Mapping the universe: need distances to galaxies!

- Identify (and calibrate) properties of galaxies that could serve as "STANDARD CANDLES" -- beyond direct measure by trigonometric parallax
  
  1. Make some measure of an object which identifies its luminosity (like period in Cepheid)

  2. Use this luminosity and measure apparent brightness to infer distance to it

Main-Sequence Fitting

- Start with cluster A (upper) whose distance known via parallax
- Compare with other cluster B (lower)
- Get distance to B from brightness difference

Cepheid variable stars

- Brighter Cepheids have longer periods

On Galaxy Evolution Lane

- Challenge of measuring distances in universe
- Most striking: many galaxies experience collisions thus becoming "interacting galaxies"
- Begin to discuss active galaxies and quasars
- Re-read 21.3 Quasars and active galactic nuclei in detail

- New Homework #11 passed out today
- Third Mid-Term Exam on Mon Apr 19 Evening review by Nick on Thur 7-9 pm
Cepheids variables as standard candles

1. Measure period of variability
2. From period-luminosity relation, infer the luminosity
3. Compare with apparent brightness and thus determine distance

Cepheid variable in M100 (HST)

Number of Fuzzier Distance Estimators

- A. Apparent brightness of (resolved) red and blue supergiants
- B. Size and brightness of H II regions (emission nebulae) or starbirth regions
- C. Intercompare distances so deduced for specific galaxies (overlapping rungs in distance ladder)

Clicker: halo stars

- Massive O-type stars are not found in the galactic halo because they are:
  A. too massive to be kicked into the halo from the disk
  B. so massive that they settle into the thinner disk
  C. too short-lived to have persisted from halo formation until today
  D. too far away for us to see them

Why no O-stars?

- C. Too short lived to be in the halo

Halo stars were born billions of years ago; the most massive stars don’t live nearly that long

Will have disappeared by now (after having “enriched” the proto-galaxy gas with heavy elements)

Distance ladder to measure universe

Different standard candles are useful for different distances

Measuring big distances to galaxies

“STANDARD CANDLES” -- important ones in ‘distance ladder’, or ‘chain’

- 1. Main-sequence fitting
- 2. Cepheid variables
- 3. Tully-Fisher relation
- 4. White dwarf supernovae

Brightness $\sim$ Luminosity / (Distance)$^2$
**Tully-Fisher Relation**

- Fast rotation speeds in spiral galaxies
- \( \rightarrow \) more mass in galaxy
- \( \rightarrow \) higher luminosity

Measure rotation speeds to infer luminosity

Need bright “edge-on” spirals, estimate tilt

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**Even brighter:** White dwarf supernovae

- “Standard explosion” = fusion of 1.4 solar masses of material
- Nearly the same amount of energy released

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**Bright enough to be seen halfway across observable universe**

Even brighter: White dwarf supernovae

- Carbon fusion explosion: mass transfer in binary takes white dwarf ‘over the edge’
- Roughly same amount of energy released (calibrate)

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**Supernovae in very distant galaxies**

Useful for mapping the universe to the largest distances

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**Practical difficulty: White dwarf SN**

- Need to catch them within a day or two of the explosion
- About 1 per galaxy per century
- Need to monitor thousands of galaxies to catch a few per year \( \rightarrow \) galaxy clusters are useful

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**White dwarf supernovae**

- Brighter SN dim more slowly!

DISTANCE ESTIMATE 3

DISTANCE ESTIMATE 4
Distance ladder

Overlapping “standard candles”

DEMO

“HUBBLE CONSTANT”

H₀ = 71 +/- 4 km/sec/Mpc

**Use Hubble’s Law itself to estimate vast distances D**

- Measure velocity, then: \( D = \frac{v}{H₀} \)
- Example: using \( H₀ = 70 \) km/sec/Mpc, and finding that \( v = 700 \) km/sec

\[ D = \frac{700 \text{ km/sec}}{70 \text{ km/sec/Mpc}} = 10 \text{ Mpc} = 32 \text{ million light years} \]

Knowing distances reveals large-scale galaxy clustering

Find clusters + super-clusters’ sheets and voids like ‘bubble bath’

**Use Hubble’s Law for “distances”**

- Measuring distances to remote galaxies is difficult, but measuring Doppler shifts (velocities) is easier from spectra
- Use Hubble’s Law to estimate biggest distances (really "lookback time")!

Telescopes are "lookback" time machines

Today, we see Andromeda as she was 2.5 M years ago!
Lookback time (in expanding universe)

- Say it takes 400 million years for light to get from galaxy A to us in Milky Way.
- Yet during travel in spacetime, both A and MW have changed positions by expansion.
- Thus "distance" is a fuzzy concept – LOOKBACK TIME is better.

Balloon analogy for expanding universe

- On an expanding balloon, no galaxy is at the "center" of expansion; no edge.
- Expansion happens into a higher dimension (2-D surface into a 3-D space).
- Is our 3-D space expanding through a 4th dimension?

Clicker – Cepheids and distance

- Two Cepheid stars, Fred and Barney, have the same apparent brightness. Fred has a period of 5 days, and Barney of 10 days. Which is closer?
  - A. Fred
  - B. Barney

Why A. Fred?

- Fred has a shorter period and so must be less luminous.
- Less luminous but the same apparent brightness means that Fred is closer to us.

Distance ladder to measure universe

Different standard candles are useful for different distances.

Velocity = \( H_0 \times \text{Distance} \)

Different standard candles are useful for different distances.

\[ H_0 = 71 \pm 4 \text{ km/sec/Mpc} \]
Hubble’s Law implies: Universe expands like raisin bread! True for very large scales between galaxies – but not for stars, planets, us!

**REVIEW**

**Making of a spiral galaxy**
- Start with a fairly uniform cloud of hydrogen
- Gravitational collapse forms protogalactic clouds
- First stars are born in this spheroid (such stars are billions of years old → “fossil record”)

**Small variant in spiral making …**
- Several smaller protogalactic clouds may have merged to form a single large galaxy
- May explain slight variations in stellar ages in the MW

**Forming a disk with spiral**
- As more material collapses, angular momentum spins it into a disk
- Stars now formed in dense spiral arms – disk stars are younger!

**Making ellipticals**
- Higher density: much faster star formation uses up all the gas
- Nothing left to make a disk
- Now we see sphere of old stars

**Or now a different story….**
- Spiral galaxy collisions destroy disks, leave behind elliptical
- Burst of star formation uses up all the gas
- Leftovers: train wreck
- Ellipticals more common in dense galaxy clusters
Birth of galaxies in clusters

Few galaxies (none?) BORN alone

Collision of small galaxy with big one

Builds "bridge" and "counterarm"

Close passage: M51 + companion

Close passage of two equal mass galaxies

Builds very long "tails" and wisps

Two galaxies form "The Antennae"

Colliding galaxies – "The Antennae"
**Tidal streams between galaxies**

**Interacting:**
- NGC 2207 + IC 2163
- Spitz + HST

**Interacting system:**
- NGC 6745

**Ring galaxy:** AM 0644-741

**Many interacting galaxy systems:**
- Very distant (big lookback time) with HST

**A major puzzle:** “The Mice” NGC 4676
"Mice" with HST Advanced Camera for Surveys

"Mice" in simulation 1

Rotate the "Mice"

"Mice" in finer simulation 1

Latest simulation 2 of "Mice"

Stefan’s Quintet in HST detail
It may happen to us in future!

Andromeda (M31) in future

M31 and Milky Way in future collision Dubinski