological Redshift (z)
	When Galaxy # Emitted the Light (d_{then})	When Galaxy 1 Received the Light (d_{now})	That the Light Traveled (d_L)	
1	0	0	0	0
2				
3				
4				
5				

The distance that the light traveled from Galaxy # to Galaxy 1 is longer than $\boldsymbol{d_{then}}$ since the universe was larger when the light was traveling.

The distance that the light traveled from Galaxy # to Galaxy 1 is shorter than $\boldsymbol{d_{now}}$ since the universe was smaller when the light was traveling.

We can approximate the distance that the light traveled from Galaxy # to Galaxy 1 by averaging these two distances.

$$d \approx \frac{(d_{then} + d_{now})}{2}$$

This is called the **coordinate distance** that the light traveled. However, on Hubble's Law plots astronomers instead use the **luminosity distance** that the light traveled. This is the distance that we would have inferred had we used a standard candle, such as a Cepheid variable star or a Type Ia supernova, instead of a ruler to measure the distance.

Luminosity distances are greater than coordinate distances, because as light travels across an expanding universe, it gets stretched out in time, and consequently we receive it more slowly. This makes the source of the light appear fainter, and consequently we infer it to be farther away than it really is.

The luminosity distance that the light traveled from Galaxy # to Galaxy 1, $\boldsymbol{d_L}$, is given by multiplying $\boldsymbol{d}$ by a correction factor:

$$d_L = d \times \text{correction factor}$$

where

$$\text{correction factor} = \frac{d_{now}}{d_{then}}.$$

Calculate the luminosity distance for each Galaxy # and record it to one decimal place in the third column of Data Table 2.

Question: Present your calculation for the luminosity distance to Galaxy 2 in Data Table 2. (3 points)

The cosmological redshift that observers in Galaxy 1 measure for Galaxy # is:

$$z = \frac{\Delta\lambda}{\lambda_{then}} = \frac{(\lambda_{now} - \lambda_{then})}{\lambda_{then}}.$$

Since λ expands as the universe expands:

λ_{then} = constant × d_{then}

and

λ_{now} = constant × d_{now}.

Substitution yields:

$$z = \frac{[(\text{constant} \times d_{now}) - (\text{constant} \times d_{then})]}{(\text{constant} \times d_{then})}.$$

Simplification yields:

$$\boldsymbol{z} = \frac{\boldsymbol{d_{now} - d_{then}}}{\boldsymbol{d_{then}}}.$$

(The value of the constant does not matter.)

Calculate the cosmological redshift for each Galaxy # and record it to three decimal places in the fourth column of Data Table 2.

Question: Present your calculation for the cosmological redshift of Galaxy 2 in Data Table 2. (3 points)

Go to this website.

Figure 2: Beginning with d_L = 0 cm, plot z (on the Y axis) vs. d_L (on the X axis). Save it as a png file.

Question: Upload your png graph. (Submit a file with a maximum size of 1 MB. 5 points)

Choose File No file chosen

Question: Hubble's Law states that the farther away a galaxy is from us, the faster it appears to be moving from us. Have you been able to replicate Hubble's Law? (2 points)

- Yes
- No

PROCEDURE: C. ARE WE AT THE CENTER OF THE UNIVERSE? DOES THE UNIVERSE HAVE A CENTER?

Since all galaxies appear to be moving away from Galaxy 1, does this mean that Galaxy 1 is at the center of the expansion?

Repeat Section B, but this time measure the distance between Galaxy 2 and each of the other galaxies. Record these measurements in Data Table 3.

Data Table 3: Universe Expanding at Constant Rate (Viewed from Galaxy 2) (6 points)

Time (min)	Distance Between Galaxy 1 and Galaxy 5 (cm)	Distance Between Galaxy 2 and Galaxy # (cm)				
		Galaxy 1	Galaxy 2	Galaxy 3	Galaxy 4	Galaxy 5

0	0		0			
1	3		0			
2	6		0			
3	9		0			
4	12		0			
5	15		0			
6	18		0			
7	21		0			
8	24		0			
9 (now)	27		0			

Yellow marks when each galaxy emitted the light that Galaxy 2 is just now receiving.

Complete Data Table 4. Note: enter the exact values from Table 3 in the first two columns of Table 4.

Data Table 4: Universe Expanding at Constant Rate (Viewed from Galaxy 2) (4 points)

Galaxy #	**Distance Between Galaxy 2 and Galaxy # (cm)**			**Cosmological Redshift (z)**
	When galaxy # Emitted the Light (d_{then})	**When Galaxy 2 Received the Light (d_{now})**	**That the Light Traveled (d_L)**	
1				
2	0	0	0	0
3				
4				
5				

Go to this website.

Figure 3: Beginning with d_L = 0 cm and in order of increasing d_L, plot z (on the Y axis) vs. d_L (on the X axis). On the same graph, overplot Figure 2 from Section B for comparison. Label each appropriately. Save it as a png file.

Question: Upload your png graph. (Submit a file with a maximum size of 1 MB. 5 points)

Choose File No file chosen

Question: Do observers in Galaxy 2 have as much right to say that they are at the center of the expansion as observers in Galaxy 1? (2 points)

- Yes
- No

Question: Can anyone realistically claim to be at the center of the expansion, and hence at the center of the universe? (2 points)

- Yes
- No

2. Question Details UNCAstro101L1 8.IL.002. [1921558]

PROCEDURE: D. IS THE UNIVERSE EXPANDING AT A DECELERATING, A CONSTANT, OR AN ACCELERATING RATE?

Although the universe is expanding, gravitational pulls between the galaxies should be slowing, or decelerating, the expansion.

Repeat Section B, but this time with a decelerating universe. Record the measurements in Data Table 5.

Data Table 5: Universe Expanding at a Decelerating Rate (Viewed from Galaxy 1) (3.75 points)

Time (min)	Distance Between Galaxy 1 and Galaxy 5 (cm)	Distance Between Galaxy 1 and Galaxy # (cm)				
		Galaxy 1	Galaxy 2	Galaxy 3	Galaxy 4	Galaxy 5
0	0	0				0
0.7	2.85	0				2.85
1.7	6.75	0				6.75
2.7	10.5	0				10.5
3.7	14.1	0				14.1
4.7	17.55	0				17.55
5.7	20.85	0				20.85
6.7	24	0				24
7.7 (now)	27	0				27

Yellow marks when each galaxy emitted the light that Galaxy 1 is just now receiving.

Go to this website.

Figure 4: Beginning with time = 0 min, plot distance between Galaxy 1 and Galaxy 5 (on the *Y* axis) vs. time (on the *X* axis) and verify that this universe is decelerating as it expands. On the same graph, overplot Figure 1 from Section B for comparison. Label each appropriately. Save it as a png file.

Question: Upload your png graph. (Submit a file with a maximum size of 1 MB. 5 points)

Choose File No file chosen

Question: Is this universe decelerating as it expands? (1 points)

- Yes
- No

Complete Data Table 6. Note: enter the exact values from Table 5 in the first two columns of Table 6.

Data Table 6: Universe Expanding at a Decelerating Rate (Viewed from Galaxy 1) (4 points)

Galaxy #	Distance Between Galaxy 1 and Galaxy # (cm)			Cosmological Redshift (z)
	When Galaxy # Emitted the Light (d_{then})	When Galaxy 1 Received the l Light (d_{now})	That the Light Traveled (d_L)	
1	0	0	0	0
2				
3				
4				
5				

Go to this website.

Figure 5: Beginning with d_L = 0 cm, plot z (on the *Y* axis) vs. d_L (on the *X* axis; decelerating expansion). On the same graph, overplot Figure 2 (constant expansion) from Section B for comparison. Label each appropriately. Save it as a png file.

Question: Upload your png graph. (Submit a file with a maximum size of 1 MB. 5 points)

Choose File No file chosen

Question: How does Hubble's Law change in a decelerating universe? (2 points)

- It curves down (to lower redshifts) at large distances.
- It does not change at large distances.
- It curves up (to higher redshifts) at large distances.

Suppose that the universe were accelerating instead of decelerating.

Repeat Section B, but this time with an accelerating universe. Record the measurements in Data Table 7.

Data Table 7: Universe Expanding at an Accelerating Rate (Viewed from Galaxy 1) (4.5 points)

Time (min)	Distance Between Galaxy 1 and Galaxy 5 (cm)	Distance Between Galaxy 1 and Galaxy # (cm)				
		Galaxy 1	Galaxy 2	Galaxy 3	Galaxy 4	Galaxy 5
0	0	0				0
0.75	0.9	0				0.9
1.75	2.25	0				2.25
2.75	3.75	0				3.75
3.75	5.4	0				5.4
4.75	7.2	0				7.2
5.75	9.15	0				9.15
6.75	11.25	0				11.25
7.75	13.5	0				13.5
8.75	15.9	0				15.9
9.75	18.45	0				18.45
10.75	21.15	0				21.15
11.75	24	0				24
12.75 (now)	27	0				27

Yellow marks when each galaxy emitted the light that Galaxy 1 is just now receiving.

Go to this website.

Figure 6: Beginning with time = 0 min, plot distance between Galaxy 1 and Galaxy 5 (on the *Y* axis) vs. time (on the *X* axis) and verify that this universe is accelerating as it expands. On the same graph, overplot Figure 1 from Section B for comparison. Label each appropriately. Save it as a png file.

Question: Upload your png graph. (Submit a file with a maximum size of 1 MB. 5 points)

Choose File No file chosen

Question: Is this universe accelerating as it expands? (1 points)

- Yes
- No

Complete Data Table 8. Note: enter the exact values from Table 7 in the first two columns of Table 8.

Data Table 8: Universe Expanding at an Accelerating Rate (Viewed from Galaxy 1) (4 points)

Galaxy #	Distance Between Galaxy 1 and Galaxy # (cm)			Cosmological Redshift (z)
	When Galaxy # Emitted the Light (d_{then})	When Galaxy 1 Received the l Light (d_{now})	That the Light Traveled (d_L)	
1	0	0	0	0
2				
3				
4				
5				

Go to this website.

Figure 7: Beginning with d_L = 0 cm, plot z (on the Y axis) vs. d_L (on the X axis; accelerating expansion). On the same graph, overplot Figure 2 (constant expansion) from Section B for comparison. Label each appropriately. Save it as a png file.

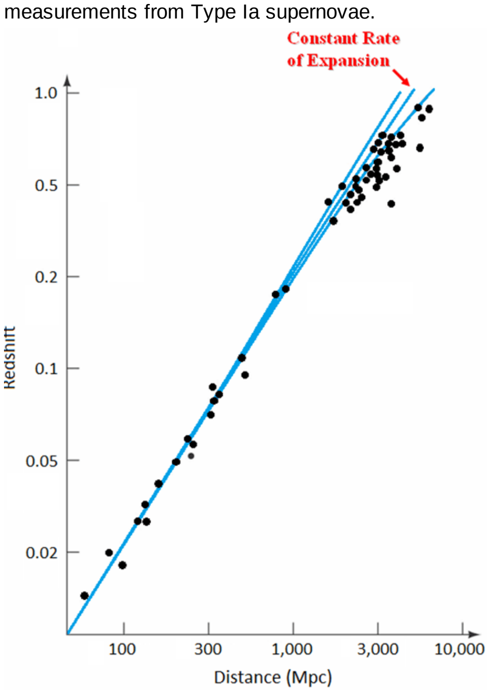
Question: Upload your png graph. (Submit a file with a maximum size of 1 MB. 5 points)

Choose File No file chosen

Question: How does Hubble's Law change in an accelerating universe? (2 points)

- It curves down (to lower redshifts) at large distances.
- It does not change at large distances.
- It curves up (to higher redshifts) at large distances.

In Lab 5, we learned how to measure the distance that light travels from Type Ia supernovae to us. Here are real distance and redshift measurements from Type Ia supernovae.



Question: What type of universe do we live in? (2 points)

- decelerating
- constant rate of expansion
- accelerating

Question: Research and discuss dark energy. (3 points)

Question: Discuss significant sources of error in your measurements. (2 points)

Assignment Details

Name (AID): **Lab 8: Hubble's Law (T) (2369717)**
Submissions Allowed: **100**
Category: **Homework**
Code:
Locked: **Yes**
Author: **Reichart, Daniel (reichart@physics.unc.edu)**
Last Saved: **Jun 19, 2013 05:42 PM EDT**
Permission: **Protected**
Randomization: **Assignment**
Which graded: **Last**

Feedback Settings
Before due date
Response
After due date
Question Score
Assignment Score
Publish Essay Scores
Key
Question Part Score
Solution
Mark
Help/Hints
Response