Lecture 32: The Expanding Universe
Readings: Sections 26-5 and 28-2

Key Ideas
Measuring the Distances to Galaxies and Determining the Scale of the Universe

Distance Methods:
- Trigonometric Parallaxes
- Spectroscopic Parallaxes
- Cepheid Period-Luminosity Relation
- Galaxy Standard Candles
- Galaxy Luminosities

<u>Hubble's Law:</u>
- Galaxies are receding from us
- Recession velocity gets *larger* with distance

<u>Hubble Parameter</u>
- Present-day rate of expansion of the Universe

<u>Cosmological Redshifts</u>
- Due to the expansion of space
- Redshift distances
- Redshift maps of the Universe

The Distance Problem (again!)
Cepheid P-L relation is good but limited:
- Limit ~30-40 Mpc (and that's with the Hubble Space Telescope)
- Very laborious to use (100's of HST orbits)
- Only works for Spiral or Irregular galaxies
  - Cepheids found in *young* star clusters
  - Ellipticals have only old stars
- Only practical out to the Virgo Cluster
- This is only just next-door in cosmic terms

Need other methods to estimate very large cosmic distances.
Large distances=many light years away=the Universe at a very young age

Mapping the Universe

No single distance method is universal.
Must work up towards large distances.
Bootstrap Process:

- Build up from near to far
- Each step calibrates the next step
- Errors made in first steps affect the accuracy of all following steps

The Distance Ladder

See Figure 26-12

Step 1: The Astronomical Unit

1 AU = Mean Earth-Sun Distance
Method: Geometric Triangulation

- Radar bounced off inner planets
- Orbits of planets give the geometry
- Works out to ~50 AU

Permits measurement of:

- Trigonometric Parallaxes to nearby stars

Step 2: Trigonometric Parallaxes

Calibrated by the AU (size of Earth's orbit)
Method: Stellar Parallaxes

- Use Earth as the baseline
- Ground-based: works out to ~100 pc
- Hipparcos: works out to ~1000 pc

Permits measurement of:

- Luminosities of nearby stars
- Distances to nearby star clusters

Step 3: Spectroscopic Parallaxes

Calibrated by Trigonometric Parallaxes
Method: Spectroscopic Parallaxes

- Relate spectral type to luminosity in calibrated H-R Diagram
- Works OK for indvidual stars
- Works best for clusters of stars

Permits measurement of

- Distance to star clusters out to ~50-60 kpc

Just reaches out the Large Magellanic Cloud

Step 4: Cepheids

Calibrated by cluster H-R diagrams
Method: Period-Luminosity Relation
- Cepheids: supergiants in young clusters
- Calibrate the Cepheid Period-Luminosity relation in the LMC

Cepheids give distances to
- Nearby spiral galaxies out to 30-40 Mpc

Only works for spirals (need Pop I stars)

Step 5: Galaxy Standard Candles

Now that we can measure the distances to nearby spiral galaxies, we need to find a way to measure distances to distant galaxies.
Look for bright standard candles found in both spiral and elliptical galaxies
- Type Ia Supernova explosions
- Planetary Nebula luminosity distribution
- Globular cluster luminosity distribution

Calibrated by
- Cepheid Period-Luminosity distances
- Nearby similar objects (from other steps)

Variety of techniques get used
- Mix and match to seek consistent results
- All rely on previous steps, especially Step 4
- Argue endlessly about the details

Bottom Line
- Works out to 50-100 Mpc, depending on method
- Gives distances out to Virgo and Coma clusters

Step 6: Galaxy Luminosities

Calibrated by the Virgo Cluster distance
Method
- Assume distant galaxies are like nearby ones
- Use correlations between luminosity & distance-independent properties of galaxies

Compute luminosity distances using the entire galaxy

Tully-Fisher Relation for Spirals

Galaxy Luminosity-Rotation Speed relation

Measure rotation speed from 21-cm radio emission (distance independent)

Fundamental Plane Relation for Ellipticals:

Galaxy Luminosity – Line Width – Size relation

Measure absorption-line widths from spectra (distance independent)

Current Status

Current critical areas:

Distance to the LMC, which calibrates the extragalactic Cepheid P-L relation

Refinement of other standard candles, especially Type I supernovae

Search for new geometrical methods

The Expanding Universe

Discovery of Expansion

1914-22: Vesto Slipher, working at Lowell Observatory, measured radial velocities from spectra of 25 galaxies

Found

21 of the 25 galaxies showed a redshift

speeds of some > 2000 km/sec

Most of these galaxies appear to be rapidly receding away from us

Hubble's Discovery

1929: Edwin Hubble measured the distances to 25 galaxies

Used Cepheids in Andromeda & Local Group

Used brightest stars in other galaxies

Compared distances and recession velocities

Discovered

Recession velocity gets *larger* with distance

Systematic expansion of the Universe

See Figure 26-15

Hubble's Law

$$v = H_0 d$$

v=recession velocity in km/sec
d=distance in Mpc
H_0= expansion rate today (*Hubble Parameter*)

$H_0 = 70 \pm 7$ km/sec/Mpc

In words:

The more distant a galaxy, the faster its recession velocity

Only good for galaxies that are "in the Hubble flow", that is, whose motions aren't dominated by random "peculiar" velocities. This formula does not work for Andromeda, for example.

Interpretation

Hubble's Law demonstrates that the Universe is expanding in a systematic way:

The more distant a galaxy, the faster it appears to be moving away from us.

Hubble Parameter: Rate of expansion today

Comments:

Empirical result – based only on data

Not an exact law

Nature of the Expansion

General Expansion of Space

All observers in different galaxies see the same expansion around them.

No center – all observers appear to be at the center

What is the recession velocity?

NOT motions *through* space…

Expansion of space: galaxies carried along

Figure 28-3

Hubble Parameter: H_0

Measures the rate of expansion today

$H_0 = 70 \pm 7$ km/sec/Mpc

Based on Hubble Space Telescope observations of Cepheids in nearby galaxies

H_0 is hard to measure:

- Recession speeds are easy to measure from the shifts of spectral lines
- But distances are very hard to measure
- Galaxies also have extra motions

Cosmological Redshifts

All galaxies (with very few exceptions) are receding from us.
Recession is quantified in terms of the *"cosmological redshift"* of the galaxy, z.

$$z = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$$

Not a Doppler shift: measures expansion of spacetime, not motions through space.
As the Universe expands, recession velocities gets larger, light waves get stretched and redder
"Cosmological Redshift" of light
Figure 28-4

Step 7: Redshift Distances

For nearby galaxies, redshift (z) is directly proportional to the distance through the Hubble Law

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

z=redshift
c=speed of light

This formula is only valid for relatively nearby galaxies.
Method:

- Measure the redshift of a galaxy with spectra

Use the estimate of the Hubble Parameter
Assume pure "Hubble Expansion" or attempt to statistically correct for random galaxy motions.

Allows us to probe the Universe on the largest observable scales.

Limitations:

Value of H_0 is only known at 10%
Need to know the distances from other methods first to measure H_0
Random motions of galaxies affects measurements of z for nearby galaxies
At large distances, the conversion between z and distance is much more complicated.

Astronomers use cosmological redshift as a surrogate for distance, especially for more distant galaxies.

Mapping the Universe

Map the distribution of galaxies using their cosmological redshifts.
Largest maps include ~250,000 galaxies

Reveals sheets and filaments of galaxies surround great voids
Depth is ~500-600 Mpc

Relative distances are good, but the *absolute scale* is only known to ~10%
See Figure 26-22

Hubble's Law & its Discontents

Ideally, we could just use the Hubble Law:

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

At least nearby, all you need to measure is the cosmological redshift, z.
Problem:

What is H_0?