

AST-051 Lab: Determining the Age of the Universe



The discovery of the expanding Universe was one of the greatest revelations in astronomy. In this lab, you will relive Hubble’s monumental discovery by using real data of supernova spectra to create a Hubble Diagram.

**Background Science**

***i. Standard Candles, Type Ia supernovae and the Distance Modulus***

Measuring distances to objects in the universe is, in principle, very difficult. One method is to use an object with a known luminosity (L), measure the flux (how bright the object looks), and use the relation between luminosity and flux to figure out the distance. Objects used for this are called “**standard candles**.” Type Ia supernovae are among the best standard candles in astronomy, for their peak luminosity is well known and they can be seen at great distances, up to 1000 mega parsecs (Mpc). Remember that one parsec is equal to 3.09 × 1016 meters, and 1 Mpc is a million parsecs.

This model implies that all Type Ia supernovae start with essentially the same mass and therefore the energy output from the resulting supernova should always be the same. Of course, it is not quite that simple, in that there is a little bit of variation, but this variation is small and so we can use the average maximum luminosity to calculate a distance.

Instead of “flux” and “luminosity,” astronomers commonly report related quantities called “**magnitudes**.” In 150 BC, the Greek astronomer noted that the stars varied in brightness, and he called the brightest stars to be “of first magnitude”, and the faintest he could see were of “sixth magnitude.” The concept of magnitudes to describe stars’ brightnesses has lasted and is still used today. This method is a bit cumbersome for the brighter stars have a lower magnitude, and so the scale is backwards, and the eye has a logarithmic sensitivity and so the math to describe magnitudes involves logarithms. Since we know today that a star’s brightness depends on its distance as well as its luminosity, astronomers define two types of magnitude. **Apparent magnitude**, symbolized by ***m***, is similar to flux, in that it describes how bright the star appears to us, and **absolute magnitude**, symbolized by ***M***, has the distance dependence removed and so is similar to luminosity.

With regards to the type Ia supernovae, astronomers measure the magnitudes using a blue (B) filter in the telescope (by using a well-defined filter, measurements made by different people on different telescopes can be more accurately compared). The average peak absolutemagnitude in the B filter of these supernovae: **-19.6**.

By measuring the apparentmagnitude for a Type Ia supernova, then, one can calculate its distance from earth. The equation relating absolute magnitude (*M*), apparent magnitude (*m*), and distance (*d*) is called the “distance modulus.” This equation gives the distance in parsecs (pc) and is given by

**d=10(m - M + 5)/5 pc**

***ii. Spectra, Redshift and Radial Velocity***

To create a Hubble Diagram, the redshift and velocity of your object is needed, as well as the distance. To find the redshift of an object we use its spectrum, measured using a spectrograph similar in principle to the one you built in an earlier lab.

The spectrum reveals the velocity or redshift of an object via the Doppler Effect.

We measure redshift by comparing an observed wavelength to a rest wavelength. For example, the rest wavelength for Hα (when there is no Doppler Effect) is 656.3 nm, if it is redshifted the observed wavelength will be longer. If both the observed and rest wavelengths are known, these can be used to calculate the object’s redshift can be calculated, where z = redshift:

**z = (observed wavelength/rest wavelength) – 1**

***iii. The Hubble Diagram and Hubble’s Law***

The idea that we live in an expanding Universe was one of the most unexpected and important discoveries of the 20th century. Until then, everyone, including astronomers, had assumed that the Universe was unchanging, having always existed and staying the same forever. But, in 1929, Edwin Hubble presented a graph the revealed the universe was expanding.

In the early 1900s, Vesto Slipher discovered that the majority of the “fuzzy objects” known then as spiral nebulae and now known to be other galaxies were redshifted, which meant they were moving away from us. In 1923, Edwin Hubble was able to resolve individual stars in the spiral nebula in Andromeda, revealing this was another galaxy. Then, following up on Slipher’s work, Edwin Hubble measured the distances to other galaxies (using Cepheid variable stars as standard candles). Hubble then graphed the redshifts on the y-axis and distances on the x-axis. This plot is now known as the Hubble Diagram.

Hubble’s graph showed that the data fit reasonably well to a straight line, meaning that a galaxy’s redshift increased linearly with its distance from Earth. The farther away a galaxy is, the faster it appears to move away from us. Since the galaxies that are farther from us are moving away faster than the galaxies that are closer, this also means that all galaxies are moving away from each other. Hence, the entire universe is expanding. If the universe is expanding, then at some time in the past, it must have started from a single point - an idea known as the Big Bang. Hubble's discovery, and the later development of the big bang theory, changed astronomy forever.

The straight line relation between redshift velocity and distance, and which goes through the origin, is represented by the mathematical equation

*v*r (km/s) = *H*0 *d*(Mpc)

where *H*0 is the slope of the straight line and has units of km/s per Mpc. H0 is called the Hubble constant and represents the rate of expansion. Hubble calculated a value for the Hubble Constant at around 500 km/s per Mpc. We now know this is much too large. The Hubble constant is very important for astronomy for two reasons. It provides a way of estimating distance to other galaxies and it is related to the age of the universe – the faster galaxies are moving away from each other, the less time it took to get to their current separation distances, and hence the younger the universe is.

In this lab, you will make your own Hubble Diagram using redshifts and distances for 10 Type Ia supernovae. You will measure the Hubble Constant or rate of expansion and compare it to the values we now believe are correct. You will then use your measured value to estimate the age of the universe.

**Instructions**

The first step is to find spectra for ten different Type Ia supernovae and work out the redshift for each. Using the redshift, you will derive the radial velocity for each. Next, you will calculate the distance to each of your objects. Using these two values you will plot the Hubble Diagram.

***Calculating Redshift***

1. Download the Hubble Diagram spreadsheet provided in Nexus, and open it in Excel. Then use any web browser and go to: <http://wiserep.weizmann.ac.il/spectra/list>

This website is an archive containing spectra for a number of different types of astronomical objects collected by a range of instruments. For this activity we will be using spectra for Type Ia supernovae collected by the STIS spectrograph aboard the Hubble Space Telescope.

1. You can ignore all fields on the first page apart from ‘**Obj Type**’. Select ‘**SN Ia**’ from the dropdown list.
2. Select **HST-STIS** from the **Instrument** list (this is an instrument on the Hubble Space Telescope).
3. Change the limit of spectra returned to a number less than 50. Then press the green “**play**” button.
4. You will see a supernova spectrum. Below the graph you will notice two values for the wavelength (WL): observed and rest. These values show us how the supernova is moving relative to us. The wavelength is shown in a unit called Ångström (Å) (which equals 10-10 m). 
5. To the right of your graph you will notice check boxes for a number of elements: hydrogen, helium, oxygen and sodium. When you click a box it will show you the emission or absorption features for each element. Find an element with a strong and clear emission line. Hover your mouse over the peak of the line and make a note of the observed wavelength and rest wavelength values and element on your worksheet.
6. Choose 10 supernovae from the list. Open the ‘B-band Max Mag’ sheet on your spreadsheet and note the list of supernovae in column A. Make sure that each supernova you pick is also listed in the ‘B-band Max Mag’ spreadsheet. And, **Do not select** the following supernovae:

PTF10pdf

 PTF10zdk

PTF10acdh

 Sn2010kg

 Sn2010fe/PTF11kly

Note: Be careful to ensure that you have ten different supernova spectra and have not duplicated any, as there are multiple spectra for some supernovae.

1. Record the **rest wavelength, observed wavelength, and element** of a chosen peak for your 10 supernovae.

***Calculating Redshift and Radial Velocity***

1. Calculate the redshift (*z*) of each supernova using

 **z = (observed wavelength/rest wavelength) – 1**

Round your answers to 3 decimal places and write them on your worksheet.

1. Derive the velocity for each supernova using the following equation:

**radial velocity = redshift × speed of light**

Given that the speed of light is approximately 300,000 km/s, you can calculate the radial velocity for each of your supernovae (in km/s).

For example, if a supernova has a redshift of 0.025, then the radial velocity is given by

**radial velocity = 0.025 × 300000 = 7500 km/s**

Write your velocities on your spreadsheet. (**Note:** This equation only works for redshift smaller than z = 1.0.)

***Calculating Distances***

1. To calculate the distance to your Type Ia supernovae, you need to note down the maximum B-band magnitude. Open the ‘B-band Max Mag’ sheet on your spreadsheet. The data in this table is from a scientific paper called “*Hubble Space Telescope* studies of low-redshift Type Ia supernovae: Evolution with redshift and ultraviolet spectral trends“ which you can find at <http://arxiv.org/pdf/1205.7040.pdf>
2. There is a column in the table called ***B*-band max (mag)** this shows the maximum apparent magnitude (m) for each supernovae. Make a note of this value in your table.
3. Use the distance modulus equation, **d=10(m - M + 5)/5 pc,** to calculate the distance to each supernova in parsecs. Remember that the peak M of type IA supernovae = -19.6. (Note that this is a negative number and you are going to subtract it in the equation.) Then convert to Mpc (1 Mpc = 106 pc).

***Plotting a Hubble Diagram***

1. Make a graph with the radial velocities, in km/sec, on the y-axis and distances, in Mpc, on the x-axis.
2. Fit a straight line through your points. The line should also go through zero. Put the equation on the graph so that you can see the slope of the line.

***Estimating the Hubble Constant***

The slope of the straight line on the Hubble diagram equals the Hubble constant. Add the value of the slope on your Hubble diagram to your worksheet.

(Although called a constant, **H** changes with time as the universe expands. The subscript ‘0’ is used to indicate its value today.)

The Hubble constant is given by:

**H0 =v/d**

where v is the radial velocity and d is the distance. The value for the Hubble constant is given in kilometres per second per mega parsec (Mpc).

**Conclusion**

Now that you have a value for the Hubble constant, one simple thing you can do is estimate the age of the Universe. If the Universe has been expanding at a constant speed since its beginning, the Universe's age would simply be the inverse of the Hubble Constant or **1/*Ho.***

Follow directions in the hand-in worksheet to estimate the age of the Universe.

*Based on Las Cumbres Observatory Activity: Measuring the Age of the Universe, under Creative Commons BY-CC 2.0.*

**AST 051 Worksheet for Determining the Age of the Universe**

**Name: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ Partner's Name: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_**

``I affirm that I have carried out my academic endeavors with full academic honesty.''\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

***Show all your work!***

1. Record your value for the Hubble Parameter on the line below.

**Using the Graph: Average Value of Ho = \_\_\_\_\_\_\_\_\_\_\_km/sec per Mpc.**

2. Using ***your***inferred value of **H** determined from your graph, calculate the recessional velocity of a galaxy that is 300 Mpc away.

 **V** = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_km/sec

Verify this velocity on your Hubble diagram by reading the y-axis value for a distance of 300 Mpc.

3. You now have two important pieces of information:

1. How far away the galaxy is.

2. How fast it is moving away from us.

You can visualize the process if you think about a trip in your car. If you tell a friend that you are 120 miles away from your starting point and that you traveled 60 miles per hour, your friend would know you had been traveling TWO hours. That is, your trip started two hours ago. You know this from the relationship:

Distance equals Velocity \* Time, which we can write as

**D = V \* T** *or* **T = D / V**

In this case, 2 hrs = 120 mi / 60 mi per hr

Now let’s determine when the universe “started its trip”. We have a distance of 300 Mpc. But, first convert Mpc into km (because the velocity is in km/sec).

 D = \_\_\_\_\_\_\_\_\_\_\_\_\_ Mpc \* (3.09x1019 km/Mpc) = \_\_\_\_\_\_\_\_\_\_\_\_\_km

4. Using the speed-time-distance equation, i.e. T=D/V, determine how many seconds ago the universe started:

**T** = \_\_\_\_\_\_\_\_\_\_\_\_\_km / \_\_\_\_\_\_\_\_\_\_\_\_\_\_ km/s = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_secs

5. There are about 3.16 x 107 seconds in one year. Convert your answer into years:

**T** = \_\_\_\_\_\_\_\_\_\_\_\_\_\_ secs / (3.16x107 secs/year) = \_\_\_\_\_\_\_\_\_\_\_\_\_ years

6. Therefore, the age of the universe is approximately **\_\_\_\_\_\_\_\_\_ billion years old**.

**For your lab report**:

Turn in this Measuring-the-Age-of-the-Universe worksheet, your Excel table, graph, and answers to the following the questions ***on a separate sheet of paper.***

1) a) What is the Hubble Diagram?

b) What is the vertical axis?

c) What is the horizontal axis?

2) What is Hubble's law? Give your answer as an equation, but also explain it in words. Make sure to identify the name of each symbol in the equation.

3) What remarkable fact does Hubble's law tell us? Explain.

4) a) What is Hubble's constant? (In words, not numbers).

b) What are the usual units given for Hubble's constant?

c) What value did you get in this laboratory exercise? (should include units)

d) What is the "accepted value" according to recent studies (it’s ok to check textbook or the web, but cite your source; is it a recent and reliable source?)

5) a) What key assumption did we make when estimating the age of the universe?

 b) How is our estimate for the age of the Universe related to Hubble's constant? (This is a formula).

c) What would happen to the calculated age of the Universe if the Hubble constant were: larger than you found? smaller than you found?

d) How does your inferred age compare to what we believe the correct age is? (13.78 billion years) Why might these values differ?