Hubble's Expansion of the Universe

How we can use type Ia supernovae to calculate the expansion of the Universe

Introduction

Galaxies were first identified in the 17th Century by the French astronomer Charles Messier, although at the time, he did not know what they were. Messier, a keen observer of comets, spotted a number of other fuzzy objects in the sky which he knew were not comets. Worried that other comet hunters might be similarly confused, he compiled a list to prevent their misidentification. Messier's list (where objects are identified by M for Messier, followed by a number, e.g. M51) contained information on 110 star clusters and "spiral nebulae" (see Figure 1). It wasn't for almost another 300 years that astronomers worked out that the "spiral nebulae" were galaxies.

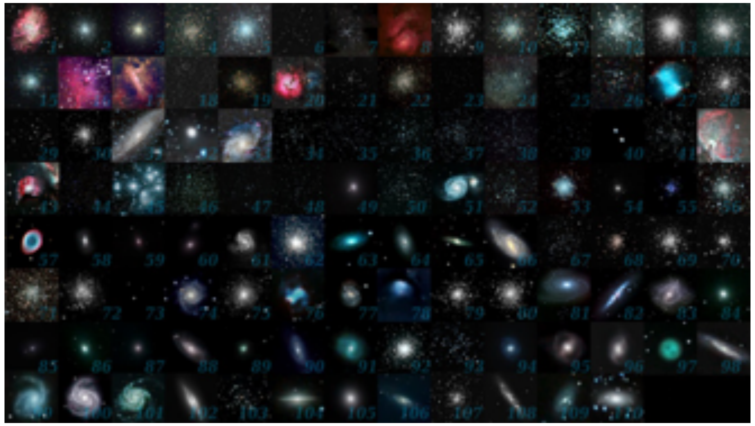

Figure 1 – A collage of observations of all 110 Messier object compiled by an amateur astronomer. Credit: Michael A. Phillips

Some people argued that these nebulae were "island universes" – objects like our Milky Way galaxy, but external to it. Others disagreed, thinking that these spiral objects were clouds of gas within our Milky Way galaxy, believing that our galaxy was the only one in the Universe. This argument continued into the 1920s, until the American astronomy Edwin Hubble measured the distance to one of these "spiral nebulae".

Hubble's Discovery

Some stars are seen to vary in brightness periodically. These are called Cepheid variables and were discovered by an American astronomer, Henrietta Leavitt in the early 1900's.

Leavitt learnt that there was a relationship between their variation period and their luminosity. This is now known as the period-luminosity (P-L) relationship where the longer the period, the more luminous the star.

A few years later, astronomer Harlow Shapley successfully calibrated Leavitt's relation and produced actual values for the luminosity side of the P-L relationship. This provides us with a true brightness for the stars, allowing us to calculate their distance. By measuring the star's apparent brightness from Earth and comparing this to its true brightness, we can assume that the difference is due to how far away the star lies from Earth.

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In 1923 Hubble used this methodology when he was studying a Cepheid variable in M31, the Andromeda Galaxy. Through calculating the distance, he discovered that it was located outside of our Milky Way galaxy. He finally ended the debate on the nature of these "spiral nebulae", proving they were in fact distant galaxies similar to the Milky Way.

Hubble continued his studies of galaxies, using this method of distance measurement, before publishing his results in 1929. In his paper, Hubble plotted a graph of the radial velocity of galaxies against their distances similar to that shown in Figure 2. Here, each point on the graph represents a galaxy.

Image Credit: By Adam Evans - M31, the Andromeda Galaxy

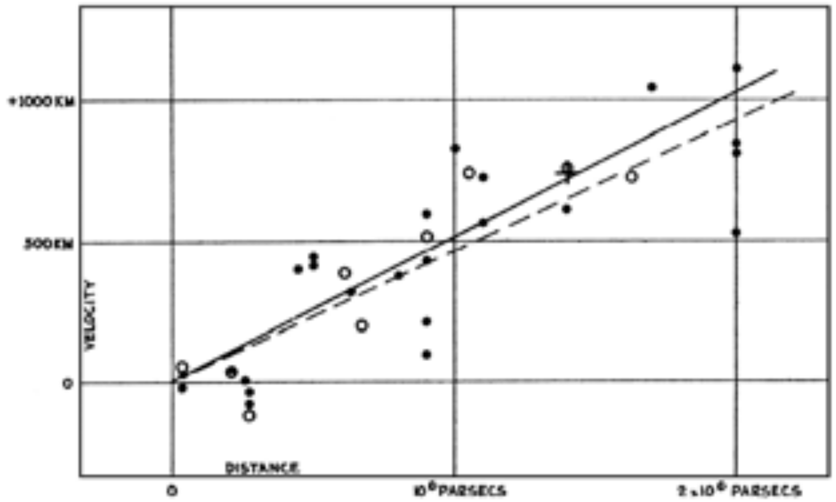

Figure 2 – An example of the Hubble diagram displaying galaxy distance on the x-axis and galaxy radial velocity on the y-axis

Hubble's plot showed not only that most galaxies are moving away from us, but also that they were moving at different speeds. From the diagram it can be seen that radial velocity is proportional to distance – distant galaxies are moving away from Earth faster than nearby ones. This became known as Hubble's Law.

Distances with Type Ia Supernovae

As we go further out into the Universe, eventually we are no longer able to use Cepheid variables as a distance indicator as they become too faint. At this point, we use another object known as type Ia supernovae.

A supernova marks the end of a star's life in an extremely energetic explosion. When a supernova explodes, its light intensity brightens to a peak, and then gradually fades over time.

For one particular classification, type Ia supernovae, this peak always reaches the same true brightness (absolute magnitude). So if we measure how bright they appear from Earth (apparent magnitude), we can compare this with their known absolute magnitude. Much like with the Cepheid variables, we can assume that the difference between the two values is due to distance.

Obtaining Radial Velocity

We now know how to calculate the distance to these supernovae, but how do we calculate their radial velocity? The radial velocity of a galaxy describes how quickly it is moving towards or away from Earth. All stars and supernovae are located within a host galaxy, just like the Sun sits within the Milky Way galaxy.

Radial velocity can be calculated by measuring the Doppler shift in a galaxy's spectra. Think about when an ambulance drives past you. As the ambulance approaches you, the siren becomes higher in pitch; once it passes and moves further away, the pitch becomes lower.

This is caused by a change in frequency and wavelength of the sound wave. We call this the Doppler effect, and it's noted by a stationary observer.

This doesn't just happen with sound however - the same occurs for a light source. The observed wavelength of a light source will decrease as it approaches and increase as it moves away. We call this blueshift (towards) and redshift (away).

The equation below describes the relationship between the speed of light, its frequency and its wavelength.

$$c = f\lambda$$

Where:
c = speed of light (3.00 x 108 m s-1) f = frequency (Hz) λ = wavelength (m)

Figure 3 shows how wavelength varies across the visible light spectrum.

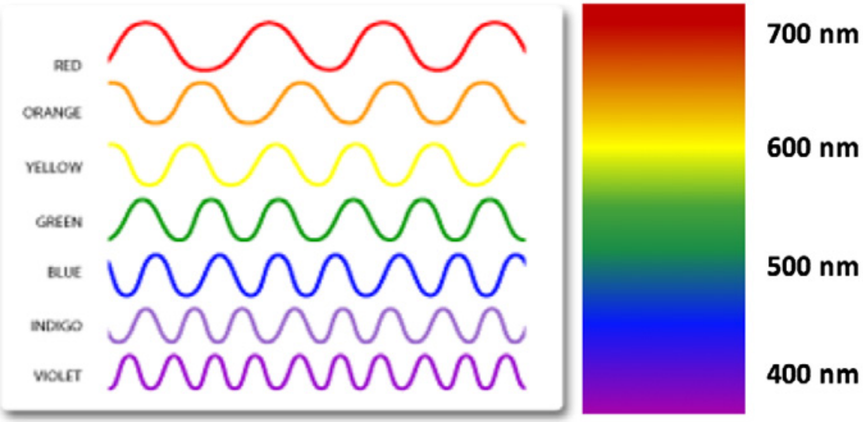

Figure 3 – Representations of the different wavelengths of light, with red having a longer wavelength and violet having a shorter wavelength.

The Universe is currently thought to be expanding. Since in figure 4 (right), galaxy B is further away, its measured wavelength will be greater than galaxy A and its frequency will be lower. Therefore its light will be shifted more towards the red end of the visible spectrum.

Figure 4 – Two galaxies located at different distances from Earth. (NOT TO SCALE)

The equation below describes the relationship between the speed of light, its frequency and its wavelength.

$$z = \frac{\lambda - \lambda_0}{\lambda_0}$$

Where:
z = redshift λ_0 = un-shifted wavelength of spectral line
λ = wavelength of observed spectral line

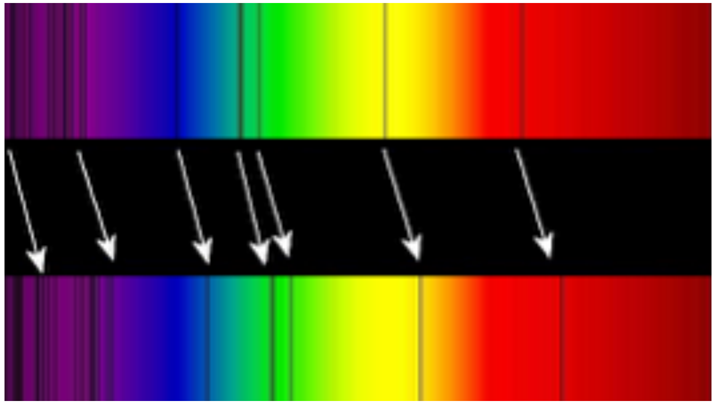

Figure 5 – An un-shifted (top) and redshifted spectrum (bottom)

Using this value of redshift, we can then calculate the radial velocity of the galaxy according to:

$$z = \frac{v}{c} \rightarrow v = zc$$

Where:
z = redshift   v = radial velocity (m s^{-1})   c = speed of light (3.00×10^8 m s^{-1})

Once you have values for both radial velocity and distance for multiple galaxies, you can begin to produce a plot like Hubble's in Figure 2.

The line of best fit on this type of plot is linear (straight). By calculating the gradient of this line, we obtain a value that describes the rate at which the Universe is expanding. This is known as the Hubble constant.

The Hubble constant, radial velocity and distance are related according to:

$$v = \frac{H_0}{d}$$

Where:
v = radial velocity (km s^{-1}) H_0 = Hubble constant (km s^{-1} Mpc^{-1})
d = distance to the galaxy (Mpc)

Once we have calculated the Hubble constant (the Universe expansion rate), we can calculate how old the Universe is with a simple velocity, distance and time calculation.

Image Credits:

Messier Catalogue: By Michael A. Phillips - http://astromaphilli14.blogspot.com.br/p/m.html official blog, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=38121043

Andromeda Galaxy: By Adam Evans - M31, the Andromeda Galaxy (now with h-alpha) Uploaded by NotFromUtrecht, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=12654493