The Age of the Universe

Physics 210 – Laboratory 3

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Introduction

The universe is believed to have started from a point of space-time thought to be similar to a singularity. It exploded into existence in a *big bang*, and since then all matter has been expanding. From our frame of reference the rest of the universe appears to be moving away from us. Either we are at the centre of an expanding universe or everything everywhere is expanding away from its neighbours. If the big bang theory is believed to be true (which it commonly is) then the second argument is the correct one.

A quick thought experiment. Suppose a universe was 1 metre in diameter, an observer on one side of the *proto universe* would easily see the other side with no noticeable delay. Now suppose that this universe has expanded to a diameter of 10 billion meters, a distance impossible to comprehend, the observer would now notice a significant delay in her observation of the other side of the universe. This effect is due to the finite speed of light. From the edge of our observable universe it takes light approximately 15 billion years to reach earth, so anything we observe at that distance happened 15 billion years ago, or in other words close to the beginning of the universe.

It took cosmologists half a century to grasp the full cosmological importance of a finite speed of light. It divides the universe into two parts: visible and invisible. At any time there is a spherical “horizon” around us, defined by the distance light has been able to travel since the universe began. As time passes, this horizon expands. Today, it is about 15 billion light years away.

As the universe exploded from the big bang it was accelerated. Matter further from the earth has had more time to accelerate and as such has a greater velocity, also true for galaxies, which were observed in this experiment.

A greater velocity results in a larger *redshift* of any electromagnetic waves emitted from an object, such that all the wavelengths would be shifted to a longer wavelength (or towards the *red* end of the spectrum). This is due to the Doppler effect. From the redshift of absorption and emission lines in a galaxies’ spectrum it is possible to deduce the velocity that it is receding. In this experiment the H and K Calcium lines were used, which normally appear at 3968.847 Å and 3933.67 Å respectively. The Hubble constant can then be derived from the linear trend of the velocity of a number of galaxies. Once an approximation of the Hubble constant is known an estimate on the age of the universe is just another small step.

Definitions

Absolute Magnitude	The magnitude a star would have if it were precisely 10 parsecs away from the sun.
Angstrom Å	The unit normally used to measure wavelengths of visible and ultraviolet light. One angstrom is 10^{-8} Cm.
Apparent Magnitude	The observed magnitude of a star or other object as seen from earth.
Big Bang	A term referring to any theory of cosmology in which the universe began at a single point, and has been expanding from that state since.
Doppler Shift	The observed shift in wavelength (and frequency) of a wave due to the relative motion between the source of the wave and the observer.
Hubble Constant	The numerical factor which describes the rate of expansion of the universe.
Light year	A unit of distance. The distance light has travelled in one earth year.

Neutron Star	A very compact, dense remnant whose interior consists entirely of neutrons, which is supported against collapse by degenerate neutron gas pressure.
Parsec	The distance to a star if it has a parallax of 1 arcsecond. 3.03 x 10^{13} km. A mega parsec is 1 x 10^{6} parsec
Photon	A particle of light having wave properties but also acting as a discrete unit.
Pulsar	An object that emits brief periodic pulses of radio energy, possibly a neutron star spinning very rapidly.
Redshift	The shifting of spectral lines toward the red end of the spectrum due to the relative motion of the source away from the observer.
Relativistic	When Einstein's theory of relativity is used rather than classical theories. eg if an object is moving >1% speed of light.
Singularity	A point in space-time of infinite density.
Spectra	An arrangement of electromagnetic radiation according to wavelength.
Signal-to-noise	Is an indication of the amount of noise relative to the signal you want to measure. A value higher than 10 gives a fairly precise trace of the spectra when measuring stellar spectra.

Quasar	A starlike object that has a very large redshift, is thought to be very distant, probably a galaxy emitting much more energy that is normal.
Wavelength	The distance between wavecrests in any type of Wave.

Results

To calculate the distance to a galaxy the following equation was used

$$\text{Log D} = \frac{m - M + 5}{5}$$

Where m is the apparent magnitude, which is measured. M is the absolute magnitude, which is *assumed.* D is the distance.

The wavelengths of the K and H lines of calcium were measured from the spectra of each galaxy. Spectra were obtained by collecting enough photons from the telescope to get a signal/noise ratio of 10 or greater on the spectrometer. These measured results were compared with the wavelengths of K and H lines obtained in the laboratory *(with no Doppler shift)* to calculate the velocity that the galaxy is receding using the following equation.

$$v = c\frac{\Delta\lambda}{\lambda} \qquad \text{where} \qquad \Delta\lambda = \lambda_{measured} - \lambda$$

Where v is the velocity of the galaxy, c is the speed of light, λ is the wavelength with no Doppler shift and Δλ is the difference between the measured wavelength and the laboratory wavelength.

The relativistic velocity was calculated using the following equation.

$$v = c\left[\frac{(z+1)-1}{(z+1)+1}\right] \qquad \text{where} \qquad z = \frac{\Delta\lambda}{\lambda}$$

Where the variables are the same as above. The relativistic velocity uses Einstein's Theory of General Relativity rather than Classical Theory to obtain a more accurate approximation when the velocity of the galaxy is greater than 1% of the speed of light. 1% the speed of light is 2998 km/s which all the measured galaxies at moving faster than.

Distance & Magnitude Measurements of Galaxy

Galaxy	*Photon Count*	*Abs Mag*	*App Mag*	*Distance (Mpc)*
Coma1	1245978	-22.00	12.80	91.20
uma1-1	304413	-22.00	14.50	199.53
CrBor1	111526	-22.00	15.40	302.00
Boot1	92630	-22.00	16.50	501.19
uma2-1	418874	-22.00	16.60	524.81

Measurements of H & K Calcium Lines in Galaxy

Galaxy	$\lambda_{k\ measured}$	$\lambda_{h\ measured}$	$\Delta\lambda_k$	$\Delta\lambda_h$
Coma1	4022.00	4058.00	-88.33	-89.15
uma1-1	4136.00	4172.00	-202.33	-203.15
CrBor1	4220.00	4256.00	-286.33	-287.15
Boot1	4450.00	4490.00	-516.33	-521.15
uma2-1	4474.00	4514.00	-540.33	-545.15

Receding Velocity of Galaxy

Galaxy	*Velocity of K (km/s)*	*Velocity of H (km/s)*	*Avg Velocity (km/s)*
Coma1	6731.80	6734.30	6733.05
uma1-1	15419.95	15345.45	15382.70
CrBor1	21821.75	21690.51	21756.13
Boot1	39350.49	39366.03	39358.26
uma2-1	41179.58	41178.90	41179.24

Relativistic Receding Velocity of Galaxy

Galaxy	Velocity of K (km/s)	Velocity of H (km/s)	Avg Velocity (km/s)
Coma1	6807.36	6871.49	6839.43
uma1-1	15815.97	15881.91	15848.94
CrBor1	22613.69	22680.96	22647.32
Boot1	41907.69	42322.74	42115.21
uma2-1	43977.20	44394.34	44185.77

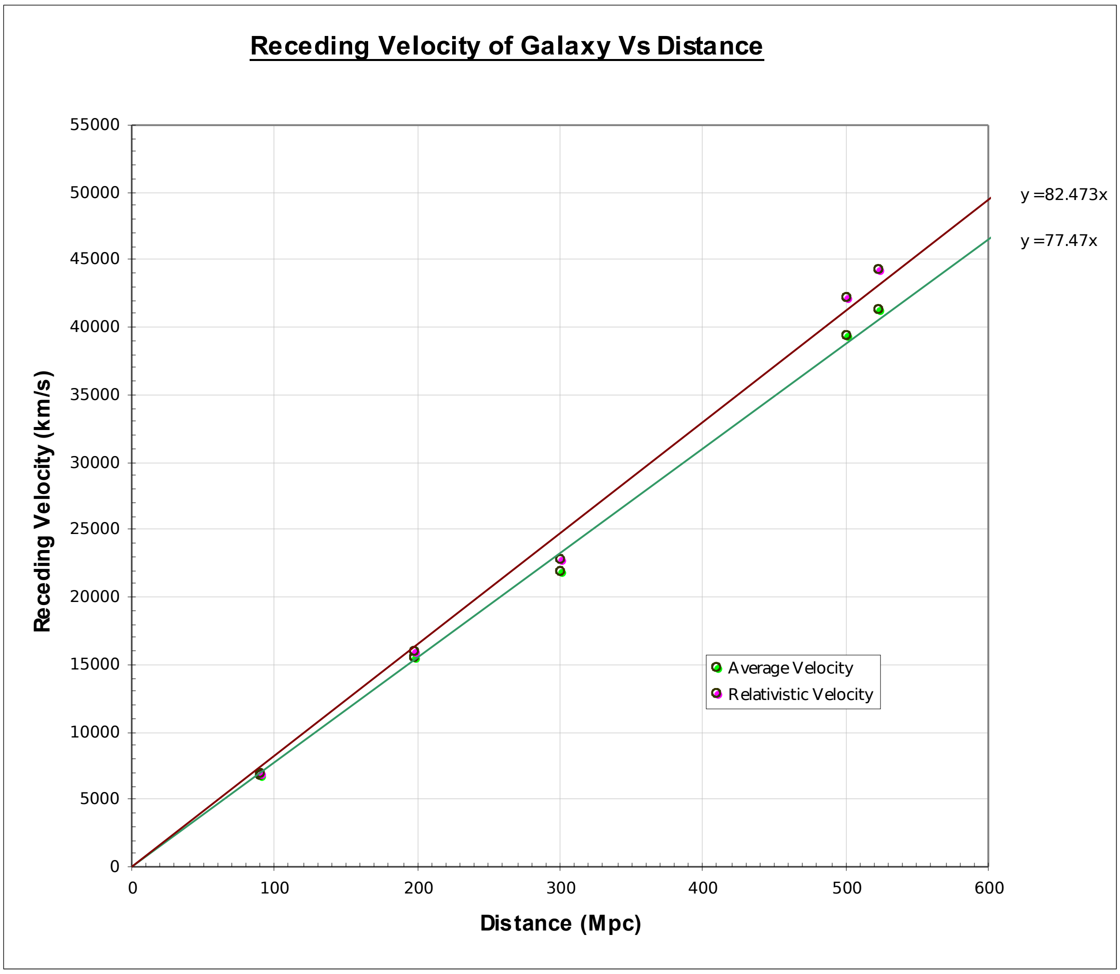
Physical Constants

Speed Light	299792458	m/s
λ_k	3933.67	Å
λ_h	3968.847	Å

Average Values of H

Average	77.47	km/s/mpc	*Determined from graph
Relativistic	82.47	km/s/mpc	*Determined from graph

* The velocity tables are absolute value. They are an indication of the galaxy receding at the given velocity not approaching, as a positive value could be interpreted as.



Determining the Age of the Universe

From the Hubble Law $H = \frac{v}{D}$ the velocity (v) of a galaxy at a certain distance (D) can be determined if the Hubble Constant (H) is known and *the law is assumed true.*

Velocity of a galaxy 800 Mpc away: 65978.4 km/s ♣

Converting mega parsecs to kilometres. (1 pc = $3.086 * 10^{13}$ km)

800 Mpc = $2.47 * 10^{22}$

The average relativistic value of the Hubble Constant determined previously was used.

To calculate the age of the Universe the relationship of

$$v = \frac{D}{t}$$

Where v is velocity, D is distance and t is time was used. If the appropriate units are used and the equation rearranged then the age of the universe can be determined.

Age of universe: $3.74 * 10^{17}$ s = $11.88 * 10^{9}$ years

The age of the universe is approximately **12 billion years** old.

Discussion

The determination of the age of the universe is full of assumptions. The largest cause of error in the calculation of the Hubble Constant, and therefore the age of the universe, was the assumption that all galaxies have an absolute magnitude of –22. Galaxies range down to an absolute magnitude of approximately –12. It would have been better to classify the galaxies according to type and used varying absolute magnitudes for each type analysed (E0 → Irregular). An absolute magnitude of –21 results in an error of +59% in the distance. Using an absolute magnitude of -23 gives an error of –37%. These are quite substantial errors. Which do have an effect on future calculations and should be taken into account. Not all distant objects would have the same absolute magnitude. For example quasar, which are very distant objects (receding at 94.3% the speed of light!) would have an absolute magnitude many times that of a pulsar or neutron star that are comparably distant.

A substantially shorter or longer integration time reduces the ability to discern the *signal* (spectra line) from the *noise*. It does not affect the wavelength that the line appears at.

The limited number of galaxies used in the experiment has limited the accuracy of determining the Hubble Constant. A larger number should most certainly been used.

The relativistic velocity calculation of the galaxies resulted in a slightly higher velocity than the Classical method and therefore a slightly younger age. Using the Hubble Constant derived from the classical calculation of velocity results in an age for the universe of 12.7 billion years, where the relativistic derivation of the Hubble Constant gives an age of 11.9 billion years.

At the edge of a galaxies' *disk* the velocity would be different from the centre. Due to the rotation of the galaxy one side of the disk would be approaching and the other side would be receding. This local velocity would be superimposed upon the radial velocity of the galaxy as it recedes from us, so the redshift on one side of the galaxy would be slightly greater and on the other side it would be slightly less. This would only apply if the galaxy were orientated *edge on* to the earth.♥

Besides the errors due to assumptions made about absolute magnitude the experiment was a success. The calculated age of the universe is a little low. The ages of the oldest stars puts a lower limit of about 14 billion years on the age of the universe, radioactive isotope studies yield ages of at least 9 to 16 billion years for our galaxy. A reasonable lower limit would be about 15 billion years. The most recent study completed concerning the Hubble Constant gives a value of 70±7 km/s/mpc. This value in an Einstein-de Sitter universe results in an age of 10 billion years, and with the uncertainty in H_0, a value of about 12 billion years is not out of the question <u>for this model</u>. But an age consistent with the implied lower limits would be closer to 15 billion years.

References

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♥ This is a method to determine the angular velocity of a galaxy.