
Measuring the Age of the Universe

Activity Guide

Author: Sarah Eve Roberts



Introduction

The discovery of the expanding Universe was one of the greatest revelations in astronomy. During this activity students will relive Hubble's monumental discovery by using real supernova spectra to create a famous Hubble Diagram.

Materials List

Per student:

- One computer with Internet connection
- [Hubble Diagram Worksheet \(google sheet\)](#)
- Hubble Diagram Instruction Sheet

Background Science

Standard Candles, Type Ia supernovae and the Distance Modulus

Measuring distances in space is a daunting task. One method is to use an object with a known absolute magnitude (M); we call these Standard Candles. Type Ia supernovae are standard candles.

There are two classes of supernovae, Type I and Type II. For this activity we will be using Type Ia supernovae only. Type Ia supernovae are very important in astronomy as they offer the most reliable sources for measuring cosmic distances up to and beyond 1000 mega parsecs (Mpc). A parsec (pc) is a unit of length used to measure the distances to objects in space. One parsec is equal to $3.08567758 \times 10^{16}$ metres.

Type Ia supernovae are thought to form when a white dwarf star accretes enough mass from a companion star to exceed the upper limit of 1.44 solar masses, this causes the star to explode as a supernova.

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, but all Type Ia supernovae do seem to have similar light curves and can therefore be related to the same common template. There is an average maximum *absolute* magnitude that these supernovae can reach in the visible wavelength band B. The peak brightness is: -19.6 mag.

If we also know the *apparent* magnitude for a Type Ia supernova, we can just the distance modulus to calculate its distance from earth. The distance modulus is the difference between the apparent magnitude (m) and the absolute magnitude (M) of an astronomical object. It can be used to provide the distance (d) in parsecs. Once m is known, the distance modulus function can be used to calculate the distance to the supernova in parsecs (pc):

$$d=10^{((m - M + 5)/5)} \text{ pc}$$

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 astronomers use spectroscopy. Spectroscopy is a branch of science that is concerned with the investigation and measurement of the spectrum of light produced when matter interacts with electromagnetic radiation. In astronomy, spectroscopy is a very useful tool because telescopes can easily measure the spectra of far away objects, such as stars and galaxies.

We measure the spectra of luminous objects by attaching a special instrument to a telescope, known as a spectrograph. Within the spectrograph, light is passed through a series of prisms and mirrors in order to split the light into its different component wavelengths (its spectrum). The intensity of those different wavelength components is then measured to create a spectrum. The spectrum can then be investigated in detail to discover useful information about the target such as chemical composition, Doppler shift and velocity.

The Doppler Effect, such as redshift, occurs due to an apparent shift in the wavelength and frequency of a wave due to relative motion between the source and the observer. For example, we experience the Doppler Effect when an ambulance drives past with its sirens on:

- As the ambulance (the source) approaches you (the observer), the sound wave is compressed (bunched up) and the resulting sound is higher pitched (shorter wavelength (λ))
- Once the ambulance has passed, the wave is stretched and the pitch sounds lower (longer λ).



Illustrating demonstrating the Doppler effect, with the shortest wavelength on the left and longer wavelengths on the right.

The same effect is observed with light, when an object is moving towards or away from observers located on the Earth. We can detect this motion in the spectrum of the star.

If the star is moving *away* from the Earth, the light waves are stretched out and the whole spectra experiences a shift towards the red end of the spectrum – a **red shift**. If the star is moving *towards* the Earth, the light waves are bunched up and the spectra experiences a shift towards the blue end of the spectrum – a **blue shift**.

We can measure comparing an observed wavelength to a rest wavelength. For example, the rest wavelength for H α (when there is no Doppler Effect) is 6563Å, 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:

$$z = (\text{observed wavelength/rest wavelength}) - 1$$

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 a stable, unchanging stage on which astronomical events played themselves out. But then, in the early 1900s scientists made several discoveries that defied easy explanation. These discoveries came together in the mind of an astronomer named Edwin Hubble, who explained all of them in 1929 with the expanding universe theory.

The discovery of the expanding universe was, like more discoveries, a combined effort. In the early 1900s an American astronomer called Vesto Slipher studied the spectra of a number of "fuzzy objects" believed to be nebula (we now know many of them were separate galaxies). He noticed that many of them were redshifted, which meant they were moving away from us. Some of them were moving away from us at amazing speeds – for example the object we now know of as the Sombrero Galaxy was moving away from us at speeds of 4 million km per hour.



Portrait of Edwin Hubble

While Slipher made this discovery, in another part of the world Edwin Hubble was using the world biggest telescope (at the time) to measure the distance to astronomical object using creative new methods. Hubble then compared his measurements of distance, to Slipher's measurements of redshift and plotted the results – this plot is now known as the Hubble Diagram.

The Hubble diagram demonstrated that a galaxy's redshift increased linearly with its distance from Earth. The farther away a galaxy is, the faster it moves away from us.

The simplest explanation for Hubble's observation was that the entire universe is expanding, just as Einstein's equations predicted it should. 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.

Introduction

In this activity students will follow the steps on the student handout to plot the famous Hubble Diagram to demonstrate the expanding Universe, beginning by determining the redshift for 10 Type Ia supernovae, from which they will derive the radial velocity for each supernova. They will then calculate the distance to each supernova and use the two values to plot the famous Hubble Diagram.

Once they have plotted the Hubble Diagram, your students will study their results and hopefully come to the conclusions that Hubble reached, now known as Hubble's Law. Hubble's law is the name for the observation in physical cosmology that: (1) objects observed in deep space (extragalactic space which is more than 10 Mpc) are found to have a Doppler shift that can be used to calculate their relative velocity away from the Earth; and (2) that the velocity, of various objects receding from the Earth, is approximately proportional to their distance from the Earth. This is normally interpreted as a direct observation of the expansion of the Universe.

The expansion of the Universe was first proposed by Georges Lemaître in 1927, he also suggested an estimated value of the rate of expansion, now called the Hubble Constant. Hubble also calculated a value for the Hubble Constant just two years later, he put it at around 500 km/s/Mpc. We now know this was incorrect. Based on the latest results, the Hubble Constant is believed to be 73 km/s/Mpc.

In this activity your students will also calculate the Hubble Constant based on their own Hubble Diagram.

Instructions

In this activity you will begin by selecting ten different Type Ia supernovae. Using their spectra, you will calculate their redshift before using your results to derive the radial velocity for each supernova. Next, you will calculate the distance to each of your objects before using these two values to plot the famous Hubble Diagram.

I. Finding Redshift

1. Begin by opening the Hubble Diagram worksheet in the spreadsheet software of your choice.
2. Then open your web browser and go to: <https://wiserep.weizmann.ac.il/search/spectra>

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

3. You can ignore all fields on the first page apart from **Obj Type**, for which you should select **SN Ia** from the dropdown list, and **Instrument/s**, for which you should select **FTS /**

FLOYDS-S or **FTN / FLOYDS-N** This is an instrument upon one of the LCO telescopes in Australia.

The screenshot shows the 'Spectra search' interface. At the top, there are two tabs: 'Object search' and 'Spectra search'. Below the tabs, there are several search filters:

- Obj. Name:** A text input field.
- Exact match:** A checkbox.
- Public:** A dropdown menu set to 'All'.
- Added within the last:** A dropdown menu set to '0' and a 'Days' label.
- Obj. Type:** A dropdown menu with options: SN I-rapid, SN Ia, SN Ia-91bu-like, SN Ia-91T-like. This field is highlighted with a red box.
- Type Family:** A dropdown menu with options: CV, Galaxy, Gap, High-Energy.
- Instrument/s:** A dropdown menu with options: FTN / EM01, FTN / FLOYDS-N, FTN / FS02, FTS / FLOYDS-S. This field is highlighted with a red box.
- Spec. Type/s:** A dropdown menu with options: Object, Host, Sky, Area.
- Quality:** A dropdown menu with options: Low, Medium, High.
- Source Group/s:** A dropdown menu with options: None, ASAS-SN, Aasn0, RRNP.
- Min spec. no. / obj.:** A text input field.
- Redshift Range:** Two text input fields separated by 'to'.
- Obs-date:** Two text input fields separated by 'to', with examples 'E.g., 2018-10-30' below.
- Advanced search:** A link with a right-pointing arrow.
- Submit:** A blue button.
- Show phase W.R.T.:** A dropdown menu set to 'Peak-light'.
- Results in page:** A dropdown menu set to '50'.
- Show spectra plots:** A checkbox that is checked, highlighted with a red box.

5. You will see a supernova spectrum. Careful analysis of spectra like this can reveal many things about an object, including temperature, density and chemical composition. The WISerEP archive calculates redshift using spectra, which can tell us how a supernova is moving relative to us.

6. Above the graph you will notice a table showing the object name and redshift, among other information. On your worksheet note down the name of the supernova (**Obj. IAU Name**), the Instrument (**Tel/ Inst**) and the redshift.

7. Repeat **Step 5** until you have the details of 10 different supernovae on your worksheet.

5. You can now calculate how much each supernova is shifted and the speed it is moving away from or toward us (its Radial Velocity) in the following way. Where z is redshift:

$$z = (\text{observed wavelength/rest wavelength}) - 1$$

6. Round your answers to 3 decimal places and note them on your worksheet where indicated.

Question: Referring back to the redshift provided by WISEREP, is it that same as your redshift for each of your supernova?

III. Calculating Radial Velocity

Using the redshift values you have calculated, we are now able to derive the radial velocity for each supernova using the simple equation:

$$\text{radial velocity} = \text{redshift} \times \text{speed of light}$$

1. Given that the speed of light is approximately 300,000 km/s, calculate the radial velocity for each of your supernovae and add the values to your worksheet.

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

$$\text{radial velocity} = 0.025 \times 300000 = 7500 \text{ km/s}$$

Note: This equation only works for redshift smaller than $z = 1.0$.

Discussion question: You may have noticed that all your redshift figures are positive. What would it mean if your redshift were negative?

IV. Measuring Distance

The final piece of information we need to plot our Hubble Diagram is the distance to each supernovae. Measuring distances in space is a daunting task. One method of measuring distances is to use an object with a known absolute magnitude (M), we call these Standard Candles. Type Ia supernovae are standard candles.

Type Ia supernovae happen when a white dwarf star reaches 1.4 solar masses causing a nuclear chain reaction to occur that causes the star to explode. This chain reaction always happens in the same way and at the same mass, which means the brightness of Type Ia supernovae is always the same, a peak light output approximately equivalent to an absolute blue sensitive magnitude of **-19.6**.

Apparent magnitude (m) is how bright an object appears in the sky, this is a function of both its actual light output, known as its *absolute magnitude (M)*, and its distance from the observer. If we have values for the former two, we are able to calculate the latter.

Once m is known, the distance modulus function can be used to calculate the distance to the Type Ia supernova in parsecs (pc):

$$m - M = 5 \log d - 5$$

Rearranged:

$$d = 10^{(m - M + 5)/5} \text{ pc}$$

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. This data is from the Open Supernova Catalog: <https://sne.space/>

If the B-band magnitude for your supernovae has not been provided, go to the Open Supernova Catalog homepage and enter your object name into the **Search** field.

There is a column in the table called **B-band max (mag)** this shows the maximum apparent magnitude (m) for each supernovae.

2. Make a note of the b-band max magnitude value down on your table.

The screenshot shows the homepage of 'The Open Supernova Catalog'. The navigation bar includes links for Catalog, About, Contribute, Derivations, Statistics, Download, API, Bibliography, and Links. A search bar at the top right contains the text 'Search: SN2018dhw'. Below the search bar, there is a table of supernovae. The table has columns for Name, Dist. Date, mag, Host Name, R.A., Dec., z, Type, Phot., Spec., Radio, and X-ray. The first row shows SN2018dhw with a date of 2018/07/04 and a magnitude of 17.22, which is highlighted with a red box. Below the table, there are options for 'Observable from' and 'Has' pre/post-max photometry and spectroscopy.

Note: If you still cannot locate the B-band maximum magnitude for your chosen supernova, return to section I. **Finding Redshift** and select new supernovae for which you have the B-band magnitude.

3. Now that you have the apparent magnitude you can use the distance modulus above to calculate the distance to each supernova in parsecs. Enter your results on your worksheet.

4. Finally, convert your distances into megaparsecs (Mpc). A megaparsec is a million parsecs. Enter your results on your worksheet.

Alternatively, enter **m** and **M** for your supernovae where indicated on the '**Calculations**' tab of your worksheet and the distance will be automatically calculated in Mpc.

Plotting a Hubble Diagram

1. Once you have worked through all of the previous steps you will be ready to plot your Hubble diagram. A Hubble diagram is a plot of radial velocity against distance (Mpc). Create the graph using your chosen spreadsheet software. If you are not familiar with plotting graphs in your spreadsheet software, you can use the Blank Graph template to plot the data points by hand.

2. The radial velocities should be plotted in kilometres per second on the Y-axis against distance in megaparsecs (Mpc) on the X-axis.

3. Once you have plotted the data for your supernovae, draw a straight line through the data points, going through as many as possible. The line should also go through zero.

Estimating the Hubble Constant

This line allows you to make an estimate of the Hubble constant. The Hubble constant is the gradient of this line.

The Hubble constant (H_0) is one of the most important numbers in cosmology because it can be used to estimate the size and age of the Universe. The Hubble constant indicates the rate at which the Universe is currently expanding, so although it is called a 'constant' it changes with time.

The Hubble constant is given by:

$$H_0 = v/d$$

Where v is the radial velocity, d is the distance and the 0 denotes that the number derived is the Hubble constant at the present time. The value for the Hubble constant is given in kilometres per second per mega parsec (Mpc).

1. Now, calculate the Hubble Constant. Simply pick any point on the line and read off the position along the y-axis and the x-axis for that point and then divide them as shown

above to find out the Hubble constant in terms of kilometres per second per mega parsec. Add the value to your worksheet where indicated.

You've now successfully determined the rate of the expansion of the Universe!

Conclusion

Now that you have a value for the Hubble constant, one simple thing you can do to wrap up the activity is estimate the age of the Universe. This can be done by finding the inverse of the value of H_0 .

If the Universe has been expanding at a constant speed since its beginning, the Universe's age would simply be $1/H_0$.

1. Calculate the age of the Universe using your value for the Hubble Constant.
2. Next, multiply your answer by 3.09×10^{19} km/Mpc to cancel the distance units. You now have the age of the Universe in seconds!
3. Divide this number by the number of seconds in a year: 3.16×10^7 sec/yr
4. Now you have worked out the age of the Universe in years using real observational data!

Evaluation

Ask the students to answer the following questions.

1. Compare your maximum age for the Universe to:
 - a. the age of the Sun (~5 billion years)
 - b. the age of the oldest stars in the Milky Way (~12.5 billion years)
2. What would happen to the calculated age of the Universe if the Hubble constant were:
 - a. larger than you found
 - b. smaller than you found
3. Why does the best-fit line to your data need to go through the origin of your graph? Where is this "origin" located in the Universe?
4. Theoretically, your plot should be a straight line, but it probably isn't. Consider and write down a few of the possible sources of error.

5. How does your result for the age of the Universe compare with other ages that have been proposed? (The Hubble Constant is currently considered to be 67.8 km/s/Mpc.)