The Expanding Universe I

- The Universe beyond our Galaxy
- Cosmic distance ladder
- Hubble’s discovery of expansion
- Relation of redshift to cosmic scale factor
- Hubble time and Hubble length

"The whole universe is expanding, so why be surprised that we’re drifting apart?"
Beyond the Milky Way

- Philosopher Immanuel Kant (1775) was first to suggest that Milky Way was disk of stars, of which Sun is one.
- Kant imagined Universe consisting of many separate, grouped collections of stars like the MW, filling all space.
- Kant’s views did not take hold, since there was no direct evidence yet of other galaxies.
Spiral “nebulae”

- Many nebulae (fuzzy patches of light) were identified by Messier; published catalogue 1780
  - These were intended as aids to comet hunters to reject “uninteresting” objects
  - Some of Messier’s nebulae are true clouds; now known as star forming regions illuminated by hot stars
  - Some looked different

- Herschel investigated nebulae further
  - Suggested they could be star collections like MW

- Lord Rosse first observed that some nebulae have spiral structure (1845)
  - Suggested that they are external “island universes”

- Others thought spiral nebulae were within MW
- Controversy continued through early 20th century
The Orion Nebula (M42)
THE GLOBULAR CLUSTER M13

Credit: Yuugi Kitahara
Andromeda “Nebula” (M31)
M51a and b

- Lord Rosse’s galaxy
More early investigations in and beyond the MW

- Vesto Slipher (1912) showed, using spectral shifts, that some spiral nebulae have very large velocities relative to anything else known in MW (>1000 km/s), suggesting external objects
- Heber Curtis (1917) observed novae (strong flares in stars’ light) in three spiral nebulae
  - Much fainter apparent brightness than other known novae, suggesting great distance
- Harlow Shapley showed, using globular clusters, that Sun is far out in disk of Milky Way
  - However, overestimated MW size by factor three
- “Great debate” between Curtis and Shapley in 1920 concerning whether spiral nebulae were inside (Shapley) or outside (Curtis) the MW
- Controversy was finally settled by E. Hubble in 1924
- Interstellar dust discovered by R. Trumpler in 1930
The “first rung” in the cosmic distance ladder is based on parallax.

- Useful for stars relatively close to the Sun.
- Uses displacement in angle against more distant stars over the course of a year to determine distance $d$. 

Stellar Parallax

[Diagram showing Earth's orbit around the Sun and how parallax is measured between two positions in a year.] 

Star distances are measured in units of the distance from the Sun to the Earth, the Astronomical Unit. The nearer the star, the larger is the angle (called the parallax) between the January and the July observations.
If star wobbles with amplitude of 1 arc-second (1/3600\(^{th}\) of a degree - 1/2000\(^{th}\) diameter of Moon), then it is at distance of 1 parsec (definition of parsec).

1 pc = 3.26 lt-yr

In general,

\[ D(\text{pc}) = \frac{1}{\theta_{\text{wobble}}(\text{arcsec})} \]
Until 1990s, could only detect parallax out to 50pc.

**Hipparcos satellite**
- Designed to measure parallax of stars
- Can detect wobble out to distance of about 1kpc (1000pc)
- Used to map out locations of nearby stars.

**GAIA satellite**
- Launched December 2013
- Can map out positions and motions of stars across the whole galaxy!!
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Distance-brightness relation of “standard candles”

- Distance $d$ based on parallax can be used to determine the intrinsic luminosity $L_{\text{std}}$ of a star of given type with brightness $b$:

$$L_{\text{std}} = 4\pi d^2 b$$

- Once the intrinsic luminosity $L_{\text{std}}$ of a given type of object is known, it can become a “standard candle”
  - For given observed brightness $b$, distance is then derived as

$$d = \sqrt{\frac{L_{\text{std}}}{4\pi b}}$$
Henrietta Leavitt discovered (1912) that a certain class of variable stars called Cepheids had properties that meant they could be used as standard candles:

- she found Cepheids’ luminosity is related to the period of fluctuations in brightness.
- intrinsic luminosity can then be obtained using their apparent brightness and distance based on parallax.
Edwin Hubble
Hubble’s observations

- In studying Andromeda “spiral nebula” with 100-inch telescope on Mt. Wilson, Edwin Hubble first observed a variable star with properties of a Cepheid in 1924
- Hubble determined that Andromeda must be well outside MW!
  - modern measurement: 2 million lyr
  - Distance to Andromeda > 20× MW diameter
- Hubble, with Milton Humason, systematically began to study many other galaxies
- Obtained distances using Cepheids and other estimates
- Obtained redshifts from stellar spectra
  \[ z = \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}} \]
- The “redshift” may actually be either \( z > 0 \) (redder, longer wavelength) or \( z < 0 \) (bluer, shorter wavelength)
Redshift-distance relation

- Ordinarily, a Doppler shifted spectrum is interpreted as a relative velocity of emitter with respect to observer, with \( v = cz \).
- By plotting redshift versus distance, Hubble (1929) found a linear relationship.

\[
\text{Apparent velocity} = c \times z
\]
Hubble’s Law

- Hubble interpreted redshift-distance relationship as a linear increase of the recession velocity of external galaxies with their distance.
- Mathematically, the Hubble law is
  \[ v = H \times d \]
  where \( v \)=velocity and \( d \)=distance.
- Modern measurement gives the Hubble constant as \( H = 72 \text{ km/s/Mpc} \).
- In fact, Hubble’s interpretation is only “sort of” correct.
- What really increases linearly with distance from the MW is simply wavelength of light observed, and this redshift is due to the cosmological expansion of space over the time since the light left the distant galaxy and arrived at the Milky Way!
Interpretation of Hubble law in terms of relativity

- New way to look at redshifts observed by Hubble
- **Redshift is not due to velocity of galaxies**
  - Galaxies are (approximately) stationary in space...
  - Galaxies get further apart because the space between them is physically expanding!
  - The expansion of space, as $R(t)$ in the metric equation, also affects the wavelength of light... as space expands, the wavelength expands and so there is a redshift.
- So, cosmological redshift is due to cosmological expansion of wavelength of light, not the regular Doppler shift from local motions.
Redshift from the expansion of space

As space expands it “stretches” the light waves moving through it, increasing their wavelength, $\lambda$.

Short wavelength implies hot. Long wavelength implies cool.
Relation between $z$ and $R(t)$

Using our relativistic interpretation of cosmic redshifts, we write

$$\lambda_{\text{obs}} = \left( \frac{R_{\text{present}}}{R_{\text{emitted}}} \right) \lambda_{\text{em}}$$

Redshift of a galaxy is defined by

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}}$$

So, we have...

$$z = \frac{R_{\text{present}}}{R_{\text{emitted}}} - 1 = \frac{R_{\text{present}} - R_{\text{emitted}}}{R_{\text{emitted}}} \approx \frac{\Delta R}{R}$$
Hubble Law for “nearby” \((z<0.1)\) objects

Thus

\[ cz \approx \frac{c \Delta R}{R} = c \Delta t \times \frac{\Delta R/\Delta t}{R} = d_{\text{light-travel}} \times H \]

where Hubble’s constant is defined by

\[ H = \frac{1}{R} \frac{\Delta R}{\Delta t} = \frac{1}{R} \frac{dR}{dt} \]

But also, for comoving coordinates of two galaxies differing by space-time interval

\[ d = R(t) \times D_{\text{comoving}} \], have

\[ v = D_{\text{comoving}} \times \frac{\Delta R}{\Delta t} = \left( \frac{d}{R} \right) \times \left( \frac{\Delta R}{\Delta t} \right) \]

Hence \( v = d \times H \) for two galaxies with fixed comoving separation
Peculiar velocities

- Of course, galaxies are not precisely at fixed comoving locations in space.
- They have local random motions, called “peculiar velocities”
  - e.g. motions of galaxies in “local group”
- This is the reason that observational Hubble law is not exact straight line but has scatter.
- Since random velocities do not overall increase with comoving separation, but cosmological redshift does, it is necessary to measure fairly distant galaxies to determine the Hubble constant accurately.
Redshift-distance relation

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Apparent velocity = \( c \times z \)
Distance determinations further away

- In modern times, Cepheids in the Virgo galaxy cluster have been measured with Hubble Space Telescope (16 Mpc away...)

Virgo cluster
Tully-Fisher relation

- Tully-Fisher relationship (spiral galaxies)
  - Correlation between
    - width of particular emission line of hydrogen,
    - Intrinsic luminosity of galaxy
  - So, you can measure distance by...
    - Measuring width of line in spectrum
    - Using TF relationship to work out intrinsic luminosity of galaxy
    - Compare with observed brightness to determine distance
  - Works out to about 200 Mpc (then hydrogen line becomes too hard to measure)
Once the Hubble parameter has been determined accurately, it gives very useful information about age and size of the expanding Universe...

Recall Hubble parameter is ratio of rate of change of size of Universe to size of Universe:

\[ H = \frac{1}{R} \frac{\Delta R}{\Delta t} = \frac{1}{R} \frac{dR}{dt} \]

If Universe were expanding at a constant rate, we would have \( \Delta R / \Delta t = \text{constant} \) and \( R(t) = t \times (\Delta R / \Delta t) \); then we would have

\[ H = (\Delta R / \Delta t) / R = 1 / t \]

ie \( t_H = 1 / H \) would be age of Universe since Big Bang
The expansion of the Universe is speeding up from “dark energy”