Chapter 11

Supernovae and the Hubble Constant

11.1 Purpose

Type Ia supernovae will be used to measure the distance to several galaxies. Using published red-shift data, a value of Hubble’s constant will be determined.

11.2 Introduction

11.2.1 The Expansion of Space-time and the Hubble Constant

The first evidence that the Universe was expanding was discovered in 1912 by V. M. Slipher. Using a spectroscope attached to a 24-inch telescope in Flagstaff, AZ, Slipher noticed that the absorption lines in the spectrum emitted by a distant galaxy had a pronounced wavelength shift toward the red end of the spectrum. At that time, this red-shift was thought to arise from the well-known Doppler Effect. When light is emitted from moving object, the observed wavelength of the light is seen to increase when the motion is away from the observer and the light is said to be red-shifted. When the motion is towards the observer, the wavelength of the light is seen to decrease and is said to be blue-shifted.

This effect is analogous to the change in pitch of a whistle on a moving train, which is heard to increase when the train is approaching and decrease when the train is receding. By measuring the change in pitch, one can calculate the speed and direction of a moving train. Similarly, by using Einstein’s Theory of Special Relativity, the velocity of a moving...
object emitting photons can be calculated by measuring the wavelength shift of the observed photons.

Slipher observed the spectra of many different galaxies and found that almost all of them were shifted towards the red end of the spectrum. This implied that almost all of the galaxies surrounding our Milky Way were receding. Assuming that the Earth does not sit at a special place in the Universe, astronomers hypothesized that this could be most easily explained if the whole Universe was expanding!

Although even today this red-shifting is quite erroneously characterized as due to a ‘velocity of recession’, it is now known that it arises instead from the expansion of space-time. The red-shifting of light from a distant galaxy is due only to the change in size of the Universe between the time the light is emitted and the time it is observed. For example, if the Universe doubles in size during this time then the photon’s wavelength will also double, irrespective of the velocity of any apparent motions between galaxies. Another way to consider this is that the photon is stretched as it travels through the expanding Universe. If the Universe were contracting during its journey, the photon would be squeezed and blue-shifted.

The red-shifting of light from distant galaxies is then more accurately described as a **Cosmological Red-shift**. Although it is true that since the Universe is expanding, the distance between galaxies is steadily increasing, it is only in a naive sense that one can say that the galaxies have a relative velocity. All galaxies are effectively at rest with respect to space with regard to this effect, and the red-shift is due to the expansion.

The change between the observed and emitted wavelength can be written as:

\[
\Delta \lambda = \lambda_{\text{observed}} - \lambda_{\text{emitted}}
\]  

This change can be expressed independently of wavelength by dividing through by the wavelength and arriving at a new quantity, \( z \), which is called the **red-shift of the galaxy**:

\[
z = \frac{\Delta \lambda}{\lambda_{\text{emitted}}} = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}
\]

Notice that \( z \) is a pure, dimensionless number.

Unfortunately, when Edwin Hubble combined his own measurements with Slipher’s, he decided to multiply \( z \) by the speed of light, \( c \), and called this product the ‘recession velocity’ as mentioned above:

\[
v = c \cdot z
\]

At least for relatively nearby galaxies (nearby on a cosmological scale), the red-shift of a galaxy is linearly proportional to its distance away. i.e., \( z = h \cdot D \), where \( z \) is the redshift, \( h \) is a constant of proportionality and \( D \) is the distance.

Multiplying this equation by \( c \) on both sides (and redefining \( H_0 \equiv c \cdot h \), which is just another constant) yields:

\[
v = H_0 \cdot D,
\]  

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where $H_0$ is called *Hubble’s Constant*.

### 11.2.2 Type Ia Supernova and Galactic Distances

A Supernova is a star that explodes violently. A supernova explosion produces enormous amounts of energy. Estimates are that only one or two supernova occur in the Milky Way galaxy each century. Some historical supernovae could be seen during daylight hours. The last supernova to be visible to the naked eye was the SN 1987A supernova which could be seen from the Southern Hemisphere. SN 1987A did not occur in the Milky Way galaxy but in the Large Magellanic Cloud, a galaxy near the Milky Way.

Supernova are classified according to their emission lines. Type II supernova have hydrogen in their emission lines in their spectra. Type I supernova have little or no hydrogen in their spectra. This implies that type II supernova are young massive stars that have ample hydrogen in their atmospheres when they explode. Only the other hand, Type II having no hydrogen lines which tells us the star has fused the hydrogen in their atmosphere to other elements and have completed their life cycle.

A white dwarf is an earth-size star made mostly of C and O nuclei that is at the end of its life cycle. All of the hydrogen in a white dwarf has been fused into carbon and oxygen. In effect the white dwarf star is a hot ball of carbon and oxygen nuclei and electrons. The gravity of a white dwarf is opposed by electron degeneracy pressure. This is a quantum mechanical effect due to the Pauli exclusion principle. The upper mass limit for a star which can resist gravitation collapse with electron degeneracy pressure is of $1.44 \, M_\odot$. This limit is known as Chandrasekhar’s Limit. Normally, the white dwarf star will slowly cool off.

Type Ia supernova are though to result from the thermonuclear explosion of a white dwarf star. This may sound contradictory since a white dwarf has consumed all of its fuel. If the white dwarf is in a close binary system with a red giant star, the white dwarf can pull material from the larger companion. Then the mass of the white dwarf can suddenly exceed the Chandrasekhar limit. The result is a rapid thermonuclear reaction that fuses the carbon and oxygen into nickel. Within a few seconds, the white dwarf has been completely destroyed. Type Ia supernovae are very uniform and easy to calibrate the light curve since the amount of energy produced when $1.44 \, M_\odot$ of C and O nuclei fuse. They are useful to astronomers as distance indicators.

In this lab, we will use the light curve of Type Ia several supernovae to measure distances to other galaxies. With these distances and red-shift data, we will make an estimate of the Hubble constant.

### 11.3 Procedure

In this lab procedure, we will use the 'The Supernova Light Curve Fitting Explorer' software shown in Fig 11.1. In a web browser, open the class web page, select 'software' on the top
menu. Open the 'The Supernova Light Curve Fitting Explorer' link.

![Image of Supernova Light Curve Fitting Explorer software]

Figure 11.1: The Supernova Light Curve Fitting Explorer software

1. Check the 'show horizontal line' box. Use the pull down menu to select one of the supernova listed in the data table.

2. If you click and drag the white area of the plot area, you can drag the supernova data points to align with the standard light curve for a type 1a supernova. The data points can be moved in the horizontal and vertical. Align the data points for the best fit of the data to the standard curve.

3. Align the horizontal bar at the peak of the curve. The horizontal bar can be moved by dragging either indicator on the side scales.

4. Input the values of the absolute and relative magnitude from the horizontal bar into the 'Distance Modulus Calculator' box at the bottom. Record the value of the distance in the data table.

5. Calculate the radial speed of the supernova using the value of the red-shift ($z$) in the table and equation 11.3

6. Using the data in the data table, make a plot with the radial speed on the vertical scale and the distance on the horizontal scale. Be sure to make a proper graph with axis labels and a title. Graph paper is provided at the end of this lab section.

7. Using a ruler and your eye, make a 'best fit' straight line to the data points. Do not
Supernova | red-shift (z) | Radial Speed (km/s) | Distance (Mpc) \\
--- | --- | --- | --- \\
1995D | 0.0066 | | \\
1999aa | 0.0157 | | \\
1999dq | 0.0136 | | \\
1998aq | 0.0045 | | \\
1999ee | 0.0114 | | \\
1994ae | 0.004 | | \\

Table 11.1: Data Table

‘connect the dots’. Determine the slope of the line. The slope of the line is the Hubble constant, $H_o$. Record the value below.

$H_o$ __________

11.3.1 Questions

1. The units of the Hubble constant are $\frac{km/s}{Mpc}$ or $\frac{km}{s \cdot Mpc}$. Since a km and a Mpc are both units of distance, dimensional analysis tells us the Hubble constant has units of $\frac{1}{time}$.

Using 1 pc = $3.1 \times 10^{13}$ km, Mpc = $10^6$ pc, and 1 year = $3.2 \times 10^7$ second, convert your value of the Hubble constant to units of $\frac{1}{year}$. Now determine $\frac{1}{H_o}$. What does $\frac{1}{H_o}$ tell us about the universe?

11.4 Conclusion

Write a conclusion about what you have learned. Include all relevant numbers you have measured with errors. Sources of error should also be included.