AS1001:Extra-Galactic Astronomy

Lecture 8: The Universal Expansion

Hubble's Discovery

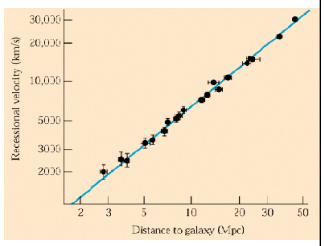
- Having shown M31 to be an external galaxy, Hubble took images and spectra of fainter galaxies.
- From photographic images he estimated distances using the brightest stars (Cepheids were not visible).
- For nearby galaxies he showed that the brightest star method works as a distance indicator and calibrated it to Andromeda
- From spectra he calculated the radial velocities of these galaxies
- Plotting distance versus velocity he found:

Hubble's Law

- Most galaxies recede
- More distant galaxies recede faster
- There is a linear relationship between velocity and distance:

$$v = H_o d$$

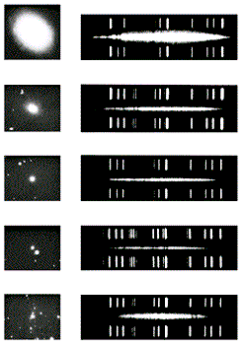
  - v = velocity (km/s)
  - d = distance (Mpc)
  - H_0 = The Hubble constant (km/s/Mpc)



Hubble's Data

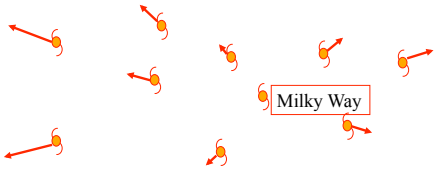
For 5 bright ellipticals in nearby clusters, fainter galaxies have Ca H & K lines further redshifted.

Assuming the brightest elliptical in a cluster is a "standard candle", we can see Hubble's law.



Universal Expansion

Hubble's law appears to violate the Copernican Principle as it seems to place us at a special location:



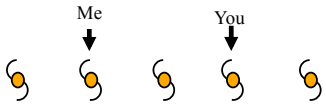
Is everything moving away from us?

Universal Expansion

Q) What is so special about our location ?

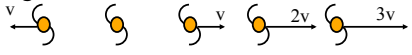
A) Nothing !

Consider:

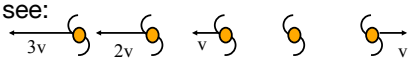


According to Hubble's Law:

I see:

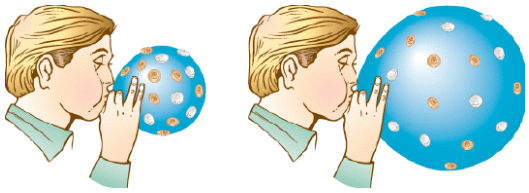


You see:



The Universal Expansion

- An observer in any galaxy will see all other galaxies moving away from it, with the same Hubble law.
- Expansion (or contraction) produces a centre-less but dynamic Universe.



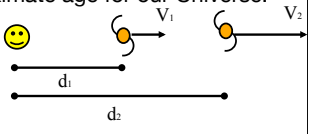
An Expanding Universe

Hubble's discovery resolves Olber's Paradox (and lets Einstein remove the Cosmological Constant from his equations).

It overturns the idea of permanency and provides an approximate age for our Universe.

Why ?

At what time would the receding galaxy be located at zero distance?
For Hubble's Law, this time is the same for all galaxies.

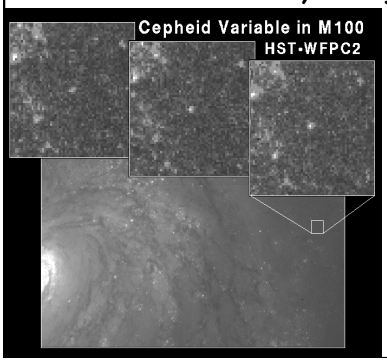


$$t_{Age} = \frac{d}{V} = \frac{d_1}{V_1} = \frac{d_2}{V_2} = \frac{1}{H_0}$$

The Hubble Constant

- The exact value of the Hubble Constant has been hotly debated since its discovery.
- Hubble measured $H_0 = 500$ km/s/Mpc.
- Hubble mistook RR Lyraes for Cepheids in most of his galaxies. When corrected, $H_0 = 100$ km/s/Mpc.
- *For several decades measurements using different "standard candles" gave 50 to 100 km/s/Mpc.*
- The Hubble Space Telescope (HST) was named after Hubble. Its primary goal was to measure H_0.

The HST Key Program



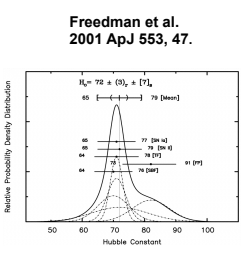
HST: designed to measure Cepheids in Virgo Cluster, galaxies, giving our first accurate value for H_0.

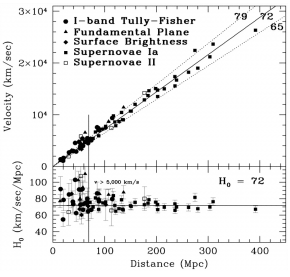
$H_0 = 72 \pm 8$ km/s/Mpc

HST Key Project

$H_0 \approx 72 \pm 3 \pm 7$ km s^{-1} Mpc^{-1}

Freedman et al.
2001 ApJ 553, 47.



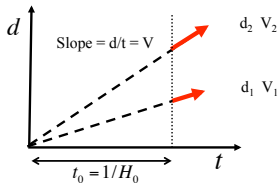


Hubble Expansion -> Finite age.

$V = H_0\, d$

$$t_0 \sim \frac{d}{V} = \frac{1}{H_0} = \left(\frac{1\,\text{Mpc}}{72\,\text{km/s}}\right)\left(\frac{3\times10^{19}\,\text{km}}{\text{Mpc}}\right)\left(\frac{1\,\text{yr}}{3\times10^{7}\,\text{s}}\right)$$

$$\approx 13\times10^{9}\,\text{yr} = 13\,\text{Gyr}.$$



Deceleration -> younger.

$V = H_0\, d$

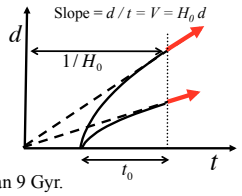
$$t_0 \sim \frac{d}{V} = \frac{1}{H_0} = \left(\frac{1\,\text{Mpc}}{72\,\text{km/s}}\right)\left(\frac{3\times10^{19}\,\text{km}}{\text{Mpc}}\right)\left(\frac{1\,\text{yr}}{3\times10^{7}\,\text{s}}\right)$$

$$\approx 13\times10^{9}\,\text{yr} = 13\,\text{Gyr}.$$

Gravity decelerates:

distance vs time: $d \propto t^{2/3}$

age: $t_0 \approx \frac{2}{3}\frac{1}{H_0} \sim 9\,\text{Gyr}.$



Problem: globular clusters older than 9 Gyr.

Acceleration --> older.

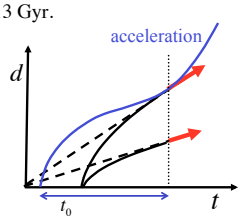
$V = H_0\, d$

$$t_0 \sim \frac{d}{V} = \frac{1}{H_0} = \left(\frac{1\,\text{Mpc}}{72\,\text{km/s}}\right)\left(\frac{3\times10^{19}\,\text{km}}{\text{Mpc}}\right)\left(\frac{1\,\text{yr}}{3\times10^{7}\,\text{s}}\right)$$

$$\approx 13\times10^{9}\,\text{yr} = 13\,\text{Gyr}.$$

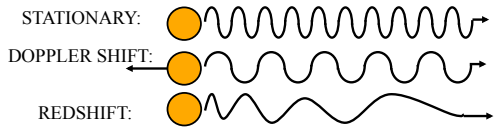
Gravity *decelerates*, but we observe an *acceleration*, attributed to "Dark Energy":

age: $t_0 \approx 13.7\,\text{Gyr} > \frac{2}{3}\frac{1}{H_0}.$



Cosmological Redshifts

- Expansion is a stretching of space-time.
- The more space-time there is between you and a galaxy, the faster it appears to be moving away.
- Expansion stretches the wavelength of light, causing a galaxy's spectrum to be REDSHIFTED:



REDSHIFT IS NOT THE SAME AS DOPPLER SHIFT

Observed Redshifts

- The observed redshift of a galaxy is:

$$z \equiv \frac{\lambda - \lambda_o}{\lambda_o} = \frac{\Delta\lambda}{\lambda_o}$$

λ = observed wavelength

λ_0 = lab wavelength

$\lambda = \lambda_0 (1+z)$

- Analogous to the Doppler shift:

$$z \equiv \frac{v}{c}$$

from which Hubble's law gives:

$$d = \frac{z\,c}{H_o}$$

- Redshift is NOT a Doppler shift:
  For $z > 1$ this would imply $v > c$!
  But OK for low-z ($z < 0.5$)

Calculating Distances

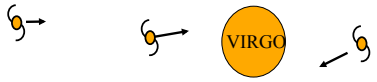
- Hubble's Law gives a distance from a galaxy's measured redshift.
- If H_0 = 75 km/s/Mpc and the redshift is z = 0.1, what is the distance ?

$$d = \frac{z\,c}{H_o} = \frac{0.1\left(3\times10^{5}\,\text{km/s}\right)}{75\,\text{km/s/Mpc}} = 400\,\text{Mpc}$$

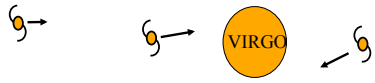
- For z = 0.1, the [O II] line, at λ_0 = 3727A, is redshifted to $\lambda = \lambda_0$ (1+z) = 4100A.

Peculiar Velocities

- Gravitational attraction causes galaxies to move.
  - MW and M31 are falling together.
  - The Local Group falls toward Virgo Cluster.
  - Virgo Cluster falls toward "The Great Attractor".
- Every galaxy has a **peculiar velocity** relative to the "**Hubble flow**".

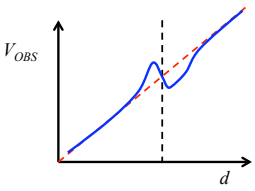


Peculiar Velocities



- We measure from spectra:

$$V_{OBS} = c\,z = c\,\frac{\lambda - \lambda_0}{\lambda_0}$$
$$= H_0\,d + V_{PEC}$$



Correcting for peculiar velocity

- MW falls toward a Virgo cluster galaxy:
  V_{pec} = -1000 km/s (approaching).
- Distance is d = 50 Mpc (from Cepheids)
- If the redshift, z = 0.01, what is H_0 ?

$$V_{OBS} = c\,z = H_0\,d + V_{PEC}$$
$$H_0 = \frac{c\,z - V_{PEC}}{d} = \frac{(3000 + 1000)\ \text{km/s}}{50\ \text{Mpc}}$$
$$H_0 = 80\ \text{km/s/Mpc}$$

Note: Take care with the sign of V_{PEC}.

It depends on the direction of the peculiar velocity:
(towards us $V_{PEC} < 0$, away $V_{PEC} > 0$.)