Hubble’s Law and the Distance Scale

Landmarks in our understanding of cosmic distances:

(1) Triangulation to determine the scale and dynamics of the solar system (Kepler)

(2) Parallax to determine the distances to the stars (Bessel)

(3) Period-luminosity relation of Cepheids/RR Lyrae’s to determine the scale of our Galaxy and the distance to other galaxies (Shapley, Hubble)

(4) The discovery of Hubble’s Law, and it’s application to determine the scale of the universe.

Hubble's Law

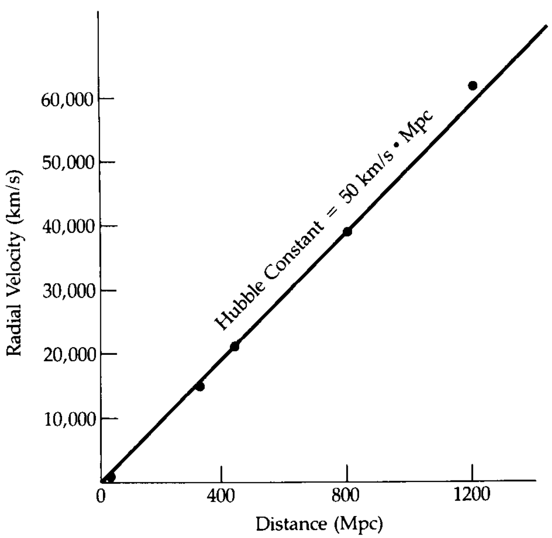
Estimate distance d to a sample of external galaxies using the Cepheid P-L relation.

Measure redshift $z = \frac{\Delta l}{l} = \frac{l - l_0}{l_0}$ of spectral lines for these galaxies.

Hubble found the relation $cz = H_0 d$ where H_0 is the Hubble constant, i.e., greater redshift => greater distance. Note: blueshift ($z < 0$) not observed for distant galaxies.

If redshifts due to Doppler shifts, $\frac{v}{c} = \frac{\Delta l}{l} = z \quad \Rightarrow \quad v = H_0 d.$

Hubble's Law



H_0: units s^{-1}

astronomer's units km s^{-1} Mpc^{-1}.

Hubble's Law

Value of H_0?

Hubble determined $H_0 \sim 500 \dfrac{\text{km}}{\text{s} \cdot \text{Mpc}}$.

But Cepheid calibration was done incorrectly.

In recent decades, various groups found $50 \dfrac{\text{km}}{\text{s} \cdot \text{Mpc}} < H_0 < 100 \dfrac{\text{km}}{\text{s} \cdot \text{Mpc}}$.

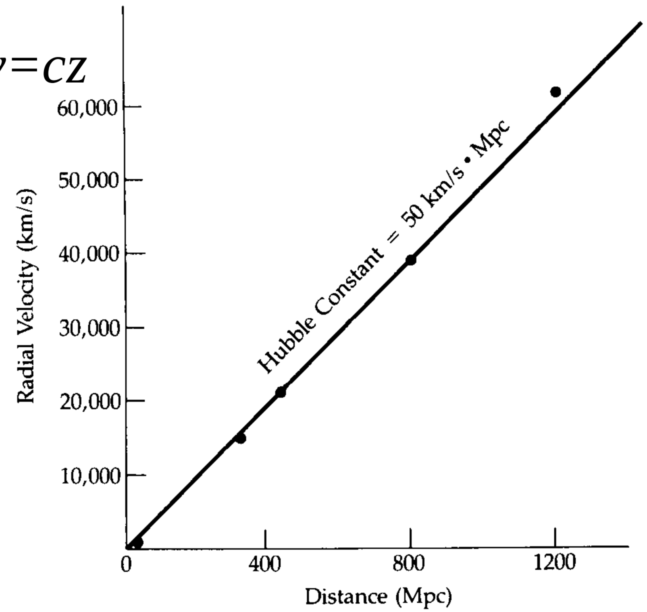
Most recent measurements, $H_0 \approx 70 \pm 10 \dfrac{\text{km}}{\text{s} \cdot \text{Mpc}}$.

Note that Cepheids can only be observed out to a distance ~ 20 Mpc, even with HST, i.e., a redshift $z = H_0 d/c = 0.004$. But we observe galaxies with redshift up to $z \sim 1$, and quasars up to $z \sim 3.5$. How do we get their distances?

Hubble's Law

Can get distances to very distant galaxies with high z by extrapolating Hubble's Law.

$v = cz$



Note that most galaxies too distant for Cepheid distance determination.

Get d directly from Hubble's Law

$$d = \frac{cz}{H_0}, \text{ where } 1 + z = \frac{l}{l_0}.$$

However, if $z > 0.8$, must use relativistic expression

$$d = cz \frac{1 + z/2}{H_0 (1 + z)^2}.$$

Question: What other distance determinants can we use that can check Hubble's Law for large z?

Interpretation of Hubble's Law

Naive interpretation: An expanding universe. Compare Hubble's Law with distance-time relation, $d = vt$. Then, assuming constant expansion velocity v, identify an expansion time

$$t = \frac{1}{H_0},$$ the Hubble time <=> "age of the universe".

$$H_0 \approx 70 \text{ km s}^{-1}\text{Mpc}^{-1} \quad \Rightarrow \quad t \approx 1.4\times 10^{10} \text{ yr.}$$

Origin of expansion => "Big Bang"

Note: we have ignored deceleration (due to gravity) or possible acceleration (due to ?).

The Distance Scale

How do we find distances to celestial objects?

Build up distance scale from direct measurements to nearby objects. Each step calibrated by previous one.

Distance	Method	Outcome
$d = 1$ AU	Radar to planets; Kepler's 3rd Law	Measure Earth-Sun distance
$d < 100$ pc	Trigonometric parallax	Measure distances to nearby stars; get absolute mag H-R diagram from nearby stars
$d \sim 45$ pc	Moving cluster method	Measure distance to nearby clusters; get abs. mag H-R diagram for a large # of stars

The Distance Scale

Distance	Method	Outcome
d ~ few - 10's kpc	Main sequence fitting	Measure distances to other open clusters; get M_V of Cepheids in clusters and calibrate the P-L relationship.
d ~ few - 20 Mpc	Cepheid P-L relation	Measure distance to nearby galaxies
d ~ 100 Mpc	Max. luminosity of Type Ia SN; rotation-luminosity of spirals; size-luminosity of H II regions; others...	Get distance to more remote galaxies with other "standard candles"
d ~ 1000 Mpc	Use Hubble's Law	Distance to farthest objects